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Values and Benefits of Improving the Performance of Existing Heat Exchangers used in the Hydrocarbon Processing Industries.

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The selection of equipment type, design, and geometry specification in the field of heat exchangers may be considered to be quite a simple task, using relatively accurate performance predictions based on well proven methodologies. In reality and for many cases this concept of assumed accuracy can be far from the truth. Limitations include the inherent in-accuracy of the fundamental data available, anomalies in predicting specific fluid flow dynamics, effects of wall friction causing fluid maldistribution, 2-Phase flow instabilities together with transient and unstable temperature gradients. A further and significant level of uncertainty is the unpredictable impact of fouling.

This all leads to the need for design engineers to make significant and 'subjective allowances' based on 'experience' to meet the level of commercial confidence required to fulfil the technical contract. It follows from the above that often heat exchangers do not meet performance requirements at the beginning or fail to maintain performance level over time. These often critical processing limitations become substantial challenges to plant engineers. An area of fundamental and applied research together with associated product development that has growing success to meet these multi-variable design and performance challenges is discussed in this paper.

The paper includes: The contribution and benefits provided by the use of CFD in determining boundary layer effects and combating fluid mal-distribution. The value of selecting the appropriate wall shear rate to reduce the effects of fouling. It explains the application of enhancement techniques to significantly improve the performance of tubular exchangers. Presentation of a refinery case study, demonstrating plant improvement energy recovery and associated improved plant economics.

1. Introduction

Tube-side heat transfer enhancement technology in the form of Wire Matrix technology (hiTRAN System) has been available for more than 35 y to improve the thermal performance of tubular heat exchangers. Its main application area is the use of this technology in new equipment design for exchangers with laminar tube side flow where considerable size reductions are achievable due to the up to 16 times increased tube side heat transfer performance. Increased focus is now given for the use of this technology in exchangers with operational problems in new and retrofit designs. Aside from the obvious potential of increased duty and therefore increased exchanger efficiency, applying this technology can also often provide improved operability as will be shown for specific operation conditions.

2. Reducing the adverse effects of uneven fluid distribution

Design calculation of the thermal performance of tubular heat exchanger does in general assume an even fluid distribution within a tube bundle but also within a single tube. For certain operating conditions, this is not necessarily the case and can lead to underperforming units. This enhancement technology can be useful to solve those issues.

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2.1 Bundle tube side fluid maldistribution

Severe uneven distribution of the tube side flow within the different tubes of a bundle can result in an underperforming heat exchanger. Low flow regions within the bundle are also more prone to fouling, resulting in an even worse performance. Geometrical aspects like large bundle diameter, single pass configurations, small nozzle sizes and axial nozzle location, in conjunction with low frictional tube side pressure drop contribute to an uneven fluid distribution. In a revamp, the geometrical conditions are difficult to alter, whereas the low frictional pressure drop offers the possibility to use hiTRAN® Thermal Systems technology. The matrix density and also installation length can be adapted to the level of pressure drop required to remedy poor distribution. With this flexibility, it is even possible to fine-tune the frictional pressure drop requirements over the cross-section of a bundle by varying Element geometries in terms of packing density. In addition to the improved distribution the Elements also contribute to an improved tube side heat transfer coefficient.

2.2 Tube fluid maldistribution

In laminar flow, the heat transfer is often dominated by mixed convection. In mixed convection, a secondary flow profile caused by density differences is superimposed on the forced velocity profile in the flow direction (Oliver, 1962). Under these conditions natural convection superimposed on the main flow causes a rise of less dense fluid towards the upper tube region, whereas the more dense fluid accumulates at the bottom of the tube. The direction of movement within the tube depends on whether the tube is heated or cooled. Computational fluid dynamic (CFD) can be used in order to simulate such behavior. This is shown in the cross-sectional flow pattern on the left (a) in Figure 7.

