Optimising shell and tube heat exchanger operation

Case studies show how inserts improve heat transfer coefficients, mitigate fouling and reduce end-of-run pressure drop, as demonstrated with the preheat train of a CDU

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Several studies published by Total Energies and Petroval have examined the improvements that can be obtained from tube inserts in heat exchangers. The benefits of using a combination of tube insert technologies are manifested in extended run lengths between cleaning shutdowns, an increased heat transfer coefficient, a reduced fouling rate, and stability of pressure drop.

From an economic viewpoint, the payback is achieved within a few months from four sources of improvements: the preheat train energy saved (by the increase in the heat transfer), the reduction in maintenance cost (reduced cleaning frequency), the increased throughput, and positive environmental impact stemming from the reduction in CO_2 emissions (as a consequence of the better heat transfer performance). Indeed, a very substantial benefit can be obtained if a unit is bottlenecked by a heat transfer limitation or the furnace.

Technology limits

Limiting the carbon footprint is now essential to achieve net-zero emissions in the oil industry by 2050. This ambitious target will require large investments in new technologies for heat transfer efficiency and carbon capture. However, the technologies that will be required in the future are not yet available at an industrial scale; time is needed for their maturation, investment, and timely operation.

The oil industry relies mainly on preheat shell and tube heat exchangers to reduce the amount of firing required in fired furnaces. However, the performance of these exchangers is often limited by fouling and mechanical designs not upgraded to the required level of operation. There are tube insert technologies available on the market that offer a quick solution to enhance the performance of shell and tube exchangers. These provide immediate improvements in heat transfer from start of run (SOR) with no modifications to the exchangers or the operating conditions.

The benefits of using tube insert technologies were previously demonstrated in terms of an increased heat transfer coefficient[1,3], reduced fouling rate,[2] and stability of pressure drop. This current study will only consider fouling in crude oil preheat trains caused by asphaltene deposition and/or coke formation on hot surfaces.

In these tests, heat exchangers forming part of preheat trains in three refineries were equipped with new inserts. Their performances were monitored over two to four years, depending on the circumstances, and compared to the durations of previous runs in similar process conditions. The improvements in heat transfer and the impact on CO_2 emissions will be further highlighted.

Fouling reduction case studies

Case A – Rotational effect

The Turbotal rotating device is hooked onto a stationary head and installed at the inlet end of the heat exchanger tube (see **Figure 1**). This system is a continuous online cleaning device, the purpose of which is to reduce the fouling layer at the tube walls by means of a mechanical effect.

The device uses the energy of the flowing medium in the tubes to achieve rotation at around 1,000 rpm during the whole run duration. This rotation speed is determined at the design stage by the mechanical design of the Turbotal and issued from correlations determined on experimental skids.

The extra pressure drop generated is typically in the range of 100 millibar per pass at a flow velocity of 1.0 m/s, with a lifetime limited to three years due to mechanical erosion of the parts. The last two pairs of heat exchangers just before the furnace were suffering from severe fouling over a period of less than one year. All four heat exchangers were equipped with Turbotal and operated in the same

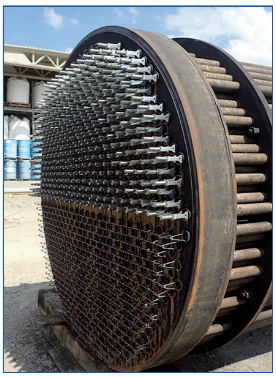

Figure 1 Turbotal on a tube bundle

Heat exchangers used in Case A – design and operating conditions	
Position in the train	Just before the furnace
Number of bundles	2 branches of 2 bundles
No. of tubes per bundle	626
Tube length	6,100mm
OD/BWG	1"/12
Product tube/shell side	Crude/atmos residue
Flow rate (tube side)	260/330/430 t/h
Flow velocity (tube side)	1.0 to 1.70 m/s
Tube inserts	Turbotal
Replacement frequency	Every 2 to 3 years

