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Minimising refinery costs using spiral heat exchangers

Case studies explore how fouling has been minimised or eliminated from high-fouling applications in oil refineries, such as the FCC and visbreaking bottoms cooling duties. Performance of spiral heat exchangers is compared with shell and tube heat exchangers

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In oil refineries, many processes are subject to problems with heavy fouling that affect overall plant performance and profitability. Operating costs associated with fouling in refinery heat exchangers typically include increased fuel needs, increased CO_2 emissions from the fired heater, increased pumping power, and reduced throughput and capacity of produced products. In addition, investment costs are higher and maintenance costs are affected by high service requirements.

Estimates have been made of fouling costs, due primarily to wasted energy caused by excessive fuel use, that are as high as 0.25% of the gross national product of the industrialised countries.[1]

The spiral heat exchanger (SHE) was invented in 1826, but production only began in 1930. The original SHE was developed for use in the pulp and paper industry. With its single-channel flow, uniform velocity profile and lack of dead zones, the SHE is tailormade for high-fouling applications. The spiral flow and counter-current design also make it more efficient for heat recovery than traditional shell-and-tube (S&T) heat exchangers.

Today, almost 80 years later, more than 160 SHEs are operating in oil refineries the world over, where they help increase uptime and reduce operating costs and emissions.

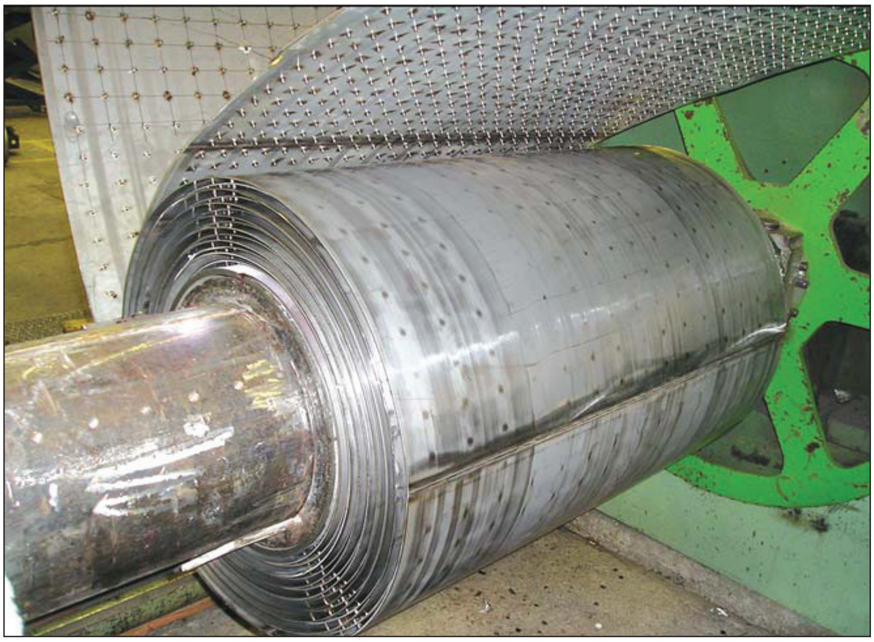

Figure 1 *Production of the SHE heat-transfer body*

Non-fouling construction

The SHE is a welded heat exchanger with no gaskets between the two media (Figure 1). It is produced by welding two metal strips to a centre tube, then winding the centre so two separate channels are formed. Each channel is closed off from the other by means of a weld. The channel spacing is maintained with studs. The length of the studs can be chosen to achieve channel spacing suited to the size of the fouling particles in question.

Single-channel design

However, the most important anti-fouling feature of the SHE is its single-channel design. The full flow rate of both medias, hot and cold, will each pass through only one heat exchanger channel and, as a result, no maldistribution is possible. In a S&T heat exchanger, however, when one tube starts to foul, the pressure drop over that tube increases, leading to a reduced flow rate through the tube and to a blocked tube. The result is a lot of lost heat-transfer surface due to the fouled tubes.

Self-cleaning effect

If fouling starts to precipitate in the SHE heat-transfer channel, the cross-section of this part of the channel is decreased. However, because the entire flow rate must still pass through it, the local velocity here increases. This causes a scrubbing effect that removes the fouling that has settled. This is called the self-cleaning effect, as shown in Figure 2.