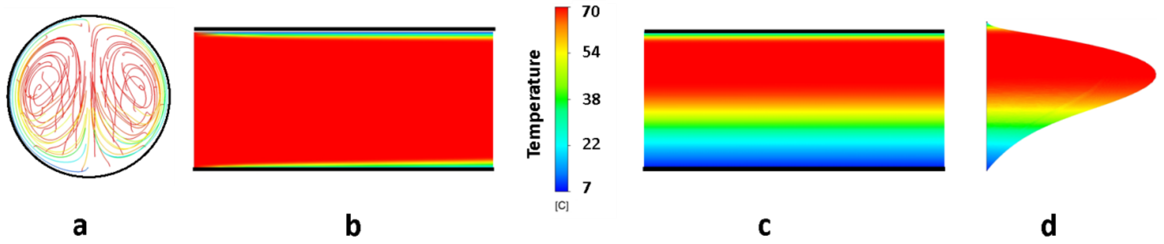

Figure 1: CFD simulation of flow in 2.5m x 25.4mm horizontal tube at Reynolds 250, inlet 70°, wall 7 °C and dynamic viscosity 12 cP (b: inlet; c: outlet; d: velocity profile at outlet)

As a result of the natural convection effects the temperature over the cross section of the tube can become stratified (c), with the highest temperature at the top and the lowest towards the bottom of the tube.

This flow stratification has an impact on the predictability of heat transfer since, as shown in Figure 1**c**, the temperature of the fluid at tube bottom area approaches the temperature of the cooling fluid outside of the tube (7°). This in effect equates to a loss in heat transfer area, since here the temperatures pinches. Due to the complex flow patterns, the extent of this pinch area is difficult to predict and can severely limit heat transfer performance (Dooley, 2010). For this reason, heat transfer in mixed convection flow is difficult to correlate. It is also evident that the stagnant flow areas can promote fouling due to the absence of sufficient fluid movement. Again, CFD simulation was employed in order to investigate the impact of fluid mixing on flow stratification with hiTRAN® Thermal Systems. The simulation results presented in Figure 2 show a flow pattern over the cross section of the tube which is substantially different to the plain empty tube.

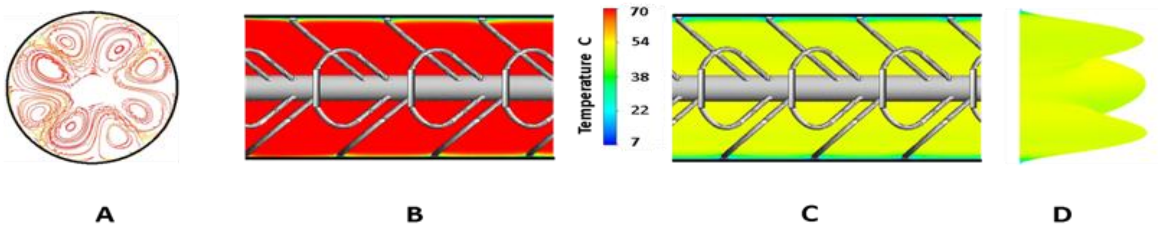

Figure 2: hiTRAN® CFD simulation of flow in 2.5 m x 25.4 mm horizontal tube at Reynolds 250, inlet 70°, wall 7 °C and dynamic viscosity 12 cP (B: inlet; C: outlet; D: velocity profile at outlet)

Due to the mixing action of the Element, temperature differences between adjacent fluid layers are much smaller. For that reason, the driving force for natural convection, which causes flow stratification is diminished.

Due to the considerably higher heat transfer the measured / simulated mixed outlet temperature is much lower with 49.9 °C compared to 61.8 °C for the empty tube case. No stagnant velocity zones towards the bottom of the tube are present when operating with hiTRAN® Thermal Systems.

This also has implications on the residence time distribution which is much narrower than in case of empty tube flow. This is beneficial for applications which are sensitive to long residence times on cooled or heated surfaces. Degradation of fluids at elevated surface temperature or crystallization of wax on cooled surfaces can be a serious problem when processing crude oil and its derivatives.