Table 1

Heat exchangers used in Study B – design and operating conditions	
Position in the train	Just before the furnace
Number of bundles	2 bundles in parallel
No. of tubes per bundle	600
Tube length	6,100mm
OD/BWG	1”/12
Product tube / shell side	Crude/bottom P/A
Flow rate (tube side)	431 t/h design
Flow velocity (tube side)	1.87 m/s
Tube inserts	Spirelf
Replacement frequency	Every 3 years

Table 2

Figure 2 Spirelf on a tube bundle

Figure 3 Fixotal devices in the heat exchanger

range of process conditions as previously (see **Table 1**). The monitoring of the performance was then compared to the previous data; the comparative trend of the outlet temperature will be presented in the results section.

Case B – Vibrational effect

The Spirelf vibrating device is fixed on both tube ends by a fixing wire (see **Figure 2**). This system also serves as a continuous online cleaning device, reducing the fouling layer on the tube walls by means of a mechanical effect.

The vibrating device uses the energy of the flowing medium in the tubes to convert it into vibrations of the device, both radial and longitudinal. The extra pressure drop generated by the device is typically in the range of 200 millibars per pass for a flow velocity of 1.0 m/s. The lifetime of the device is limited to six years since it must be removed and replaced at each turnaround for internal cleaning and inspection of the heat exchanger tubes.

The last pair of heat exchangers, just before the furnace, suffered from severe fouling over a period of less than one year. The two heat exchangers were equipped with Spirelf and operated in the same range of process conditions as previously (see **Table 2**). The monitoring of the performance was then compared to the previous data. The comparative trends of the duty achieved and the flow rates will be presented in the results section.

Case C – Heat transfer effect

To promote turbulence at the inside tube surface, the Fixotal system significantly increases shear stress at the wall, preventing product stagnation in the boundary layer adjacent to the tube. The purpose of this fixed device is mainly to increase the rate of heat transfer by renewing the boundary layer at the tube wall, with an appreciable side effect on fouling mitigation, including certain types of fouling linked to wall temperature, such as polymerisation, paraffin solidification, scaling, and crystallisation.

The extra pressure drop generated by the device is typically in the range of 200 millibars per pass for a flow velocity of 1.0 m/s. An example of Fixotal installed in a tube bundle is presented in **Figure 3** to illustrate the device once installed.

The chosen case study will review the performance of a complete preheat train of 12 heat exchangers that are all operated with the same fluids. Crude is flowing on the shell side from the desalter to the furnace, and atmospheric residue is flowing counter-current on the tube side from the tower towards the beginning of the hot train.

Only the last three exchangers out of the 12 were equipped with Fixotal technology and operated in the same range of process conditions as previously (see **Table 3**). The monitoring of the performance was then compared with the previous data; the comparative trends of the overall heat transfer coefficient (OHTC) and duty will be presented in the results section.

Due to a lack of instrumentation, only three temperature measurements points were available on each flow pass: at the inlet, in the middle (after six bundles), and at the outlet. Consequently, the improvements achieved in the last three heat exchangers were mitigated with the normal performance of the other three that were not equipped between the two temperature indicators.

Heat exchanger used in Study C – design and operating conditions	
Position in the train	Just before the furnace
No. of tubes per bundle	732
Tube length	5,000mm
OD/BWG	1”/12
Product on tube / shell side	Reduced crude / crude
Flow rate (tube side)	134.2 t/h
Flow velocity (tube side)	0.80 m/s
Tube inserts	Fixotal
Replacement frequency	Every 4 years

Table 3

Case A results

The trend presented in **Figure 4** shows the OHTC of the four heat exchangers in operation on comparative runs. The reference run in blue lasted only 183 days, with a significant loss of performance as the OHTC dropped from 230 kcal/h.m² °C at SOR to 87 kcal/h.m² °C within this six-month period. After this a shutdown and mechanical cleaning were required to recover heat transfer on these exchangers.