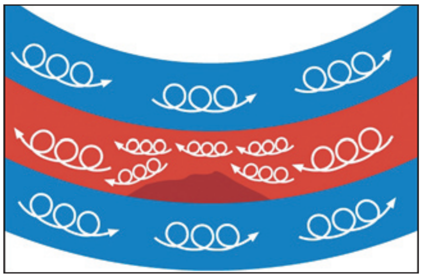

Figure 2 *The self-cleaning effect*

Other features that minimise fouling in a SHE are the uniform velocity profile, the design without dead zones and efficient heat transfer, which minimises the wall temperature and thereby the reaction rate in the case of chemical fouling.

Heat-transfer efficiency

In addition to possessing important anti-fouling properties, the SHE also offers very high heat transfer as a result of its spiral design. The amount of turbulence created in the spiralling channels ensures heat-transfer efficiency that is two to three times higher than in a S&T.

Counter-clockwise flow

Furthermore, the flow arrangement in the SHE is completely counter-current,

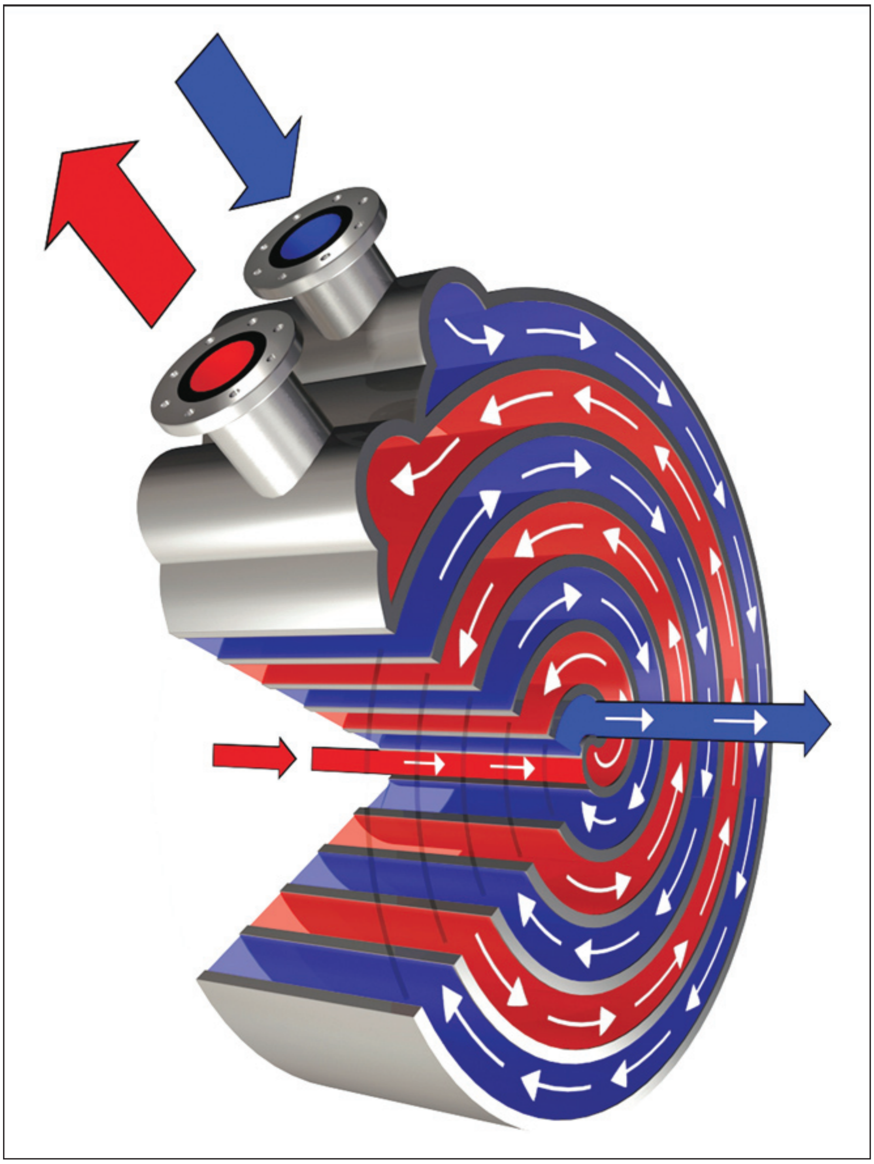

Figure 3 *The counter-current flow pattern in a SHE*

Heat exchanger performance summary

	SHE	S&T
Heat-transfer efficiency	2–3	1
Heat-transfer area	1	2–3
Pressure drop	1–1.5	
Temperature pinch, °C	5	N/A
Number of units	1	1.5–2
Footprint	1	2–2.5
Service area	1	1.5–2

Table 1

as shown in Figure 3. It can therefore handle crossing temperature programmes with pinch temperatures as low as 5°C in a single shell. This means less heat-transfer area and (normally) fewer shells are needed for any given heat-recovery duty, so less installation space and piping are required. A SHE with a heat-transfer surface of 500 m^2 has a footprint of only 5.2 m^2, and only 26 m^2 surface area is needed, including service space.