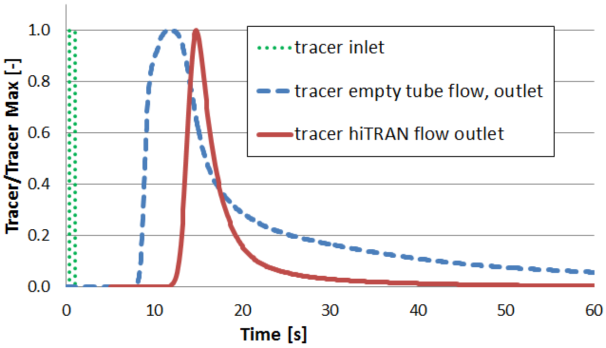

Figure 3: Calculated residence time distribution in plain empty tube and tube equipped with hiTRAN® at Re = 250

2.3 Thermodynamic non-equilibrium in stratified two phase flow

Another form of fluid mal-distribution within the tubes can be encountered in two phase flow heat transfer. In gravity controlled two phase flow regimes the liquid phase will accumulate towards the bottom of the horizontal tube.

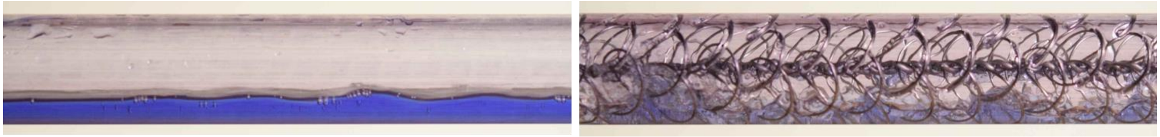

Figure 4: Wavy stratified two phase flow at mass flux of 50kg/m2sec and gas mass fraction of 0.18 in transparent tube; left plain empty, right hiTRAN® enhanced.

In Figure 4 the flow conditions in a 20 mm transparent tube are shown with an air water mixture. The two phases are separated and flow with different velocities of 3.3 m/s (Re ~11,000) for the gas and < 0.1m/s (Re ~ 1.000) for the water. There is little interaction between the water and gas phases. Those situations can be found often towards the end of a condensation process in a horizontal tube. In multicomponent condensation, the gas and vapour phase have to be cooled in order to maintain the condensation process but due to the low Reynolds numbers the cooling potential is limited. In addition, due to the limited interaction between gas and liquid phases non-condensable components will accumulate at the interface and limit the mass transfer in turn limiting the condensation process. In general heat exchanger design programs assume equilibrium conditions for their calculations and in such situations temperatures can be very different for the phases causing insecurity when designing for those scenarios. As shown in Figure 4 the technology improves the interfacial mixing and mass transfer. In addition, the heat transfer and therefore the cooling duty will increase considerably in the liquid and vapour phases. Since those situations are often encountered towards the exit of condensers, Wire Matrix Systems may be installed as a partial length to limit the pressure drop penalty which can be important for such applications.

3. Operational benefits in terms of more stable operation

Creating flow stability in shell and tube heat exchangers using enhancement techniques can also be a practical option for improvement.