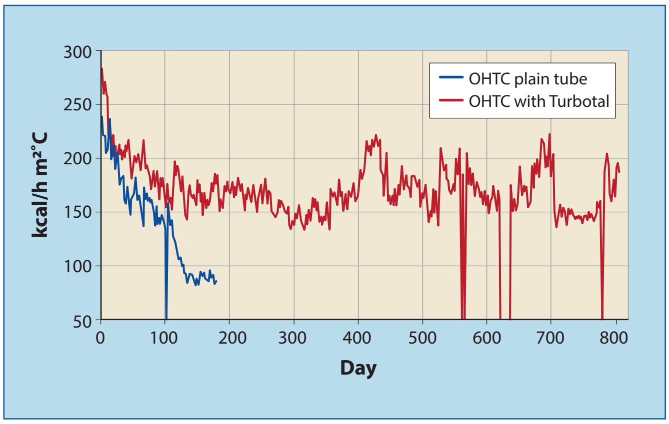

Figure 4 Trend of OHTC for both cases with (red) and without Turbotal (blue) in the same flow conditions

Impact on energy savings and CO_2 emissions on heat exchangers used in Study A* **	
	With Turbotal
Gain on energy recovery (Gcal/yr)	18,200
Gain on energy recovery (TOE/yr)	1820
Energy savings	**1092 k€**
Gain on CO_2 emissions (tons first yr)	5,460
Reduction in CO_2 emissions	**546 k€**

Table 4

The comparison of the first six months with the Turbotal rotating device highlighted the direct benefits that are summarised in **Table 4** on heat recovery in the range of 1,092 k€. There was also a significant reduction in the CO_2 emissions from the furnace, about 560 tons of CO_2. Depending on the location, these emissions can be subjected to taxes at different rates over the world (CO_2 emissions are being taxed at 100 €/ton in Western Europe.)

In comparison, the run with the rotating device lasted 820 days of continuous operation. The SOR was typically with an OHTC of 270 kcal/h.m² °C, which dropped slowly to 150 kcal/h.m² °C within 300 days and remained in the range of 150 to 200 kcal/h.m² °C depending on the flow conditions.

This phenomenon is due to the fouling mitigation during the run. The Turbotal rotating device significantly reduces the fouling rate but cannot prevent fouling deposition from occurring. Some previous work identified that fouling resistance with the rotating device ends up with an asymptotic profile corresponding to the distance between the tube wall and the rotating device.[4]

Run lengths were multiplied by a factor of four, from 183 days for bare tubes to 820 days with the rotating device. The fouling mitigation allowed improved fouling rate control and, consequently, control of heat exchanger performance and pressure drop related to the fouling layer, even though no direct pressure drop measurement was available on these four exchangers.

A payback analysis was done on this application to evaluate the energy gains (see **Table 4**) compared to the Turbotal cost installation, which was in the range of €130,000. The payback calculated by considering only the cost of energy and the gain on CO_2 emissions was about one month. However, some other sources of savings should also be considered, such as reduction of maintenance cost (avoidance of mechanical cleaning) and production losses (reduction of throughput during partial shutdown for cleaning).

Case B results

The trend presented in **Figure 5** shows successive runs during which the duty (blue trend) was plotted. The reference run, bare tubes, started in November 2014. The average duty from 30/11 to 22/04 was roughly 36 GJ/h. The duty then decreased from roughly 36 GJ/h to 22 GJ/h by 28 November 2015, for an average of 30 GJ/h over the entire reference run.