Service requirements

Should service be required, despite its superior resistance to fouling, it can be easily cleaned, either mechanically or by circulating a cleaning chemical through the spiral channels (Figure 4). Opening the two end-covers gives complete accessibility for cleaning the heat-transfer surface with high-pressure water jets. Table 1 compares performance of the SHE vs S&T heat exchangers.

Heavy fouling in refinery apps

Many processes in oil refineries are prone to heavy fouling. This fouling affects overall performance as well as profitability. As previously mentioned, estimates have been made of fouling costs, due primarily to wasted energy caused by excessive fuel use, that are as high as 0.25% of the gross national product (GNP) of the industrialised countries.[1] In a study made in 1995, the cost of fouling-related problems in the industrialised countries was estimated at $45 billions per year.[2]

A similar study, carried out just for US petroleum refineries, put the average yearly cost of fouling at $2 billion. Another detailed study done by Exxon in 1981 showed that for a typical refinery with a capacity of 100 000 bpd fouling-related costs were about $12 million per year. Approximately one-third of those costs were for increased energy expenditure.[3]

Finally, in 2002, it was estimated that fouling was responsible for the discharge of more than 180 000 tons of additional CO$_2$ into the atmosphere every year from UK refineries alone.[4] Based on these numbers, it is evident that the refinery industry has a lot to win by studying fouling mitigation.

Investment costs

The initial investment costs for heat exchangers are greatly affected by fouling. S&T heat exchangers for refinery applications are designed using industry-standard TEMA fouling factors, and heat-transfer surface area is added to make up for lost performance due to fouling. HTRI and TEMA5 estimate that between 11 and 67% more heat-transfer surface area is added to heat exchangers to compensate for the effects of fouling, and Garrett-Price *et al*[1] estimates that an additional surface area of 30–40% adds around 25% to the equipment price.

Furthermore, for high-fouling refinery applications, investments are often made for standby equipment to avoid capacity reduction during the maintenance of fouled heat exchangers. In other words, duplicate heat exchangers with equal amounts of extra surface area are purchased.

The installation costs for heat exchangers increase as the equipment gets bigger and heavier, because stronger foundations and more space are required. The installation cost for S&Ts is normally estimated as two to three times the purchase cost.[6] Therefore, extra surface area added to compensate for fouling directly affects installation costs.

Finally, heavy maintenance reduces the lifetime of a heat exchanger and means more frequent replacement. For example, the lifetime of a carbon-steel S&T used in a high-fouling application would be reduced by two to three times compared to that of a S&T used in clean duty.

Operating costs

In a refinery, energy is recovered by preheating various feeds using hot hydrocarbon fractions leaving distillation or fractionating towers. In many processes, the final feed preheating is done in a fired heater.

Fouling reduces the heat-recovery performance of heat exchangers, which results in an increased duty requirement in the furnace. This leads to both higher fuel costs and higher CO$_2$ emissions from the fired heater. In high-fouling refinery applications, this loss of heat-recovery performance can lead to up to 10–15% higher furnace duty.

Increased CO_2 emissions can mean that a refinery has to purchase more CO_2 credits. A CO_2 credit is valued at around 20 $/ton. Using a furnace-fuel cost of 40 $/bbl, the emission cost ends up at around 25% of the increased fuel cost.[7] In addition, exceeding CO_2 limits can lead to additional penalties of 100 EUR/ton of non-credited CO_2 emitted.

Furthermore, fouling causes the pressure drop over the heat exchangers to increase, which results in a need for more pumping power leading to increased power consumption – which, in many cases, is not negligible. Garrett-Price *et al*[1] estimates that around 1–5% of the energy consumed by the industrial sector is used to compensate for the total energy loss (excess fuel burn and increased electricity consumption) caused by fouling.