3.1 Suppression of flow instabilities in thermosiphon reboilers

Unsteady flow in reboiler applications can cause operational and performance problems. The causes for these instabilities are complex. Instabilities in two-phase flows are sensitive to pressure changes in the system. Low system pressures tend to show a higher tendency towards instabilities. Under thermosiphon operation conditions “density wave oscillations” are the most common form of fluid fluctuations. According to Boure et al. (1973) certain types of flow instabilities encountered in reboilers can be avoided by installing a throttle valve upstream of the exchanger. According to Arneth and Stichlmair (2001) it is common practice to restrict the flow with a suitable orifice or gate valve in the inlet piping of the reboiler to manage fluctuating flow behaviour. In a more recent review paper Nayak and Vijayan (2008) report always positive effects in forced circulation reboiler in case of additional pressure drop in the subcooled single-phase region. In general this is also the case for thermosiphon reboiler applications. When designing a reboiler in such a way that hiTRAN® Thermal Systems are installed only in the sub-cooled region additional pressure drop is induced into this region. This has similar effects as a flow restriction in the inlet of the exchanger with the additional benefit that the additional pressure drop is converted into flow turbulence with higher tube side heat transfer in this region. Hammerschmidt and Scholl (2012) investigated flow instabilities in a single tube thermosiphon reboiler. Under empty tube vacuum conditions, the water flow collapsed, when operating with liquid heads below 80 % of the tube length, whereas with hiTRAN® Thermal Systems a stable recirculation was maintained with even lower liquid heads. When operating with the more viscous water/glycerol mixtures under vacuum conditions the changes in flow stability were even more pronounced. In the empty tube experiments for liquid levels of 100 % tube length and below severe fluctuations were measured. In contrast, the tube with Wire Matrix installed over the whole tube length showed, for all liquid levels investigated, higher recirculation flow with only minor fluctuations. As reported previously this also has a beneficial impact on the measured heat transfer in such scenarios.

3.2 Operation in transitional and film boiling flow regime

Vaporizers which operate under dry wall conditions can be difficult to predict since the mechanism for the onset of transitional and film boiling are poorly understood. The extent of the so called transitional and film boiling region has to be known since dry wall heat transfer rates can be as low as 1/30th of the wet wall heat transfer coefficient (Thome, 2004). As shown in the case study below (Table 1) hiTRAN® Thermal Systems technology can be used to debottleneck poor performing vaporisers where the cause is dry wall condition. The use of this type of enhancement affects film boiling mechanisms in two ways.

Table 1: Revamp of ethylene vaporizer with hiTRAN®

	Plain empty	hiTRAN® (after retrofit)
Flow rate [kg/sec]	14.5	21.1
Temp. in/out [°C]	-100 / - 1 (saturated)	-100 / 30 (superheated)
Pressure in / out [bar]	40 / 39.9	40 / 39.7
Heat transfer [W/m^{2}K]	613	2,390
Heat duty [kW]	261	618

Experimental research shows increased critical heat flux values for the onset of film boiling when compared with empty tube conditions (Mergerlin et al., 1974). The shift to higher heat flux can be explained with lower wall superheat due to higher convective boiling rates and a suppression effect on the generation of nucleation sites (Drögemüller, 2015).

In cases where film boiling is sustained even in the presence of enhancement, it can be expected that the heat transfer rates in the vapour blanket are increased. The mechanism of enhancement is similar compared to single phase flow where the matrix generates near wall turbulence in the vapour blanket.

Feedback from industrial applications does confirm these assumptions. This is illustrated in a real case study, a BEU 2 pass TEMA type shell and tube heat exchanger (702 tubes, 4m length) with ethylene evaporating on the tube side. The exchanger originally performed below specification. Evaluating the process conditions, convective film boiling over large sections of the exchanger was suspected. After retrofitting the exchanger with hiTRAN® elements the increase in performance indicated suppression of film boiling with much higher heat transfer. In Table 1 the conditions before and after retrofit are shown.

3.3 Reduction of mist flow in vaporisers

Droplet carry-over can lead to operational problems with rotating process equipment. Mist flow in vaporizers is where remaining liquid is dispersed as small droplets in the vapour stream. The saturation temperature of the droplet increases with decreasing radius and makes it more difficult to evaporate small droplets. In addition, the velocity-slip between the vapour and the droplet decreases with smaller droplet size. A smaller velocity difference in turn reduces the interfacial heat transfer. This means that for small droplets the vaporization is mainly controlled by the temperature difference between droplet and vapour. Since hiTRAN® Thermal Systems increases the single phase heat transfer in gas flows several fold the superheat can be increased substantial for a given tube length compared to an empty tube. This superheat relative to the droplets is beneficial in vapourising the remaining liquid.