The drop in duty was about 40% in one year, even though the flow rates on tube and shell sides remained very stable and close to the design case. The flow rate across the heat exchangers remained close to the design value, which resulted in a lower coil inlet temperature (CIT) at the furnace and extra consumption of fuel to compensate for this

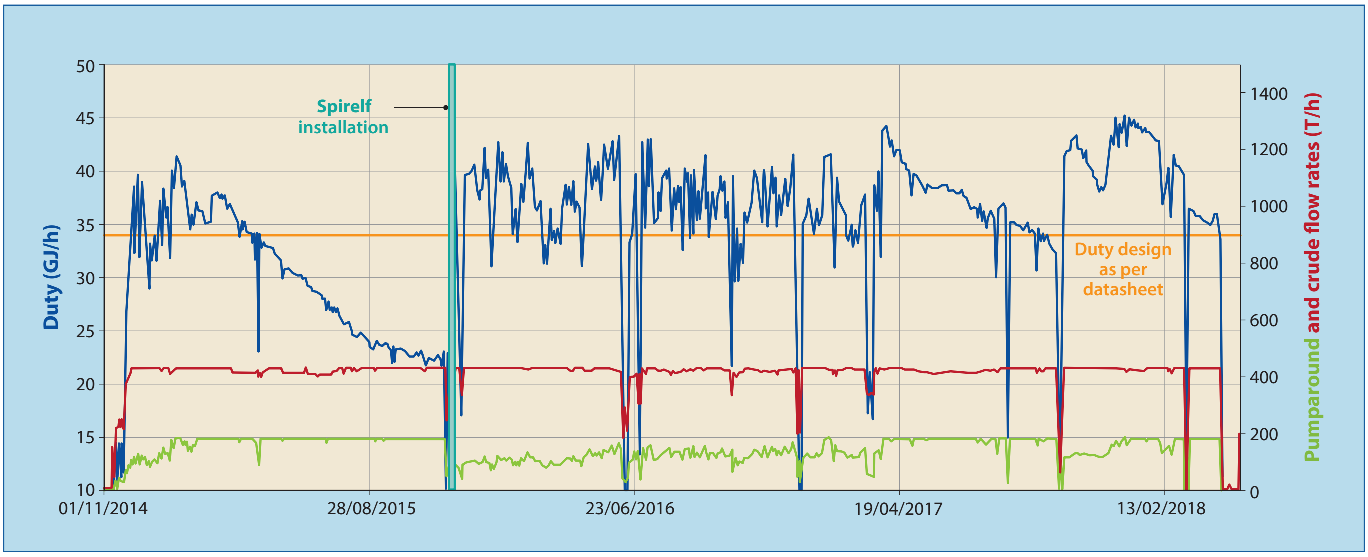

Figure 5 Trend of exchanger duty (blue) equipped with Spirelf vs crude flow rate (red) and bottom pumparound flow rate (green)

loss of preheat.

The Spirelf vibrating devices were implemented during a cleaning shutdown, and the performance of the exchangers was represented on the same trend. After the installation on 29/11/2015, the average duty was 37 GJ/h, and it was perfectly maintained at this level until 19/04/2018, the date of the turnaround of the unit after 872 days in operation.

Over the entire run with the vibrating devices, the crude flow rate was at design value. However, the performance of the heat exchangers was limited by the regulation of the unit operating on the shell side flow (specifically the bottom pumparound flow rate). A few unit upsets occurred, but the exchangers were never opened, and performances benefited from occasional unit recirculation, such as October 2017.

The implementation of Spirelf in these heat exchangers considerably increased the run length from one year to two-and-a-half years. Additionally, there was a significant increase in duty, averaging at 25% and equivalent to the firing of more than 100 tons of fuel gas per month.

The savings on fuel consumption over the first year amounted to 872 k€, and the benefit related to avoided CO_2 emissions was in the range of 436 k€, as summarised in **Table 5**.