Finally, if the capacity of the process is limited by the pumping power and/or the furnace duty, throughput must be reduced when the pump and/or the furnace reach their maximum capacity. When the cost of lost production exceeds the cost of maintenance, the heat exchangers are taken out of service for cleaning. During maintenance, if there is no standby equipment, the heat-transfer efficiency is further reduced, as is the production capacity, until the cleaned heat exchanger is put back in service again.

This situation can cost a refinery up to 5–10% of their production capacity and result in a severe profit loss. As detailed in Figure 5, this kind of capacity loss can affect profits three-and-a-half to six times more than profit losses due to increased energy consumption.[8]

Maintenance costs

In high-fouling processes, maintenance costs are high as well. These costs can be divided into capital expenses (Capex) and operating expenses (Opex). Expenses include costs for all kinds of anti-fouling equipment that a refinery invests in. Some examples are online or offline cleaning equipment, extra costs for special types of non-fouling heat exchangers (such as spiral heat exchangers), pre-treatment plants, cleaning-in-place equipment, dosing pumps, cranes for transporting tube bundles to cleaning sites, tanks for anti-fouling or cleaning chemicals, and so on.[9] The total amount of money spent on this kind of equipment is very difficult to estimate.

Depending on the type of fouling, cleaning can be quite time-consuming in terms of man hours (Figure 6). The cost of manhours spent on removing fouling also affects operating costs.

Figure 4 *High-pressure water jet cleaning of the SHE heat-transfer surface*

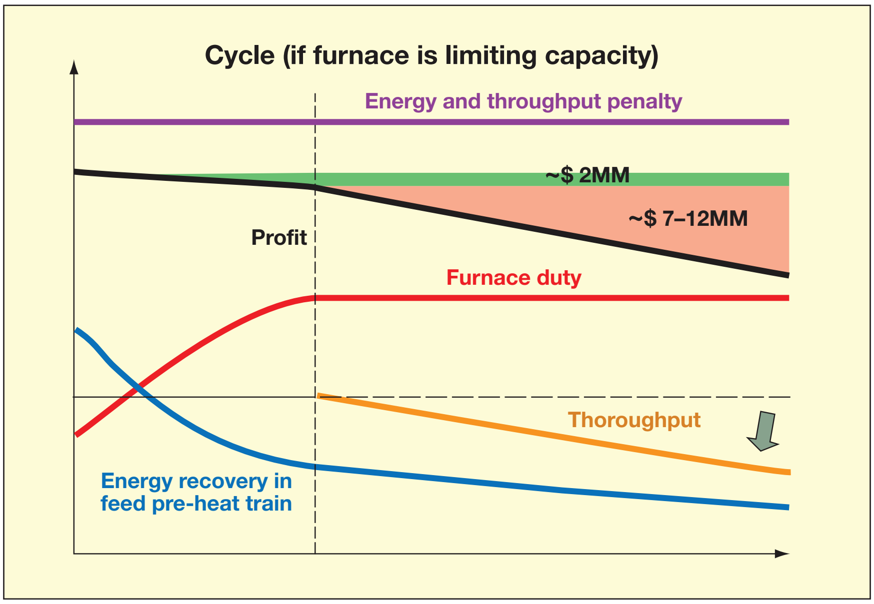

Figure 5 *Energy and capacity cost due to fouling in a crude preheat train if the furnace capacity is limiting*[8]

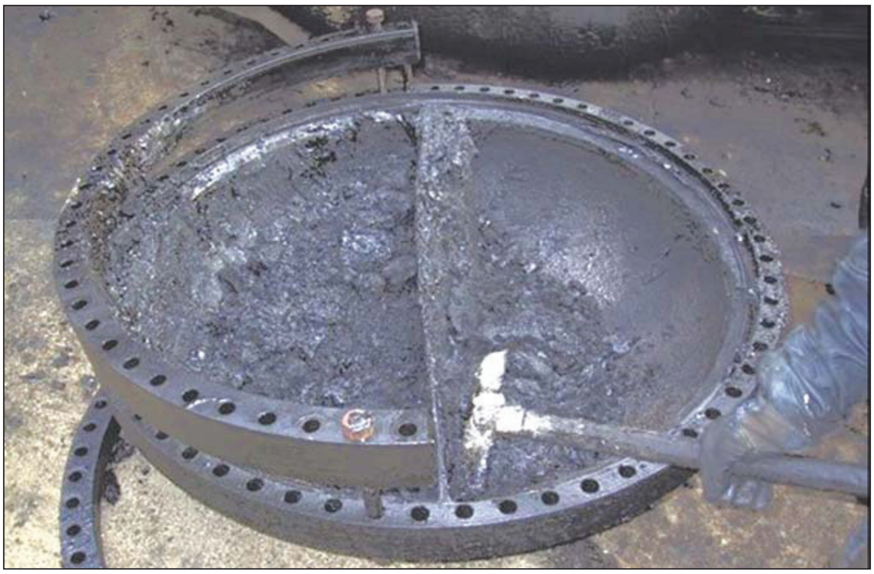

Figure 6 *Manual removal of coke formation in the S&T turning chambers in a high-fouling visbreaking process*