Additionally, Wire Matrix Systems can have a demister effect agglomerating droplets and therefore increasing the relative velocity between vapour and droplets, increasing therefore the heat transfer at the interface. In revamp applications, it is often advised to install the wire matrix only over a short flow length where droplet carry over is most likely, this will help to reduce the additional pressure drop after the revamp.

4. Longer operation time under certain fouling conditions

Fouling characteristics are influenced largely by the properties of the thermal and hydrodynamic boundary layers. Heat transfer enhancement devices such as hiTRAN® Matrix Elements have been used successfully as a tool to influence both wall temperatures and wall shear stress in revamp situations. Research into the change of velocity profile in Wire Matrix enhanced flow shows a much steeper near wall velocity gradient compared to empty tube behaviour (Droegemueller et al., 2013). This equates to higher wall shear stress as indicated by equation (1):

$$\tau_W = \eta \cdot \frac{\partial v}{\partial y} \tag{1}$$

Wall temperatures are affected by the increased tube side heat transfer coefficient. Neglecting wall resistance and any fouling layer, the wall temperature can be expressed as follows:

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

For an increased tube side heat transfer coefficient, the wall temperature approaches the tube side bulk temperature.

4.1 Chemical reaction fouling

Crude oil fouling can be characterized as chemical reaction fouling. The fouling behaviour can be modelled reasonably well with the Ebert and Panchal Model (Ebert and Panchal, 1997) and its variants. Common to these types of model is a deposition and a suppression term. The deposition term is strongly influenced by the film (wall) temperature of the fluid. The suppression term describes how the influence of wall shear forces counteracts the build-up of foulant. Those models indicate that crude oil fouling is sensitive to wall temperature level and wall shear forces. Research also show that for particular crude a threshold temperature and wall shear force for which fouling can be suppressed can be found (Mengyan, 2012).

hiTRAN® Thermal Systems is of special interest where the wall temperature can be reduced considerably. Another area of successful applications in crude oil services are revamps in exchangers with very low flow velocities and therefore also very low wall shear forces. These revamps are undertaken without modification of pass partitions and can lead to a considerable increase in wall shear force and tube side heat transfer.

4.2 Waxing inside tubes

In viscous cooling applications, the viscosity gradient of the fluid to be cooled can be very steep. Particularly in air cooled applications, where the temperature outside the tubes is a function of ambient conditions, the wall temperatures can fall below the pour point temperature resulting in waxing inside the tubes. The stagnant fluid will form an insulating layer which significantly impacts the heat transfer and hydraulic performance of the cooler. Wire Matrix Systems, can be used to mitigate these problems. As shown in equation (2) due to the increased tube side coefficient the temperature gradient from the bulk flow to the wall is reduced considerably which can help to keep the temperature level above the pour point temperature. Figure 1 and Figure 2 in section 2.2 also indicate the improved back mixing of viscous fluid near to the wall to the bulk flow.

5. Conclusion

This paper gives detailed information about the potential benefits when using heat transfer enhancement technologies such as hiTRAN® Thermal Systems in situations where the real condition in a heat exchanger differs from the ideal condition assumed in heat exchanger design software. Due to tailored pressure drop and increased mixing a more homogeneous fluid distribution within tubes and bundles is achieved eliminating uncertainties in empty tube design. Operational problems such as flow instabilities or operation under film boiling mist flow or fouling conditions can also be improved, when using tube side enhancement. The technology can be used for new exchanger design and also in retrofit scenarios.

Nomenclature

Symbols

h	[W/m^{2}K]	heat transfer
T	[°C]	temperature
Y	[m]	Wall coordinate
τ	[Pa]	shear stress
η	[Pas]	dynamic viscosity
∂		differential

Subscripts

i	internal, inside
o	external, outside
W	Wall

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