Impact on energy savings and CO_2 emissions on heat exchangers used in Study B* **	With Spirelf
Gain on energy recovery (Gcal/yr)	14,500
Gain on energy recovery (TOE/yr)	1,450
Energy savings	**872 k€**
Gain on CO_2 emissions (tons first yr)	4,350
Reduction in CO_2 emissions	**436 k€**

Table 5

Case C results

The trend presented in **Figure 6** shows a reference run from November 2016 to October 2020. From November 2020, a new run started, and the OHTC of the six exchangers, including the three equipped with Fixotal (red), was plotted. The trend in blue is the OHTC of the train's first six heat exchangers (HXs), and the green trend is the crude flow of the unit showing operating condition sustainability. The trend presented in **Figure 7** shows the duty comparison between the last six HXs (red) and the first six HXs (blue) between the two consecutive runs.

- **SOR**: From the reference run, it was identified that within six months, the OHTC of the last six HXs (red) dropped to the level or below the first six HXs (blue), showing the large impact of fouling on the performance of the exchangers.

The implementation of Fixotal tube inserts to promote shear stress in the last three HXs was visible from the SOR, with an OHTC 26% higher than the reference run over the first three months. This was a consequence of the higher turbulence generated on the tube side, which is visible in the duty exchanged in **Figure 7**, with a +8.3% increase compared to the reference run.

- **Until chemical cleaning:** From the reference run, after six months, the performance of the last six HXs continued declining to an OHTC of 200kJ/h.m² °K until a chemical cleaning (vertical dotted line) was performed in late October 2018 (two years of operation).

The comparison with the Fixotal run showed that the OHTC of the last six HXs consistently remained above the OHTC of the first six HXs but declined significantly to 350 kJ/h.m² °K late in September 2022 (period of chemical