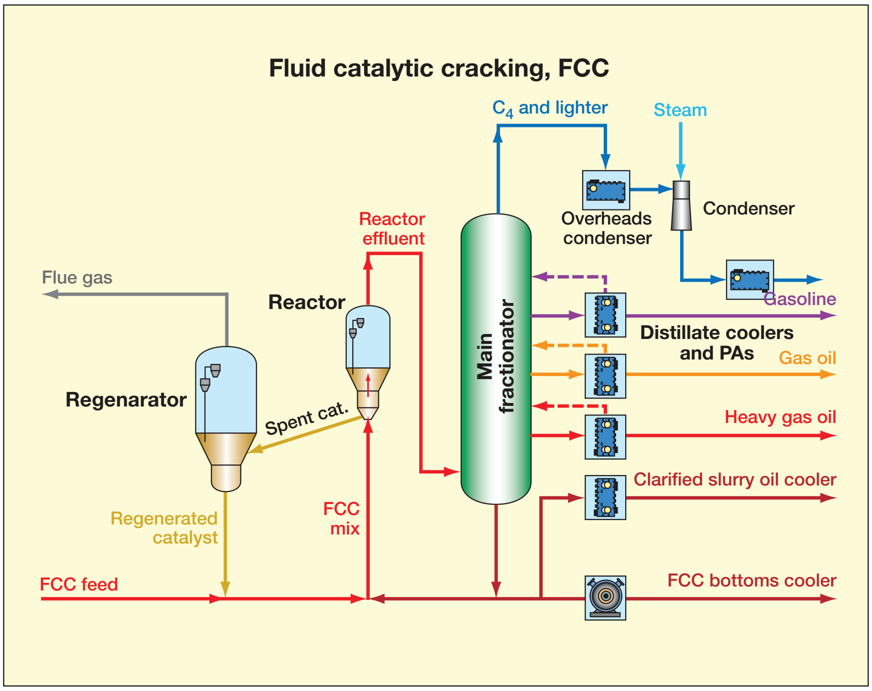

Figure 7 *Schematic view of the FCC process*

Summary of costs due to fouling

Parameters affected by fouling	Cost comparison	
	Non-fouling duty (best case)	Fouling duty
Investment cost	X	X
Additional surface area	0	0.25X
Spare heat exchanger	0	1.25X
Installation cost	2*X	2*(1+0.25+1.25)X=5X
Replacement frequency	0	2*(1+0.25+1.25)X=5X
Operating cost	Y	Y
Increased fuel consumption	0	0.05Y*
Increased emissions	0	0.25*0.05=0.0125Y
Increased electricity consumption	0	N/A
Reduced production capacity	0	3.5*0.05Y=0.175Y
Maintenance cost	Z	Z
Anti-fouling equipment Capex	0	N/A
Man hours for fouling removal	0	
Cleaning chemical consumption	0	0.075Z
Disposal of cleaning chemicals	0	

* Assuming 50% of operating cost is energy cost, which is, on average, the case in an oil refinery.

Table 2

Any chemicals needed to prevent or dissolve fouling are also included in maintenance costs, as is the cost of disposing of these chemicals. Pritchard[10] and Thackery[11] estimate that around 15% of plant maintenance cost is for heat exchangers and boilers, and that around 50% of these costs are due to fouling.

As shown in Table 2, the total added cost due to fouling in an oil refinery is very high, even at the lowest levels of the estimates. During the time that constitutes the lifetime of a heat exchanger in a non-fouling process, the cost of the investment for a heat exchanger in a fouling process is five times higher. The extra costs are due to added surface area, the need for standby equipment and shorter equipment life. In addition, heavier, bulkier heat exchangers and more shells push installation costs two-and-a-half times higher.