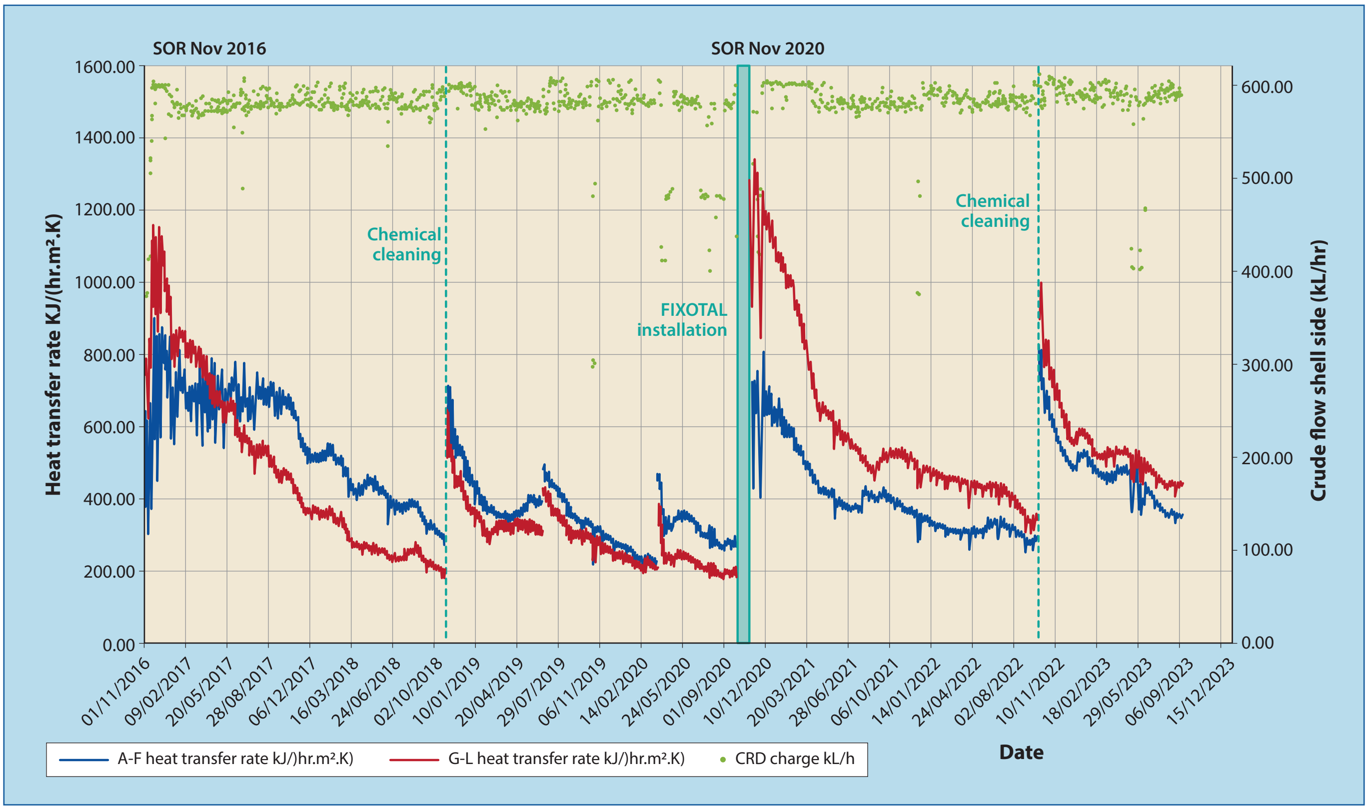

Figure 6 Trend of OHTC with Fixotal equipment on half of the exchangers (red) Study C

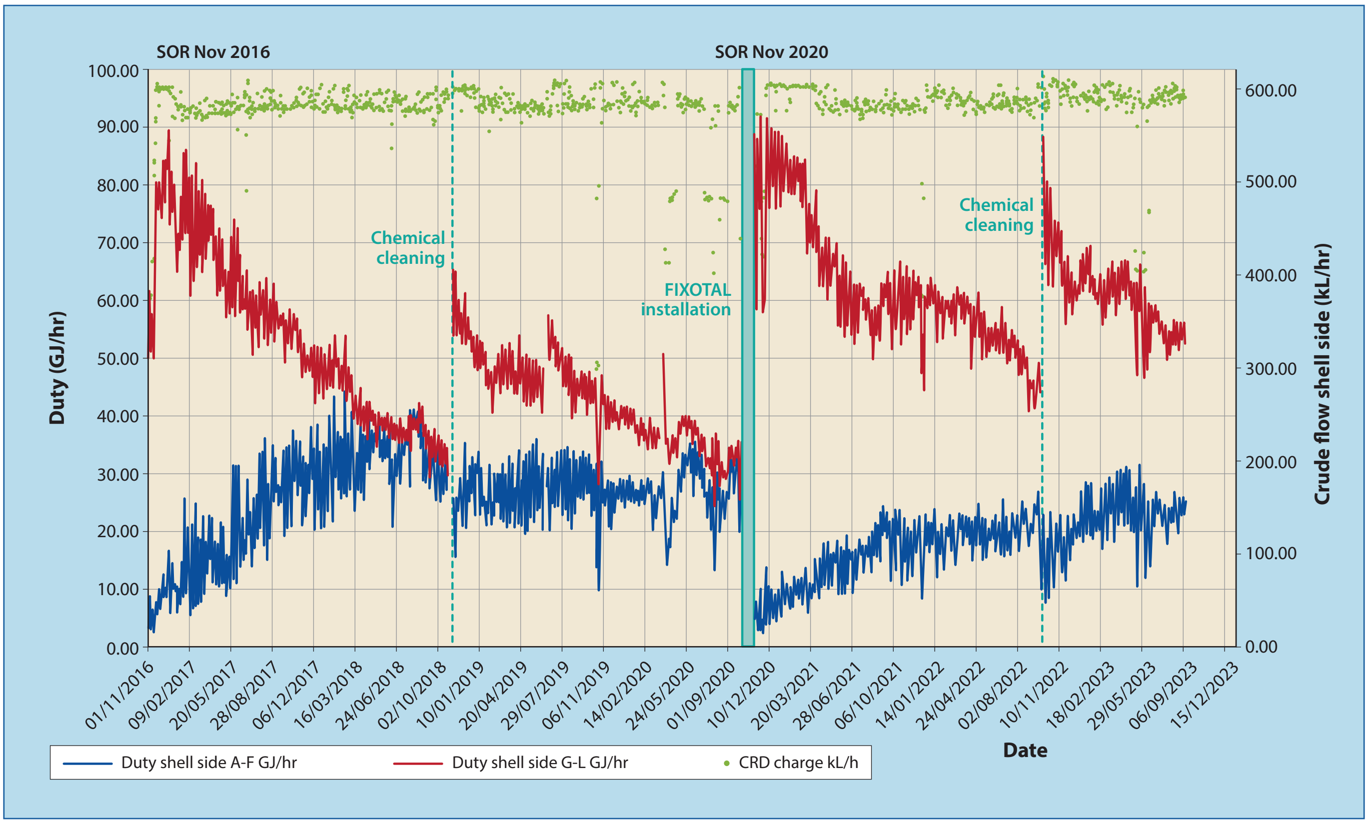

Figure 7 Trend of duty with Fixotal equipment on half of the exchangers (red) Study C

cleaning of the exchangers, vertical dot line) after two years of operation. The last six HXs were then delivering +75% OHTC compared to the reference run at the same duration, even though only the half of the HXs were equipped with the shear stress promoter.

The evaluation of the duty exchanged before the chemical cleaning revealed that 66% of the train's total duty was achieved through the last six HXs, compared to only 52% during the previous run. The gain in duty before the chemical cleaning was in the range of 14% of duty on the complete train, compared to the reference run for the same run duration.

Knowing that the shear stress promoter will only influence the tube-side fouling rate and heat transfer coefficient, the performance of the last six HXs was impacted significantly by the fouling on the tube side of the first three HXs and the fouling on the crude oil shell side of the six HXs, which was the main contributor to the performance limitation.

- **From chemical cleaning:** Chemical cleanings are typically performed after two years of operation, halfway through the four-year turnaround cycle. This cleaning consists of light aromatic gasoil recirculation on both tube and shell sides to soften the fouling material, followed by steaming to flush and remove part of the fouling material. It is well known that this type of operation does not allow a full recovery of performance, as the older deposits harden and age, so only mechanical cleaning would be efficient to fully recover heat exchanger performance.

The evaluation of the OHTC after the chemical cleaning revealed a significant recovery for both runs. However, the reference run still indicated a lower OHTC for the last six HXs. In contrast, for the run with the shear stress promoter, the last six HXs were still producing a significantly higher OHTC of 990 KJ/h.m² °K in comparison to the reference case at 660 KJ/h.m² °K +50%. This was proof that fouling on the crude shell side was the limiting factor and that the chemical cleaning significantly improved the heat transfer performance of the preheat train. At this stage, a comparison of the duty of the complete train reveals a gain with the Fixotal of 9% of duty at 96.67 GJ/hr vs 88.5 GJ/hr.

- **End of run (EOR):** The comparison of the two runs still shows better heat transfer for the last six HXs when the last three are equipped with the shear stress promoter (typically 50% higher than the reference run). After 1,035 days of operation, the last six HXs achieved 69% of the total duty of the train, which was typically 10% higher than the previous run (after the same duration).
- **Average on the complete run:** By evaluating the complete run of 1,035 days, the run with the Fixotal inserts equipped in the last three exchangers of the preheat train generated, on average, 34% higher OHTC on the last six bundles and a total average increase in duty of 20% on the last six exchangers. Overall, the preheat train with the inserts was generating 3% more duty, equivalent to 56,600 GJ over 1,035 days of operation.

The energy savings from reducing the firing of the furnace and, consequently, the reduction in CO_2 emissions of the plant yielded economic benefits, as summarised in **Table 6**. This is equivalent to 405 k€ per year, even though some heat transfer limitations were reached.