Around 50% of the operating costs in a refinery are for energy consumption. This means that a 10% loss of heat-recovery efficiency increases total operating costs by 5% as the result of increased energy consumption and an additional 1.25% as the result of increased emissions. However, the greatest loss of profit compared to a non-fouling process will come from production losses due to pump and/or furnace capacity limitations. This could reduce profit by an additional 17.5%.

Finally, maintenance costs increase by 7.5% as a result of fouling in heat exchangers. This number does not include all the Capex required to keep maintenance needs resulting from "under-control".

Particle fouling

Fouling seen in refineries is often the result of particles in fluids. These particles can, for example, be corrosion products from carbon steel equipment in the refinery, sand in seawater or other particles in poor-quality cooling water and catalyst fines from the reactor chambers in catalytic processes.

One such catalytic process is the fluid catalytic cracking (FCC) process (Figure 7). In this process, the reactor effluent entering the main fractionator can contain a lot of catalyst fines. The amount depends on the operation of the reactor, but up to 3–5 wt% of catalyst fines can often be found in the bottom fraction, which is called slurry oil. During cooling of this slurry oil, the catalyst fines agglomerate and deposit on the heat-exchanger walls, severely reducing heat-transfer performance and increasing the pressure drop. Often, several cleaning periods per year are required for heat exchangers operating in this duty, and during cleaning a standby heat exchanger is used. Even if the duty does not involve heat recovery, the maintenance and investment costs related to fouling still affect the total profitability of the process unit.

Chemical fouling

In addition to the particle fouling seen in refineries, chemical fouling is another type of fouling occurring in refineries. This type of fouling is primarily found in heat exchangers operating with fluids in which salt crystals can form and precipitate, or at high temperatures where there is a risk of coking or of precipitation of asphaltenes. Chemical fouling will intensify at low flow velocities and in heat-exchanger dead-zones, such as in the tube turning chamber and/or behind the shell-side baffles.

Due to the high temperatures involved, many of these duties are heat-recovery duties, resulting in long crossing temperature programmes with a close pinch. S&T heat exchangers installed in such duties require large surface areas and are designed with a large fouling margin. In addition, many tube passes and/or shells connected in series are required because the cross-flow arrangement of an S&T cannot handle crossing temperature programmes.

As the heat-transfer surface area required in these S&T heat exchangers is very large, many tubes are needed and the velocity in each of them becomes very low, which both further reduces heat-transfer efficiency and makes the S&Ts even more prone to fouling. In this sense, the TEMA fouling factor, which adds surface area to the S&Ts, counteracts its own purpose. It actually creates a risk of increasing the rate of fouling if the velocity through the heat-exchanger channels drops too much. Typical refinery applications in which one would expect chemical fouling are the preheating of crude before distillation and in processes operating at high temperatures, such as thermal cracking and coking.

In the visbreaker process (Figure 8), the bottoms fraction, called visbroken residue, tar or fuel oil, leaves the fractionating tower at temperatures of above 360°C. This fraction is used to preheat the visbreaker feed (atmospheric or vacuum residue) to as high a temperature as possible before final preheating in a furnace.

In this heat-recovery duty, fouling occurs due to coking of the visbroken residue on the hot heat exchanger walls, continued cracking reactions inside the heat exchangers and precipitation of asphaltenes.

The situation is made worse because the huge S&Ts normally needed for this heat-recovery duty suffer from hydraulic problems. They operate with very low heat-transfer efficiency and flow velocities and are thus very much prone to fouling. The fouling is also very difficult to remove, as previously seen in Figure 6. Any reduction in heat-transfer efficiency directly affects energy consumption in the furnace, so a great deal of money is spent on increased fuel consumption. At many refineries, the visbreaker process is regarded as one of the most problematic fouling applications in the plant.

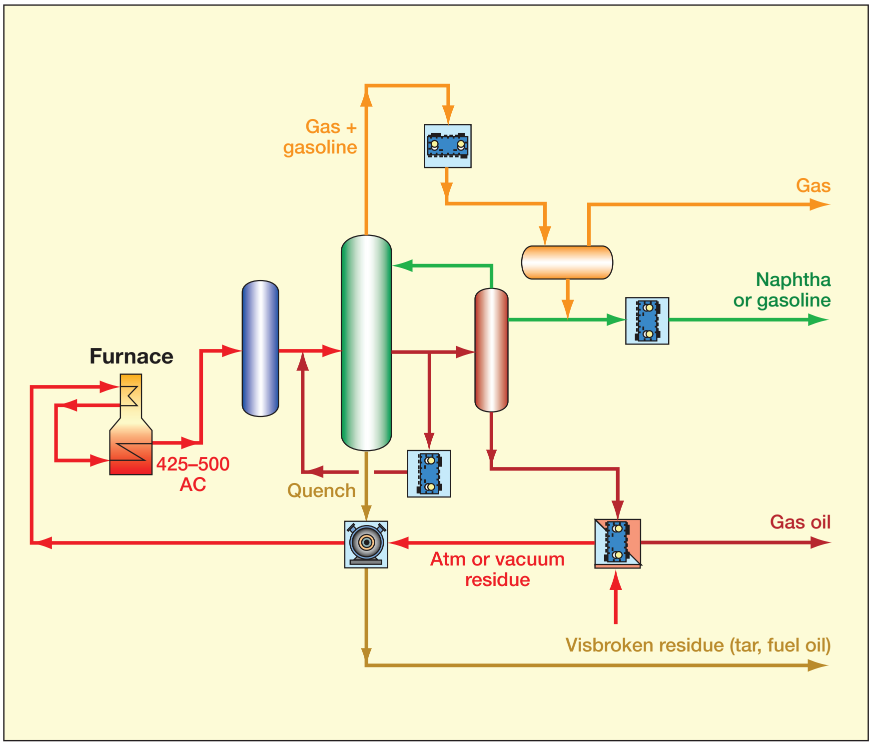

Figure 8 *Schematic view of the visbreaking process*

Figure 9 *One SHE operating as FCC slurry oil cooler*

FCC slurry oil cooling

In a European refinery, two double-pipe S&T heat exchangers, one in operation and one in standby, were used to cool down FCC slurry oil using tempered water, as follows:

FCC slurry oil 15 ton/hr 180 °C -> 75 °C
Tempered water 65 °C <- 45 °C

Q = 0.9 MW

The slurry oil normally contained up to approximately 1 w/w% of catalyst fines and 500 ppm of coke particles, creating severe fouling problems in the S&Ts. They plugged up frequently on the process side and had to be taken out of operation around every ten days for cleaning. Cleaning the exchanger with a high-pressure water jet took almost ten days. The refinery therefore had to switch the double-pipe S&T every ten days, and they were constantly cleaning one of them. In the first 15 months, the S&Ts were cleaned 40 times.

In 1999, two SHEs were installed to replace the S&Ts (one in operation and one in standby). During normal operation, they have required no cleaning at all, and the standby SHE has therefore not been needed (Figure 9).

In 2001, 2002 and 2006, the plant suffered from catalyst carryover into the fractionator. The S&Ts and other equipment had to be opened and cleaned, while the SHE was successfully chemically cleaned just by circulating wash oil. The same cleaning procedure was also used before inspection during the refinery's scheduled shutdown. The SHE has now been operating with consistent heat-transfer efficiency for the last three years.

The installed cost for one SHE was around 180 kEUR, which was practically equal to the annual maintenance cost for the double-pipe S&T heat exchangers. Hence, the payback time for this project was approximately one year.

Visbreaking bottoms cooling

A European refinery had severe fouling problems in their visbreaking feed/bottoms S&T interchangers. In total, 12 four-pass S&Ts were used, two in parallel and six in series, preheating the

Figure 10 *Two out of eight SHEs operating as visbreaking feed/bottoms interchangers*

visbreaking feed (atmospheric residue, AR) using visbroken residue as heating media, as follows:

Visbroken residue 210 m^3/hr
380 °C -> 189 °C dP = 9 barg
Visbreaking feed (AR) 310 m^3/hr
246 °C <- 115 °C dP = 8 barg

Q = 20.8 MW

Due to the many shells in series and the high number of passes per shell, the S&Ts suffered from hydraulic performance problems, giving rise to very low cooling performance and flow velocities. This, in combination with the high inlet temperature of the visbroken residue, the on-going cracking process and the precipitation of asphaltenes, led to a very high fouling rate in the S&Ts. This meant the visbroken residue (tube) side of the hot-end heat exchangers had to be cleaned every two to three months. The time-consuming cleaning process involved many steps including flushing, steaming, hydro-jet cleaning and drilling, and took between 20 and 30 days. In addition, the tubes had to be made of stainless steel in order to minimise wear during cleaning.

During the cleaning period, heat recovery was reduced and, because the furnace could not provide sufficient additional heat, the throughput had to be reduced, too. The increased operating costs and emissions, reduced capacity and high maintenance costs were very expensive for the refinery.