As the residue on the tube side cooled down much faster than during the reference run, there was less potential for heat recovery through the first six HXs. In addition, the total crude flow was 8% lower during the run with Fixotal (due to some

Impact on energy savings and CO_2 emissions on heat exchangers used in Study C* **

	With Fixotal
Gain on energy recovery (Gcal/yr)	4,500
Gain on energy recovery (TOE/yr)	450
Energy savings	**270 k€**
Gain on CO_2 emissions (tons first yr)	1,350
Reduction in CO_2 emissions	**135 k€**

Table 6

unit upsets), which reduced the heat transfer performance as a result of the lower Reynolds number. Nevertheless, the unit achieved better overall heat transfer performance.

Combined benefits

Significant improvements related to the use of tube inserts were highlighted by the three studies presented, and some concluding remarks can be drawn from these field data analyses. For applications A and B, the run lengths with the tube inserts were, at minimum, doubled compared to the same run with bare tubes without any modifications of the heat exchanger tubes.

In Study C, the operator is constrained by regulation to shut down and inspect the whole plant every four years. It is not possible to target extended run length since a single chemical cleaning in the middle of the run is sufficient to recover enough heat transfer capacity. The implementation of Fixotal was, therefore, used to optimise heat recovery, even though the fouling on shell side was predominant.

In each case, the performances of the heat exchangers were increased in terms of heat transfer. This improvement was translated in OHTC (Study A) with both an increased and a stabilised level of heat transfer over the run.

For Study B, the benefit was directly expressed in duty, with an average increase of 25% during the run, significantly reducing the firing of the downstream furnace by about 100 tons of gas per month. For study C, the increase of OHTC with only three HXs equipped with Fixotal out of 12 unbalanced the preheat train performance and allowed an increase in duty and heat recovery even though the operating conditions were unfavourable compared to the reference run.

The benefits achieved in the three applications demonstrate the potential improvements achievable with standard shell and tubes heat exchangers when limitations come from either tube side or shell side film coefficient or from fouling deposition in either tube or shell side. The complete range of operation must then be evaluated to highlight the main contributors to the thermal resistances of the exchangers and assess if these limitations can be tackled with these inserts. This must be done by comparing the effect of tube inserts with bare tubes at different levels of throughput, but also taking into account the level of fouling typically reached in these flow conditions at SOR and EOR.

Comparisons

Nowadays, many incentives are in place to encourage the reduction of CO_2 emissions at every level, and the industry sector is one of the largest contributors.[5] Refineries and chemical plants are mainly operating with shell and tube heat exchangers for heat recovery. Reducing their CO_2 emissions can be done right now thanks to these technical solutions, even as longer-term projects are ongoing for large-scale impacts. These technologies are available and can be retrofitted to any shell and tube exchanger within a few weeks.

Comparing the three technologies would be a difficult exercise, as they are not designed to operate on the same type of feed, the same level of flow conditions, and do not have the same mechanical lifetime. However, whenever it is possible, and if fouling mitigation is the driving force to use inserts, priority should be given to selecting the inserts that provide a mechanical cleaning effect (Turbotal and Spirelf).

Although there are already a wide range of potential applications, exploring benefits in different flow conditions or with various types of fluids and processes could be very interesting. Future technological developments could focus on implementing new technologies for dual-phase flows to improve heat transfer at minimum cost on pressure drop.

Nomenclature

HXs	Heat exchangers
BWG	Tube wall thickness in Birmingham wire gauge
OD	Outside diameter of tube (mm)
CIT	Coil inlet temperature
OHTC	Overall heat transfer coefficient kcal/h.m² °C or kJ/h.m² °K
SOR	Start of run
EOR	End of run
TOE	Ton of oil equivalent = 10 Gcal
(*)	Cost of energy considered €600 per TOE
(**)	Taxes on CO_2 emissions = €100 per ton

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