In 2002, eight SHEs replaced the original S&Ts in the preheat train. Since the heat-transfer efficiency of this equipment is now four times higher, the visbreaking feed furnace inlet temperature has now increased by more than 10°C, but the pressure drop is lower. In addition, due to the low hold-up volume, pre-heating of the exchangers before startup of the process is now much faster than before.

Heat-recovery performance is stable, and no increased pressure drop has been noticed over time. Every one-and-a-half to two years, during scheduled maintenance, the SHEs are opened and a thin layer of coke (max 5 cm) is removed from the hot-side cover with a high-pressure water jet. The heat-transfer channels and the cold-side cover do not need any cleaning, so a total of only five days of downtime is required for service (dismantling, cleaning, changing of cover gaskets and closing the covers).

The installed cost of the eight SHEs was around 2.2 MEUR, but the annual savings in terms of improved heat recovery, no capacity loss and reduced maintenance costs amounted to around 1.1 MEUR, which means the payback time for the project was approximately two years.

Conclusion

Heat exchanger fouling in refinery processes directly affects profitability. The investment costs for heat exchangers increases by a factor of five, and installation costs are more than twice as high in duties where the probability of fouling is high. If heat exchanger fouling leads to increased energy consumption in furnaces, operating costs can be increased by up to more than 6% due to increased fuel consumption and higher emissions. However, the biggest effect on profit occurs in cases where production capacity is negatively affected by fouling. Profits can be reduced by up to 17% in such cases. Increased maintenance costs due to fouling, which can reach up to 7.5% (not including Capex for required anti-fouling equipment) should also be added to these numbers.

Many studies have been carried out that attempt to estimate how much money is lost due to fouling in industry in general, and in refineries in particular. Just as many studies have been done on how to limit or mitigate fouling.

One possible way to greatly reduce the high cost of fouling is to use special types of heat exchangers, tailormade for handling fouling duties. The SHE is one such heat exchanger. With its single-channel flow, uniform velocity profile and no dead zones, it is the heat exchanger of choice for very heavy fouling duties. In addition, its gasket-free construction makes it possible to design for high temperatures and pressures, and the spiralling counter-current flow ensures very high heat-transfer efficiency and a perfect fit for heat-recovery duties.

The investment cost for such a heat exchanger is normally higher than for a traditional S&T heat exchanger, but as no standby equipment is needed, and the number and size of the shells are reduced, the total Capex is normally in the same range. In addition, with improved heat-recovery performance, no loss of heat-recovery efficiency and minimised maintenance costs, investment in SHEs is normally paid off in one to two years.

Refineries worldwide are starting to see the advantages of SHEs, and presently there are more than 160 units installed in high-fouling processes such as FCC, visbreaking, coking, desalting and wastewater treatment.

References

1 Garrett-Price B A, *et al*, *Fouling of heat exchangers. Characteristics, cost, prevention, control and removal*, Noyes Publications, Park Ridge, NJ, USA, 1985.
2 Müller-Steinhagen H, Fouling of heat exchanger surfaces. *Chemistry & Industry*, 5, 171–174, 1995.
3 Technology Roadmap for the US petroleum industry.
4 Pugh S J, Identification of R&D needs relating to the mitigation of fouling in crude oil preheat trains, 2002, www.pinchtechnology.com
5 Chennoweth J, Final report on the HTRI/TEMA Joint Committee to Review the Fouling Section of the TEMA Standards, *Heat Transfer Eng.*, 11, 1, 73–107, 1990.
6 Woods D R, *et al*, Evaluation of control cost data: heat exchangers, *Can. J. Chem. Eng.*, 54, 469, 1976.
7 Andersson, E, Using Compact plate heat exchangers to optimize heat recovery in refineries, *PTQ, Q1 2007*.
8 Picou J, Total Cert, Moore I, AspenTech, Achieving CDU energy savings through the practical application of pinch technology, ERTC Energy workshop, 16 Nov 2006.
9 Steinhagen R, Müller-Steinhagen H, Maani K, Problems and costs due to heat exchanger fouling in New Zealand Industries, *Heat Transfer Eng*, 14, 1, 19–30, 1993.
10 Pritchard A M, *The Economics of Fouling, Fouling Science and Technology* (Melo L F, Bott T R, Bernardo C A, eds), NATO ASI Series E, 145, Kluwer Academic Publishers, 1987.
11 Thackery P A, The Cost of Fouling in Heat Exchanger Plant, Effluent and Water treatment J, March, 1980.

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