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# Fouling Mitigation Using Helixchanger Heat Exchangers

Bashir I. Master[*] Krishnan S. Chunangad[†]
Venkateswaran Pushpanathan[‡]

[*]ABB Lummus Heat Transfer, bashir.i.master@us.abb.com
[†]ABB Lummus Heat Transfer, krishnan.s.chunangad@us.abb.com
[‡]ABB Lummus Heat Transfer

# FOULING MITIGATION USING HELIXCHANGER® HEAT EXCHANGERS

**Bashir I. Master[1], Krishnan S. Chunangad[2] and Venkateswaran Pushpanathan[3]**

[1] ABB Lummus Heat Transfer, 1515 Broad Street, Bloomfield, NJ 07003, USA; bashir.i.master@us.abb.com
[2] ABB Lummus Heat Transfer, 1515 Broad Street, Bloomfield, NJ 07003, USA; krishnan.s.chunangad@us.abb.com
[3] ABB Lummus Heat Transfer, 1515 Broad Street, Bloomfield, NJ 07003, USA; venkateswaran.pushpanathan@us.abb.com

## ABSTRACT

One of the major indeterminates in the design as well as operation of heat exchangers is the rate of fouling a select heat exchanger geometry would exhibit over the operation cycles.

Gradual deterioration of heat exchanger performance due to the accumulation of fouling film on the heat transfer surface is often accounted for in the form of a fouling resistance, or commonly known as the fouling factor, while determining the heat transfer surface required for a specific heat duty.

More often, the fouling mechanism responsible for the deterioration of heat exchanger performance is flow-velocity dependent. Maldistribution of flow, wakes and eddies caused by poor heat exchanger geometry can have detrimental effect on heat exchanger performance and reliability.

Helixchanger heat exchangers have demonstrated significant improvements in the fouling behavior of heat exchangers in operation. In a Helixchanger heat exchanger, the quadrant shaped shellside baffle plates are arranged at an angle to the tube axis creating a helical flow pattern on the shellside. Uniform velocities and near plug flow conditions achieved in a Helixchanger heat exchanger, provide low fouling characteristics, offering longer heat exchanger run-lengths between scheduled cleaning of tube bundles.

This article demonstrates the Helixchanger heat exchanger option in reducing the velocity-dependent fouling in heat exchangers.

## INTRODUCTION

Heat exchanger fouling causes a major economic drain on industries today. In most industrialized countries these losses amount to 0.25 to 0.30 percent of the gross national product (GNP) (ESDU Item 00016, 2000). Costs associated with exchanger fouling are reflected in over-sizing of the heat exchangers leading to not only the incremental capital and installation costs but also the operation, maintenance and downtime costs adding up to a staggering 2.5 to 3.0 times the initial purchase price of heat exchangers.

More than 35-40% of heat exchangers employed in global heat transfer processes are of the shell and tube type of heat exchangers. This is primarily due to the robust construction geometry as well as ease of maintenance and upgrades possible with the shell and tube heat exchangers.

In a shell and tube heat exchanger, the conventional segment baffle geometry is largely responsible for higher fouling rates. Uneven velocity profiles, back-flows and eddies generated on the shellside of a segmentally-baffled heat exchanger result in higher fouling and shorter run lengths between periodic cleaning and maintenance of tube bundles.

In a Helixchanger heat exchanger, the conventional segmental baffle plates are replaced by quadrant shaped baffles positioned at an angle to the tube axis creating a uniform velocity helical flow through the tube bundle. Near plug flow conditions are achieved in a Helixchanger heat exchanger with little back-flow and eddies. Exchanger run lengths are increased by two to three times those achieved using the conventionally baffled shell and tube heat exchangers. Heat exchanger performance is maintained at a higher level for longer periods of time with consequent savings in total life cycle costs (TLCC) of owning and operating Helixchanger heat exchanger banks.

Feedback on operating units are presented to illustrate the improved performance and economics achieved by employing the Helixchanger heat exchangers.

## FOULING CHARACTERISTICS

The principal mechanisms of fouling are reported to be as follows:

- Particulate matter in flows
- Crystallization
- Chemical Reaction

- Corrosion processes
- Biological mass accumulation

This paper covers the impact of shellside fouling on the thermal performance and economics of shell and tube heat exchangers employed in the refinery and petrochemical plant processes.

**Refinery Applications**

Generally, the fouling deposits occur as high molecular weight polymers are formed in the crude preheat systems. Products of corrosion and inorganic salts mix with the polymers and increase the volume of the fouling deposits.

Most of the heat input in a refinery takes place in the crude unit where the crude oil is preheated in heat exchanger trains prior to further heating to elevated temperatures in a fired heater (furnace). See Fig. 1. The total refinery output relies on the uniform operation of the crude unit with consistent outlet temperatures at desired flow rates. Preheat exchanger performance is, therefore, vital in reducing the fuel consumption in the downstream furnace and supplying uniform crude flow rates to the furnace over a desired run cycle.

The second most important process unit in a refinery is the hydrotreater. The process stream in a hydrotreater reacts with hydrogen in the presence of a catalyst at elevated temperatures and pressures to remove sulfur and nitrogen. The major fouling in this unit occurs in the feed/effluent heat exchangers. In these exchangers, the cold naphtha feed is preheated using the hot product effluent. See Fig. 2. Fouling in the feed/effluent heat exchangers can decrease the outlet preheat temperature of naphtha causing more fuel consumption in the furnace and/or reduction in the naphtha flow rate.

The last refinery process where heat exchangers are employed as feed/effluent heat exchangers is the reformer unit. See Fig. 3 for a schematic of this unit. Reforming is a catalytic process designed to increase the anti-knock quality of the naphtha streams. The dehydrogenation in this unit converts the naphthenes to aromatics. Fouling in the preheat exchangers play a vital role in reducing the heat transfer coefficient, often by 25-30% in three months and to as low 50% in six months after start-up. Added fuel costs in the downstream furnace as well as maintenance and cleaning costs of heat exchangers could significantly affect the plant operating costs. Anti-fouling agents are often added to the process streams to reduce the fouling tendencies and improve the plant economics.

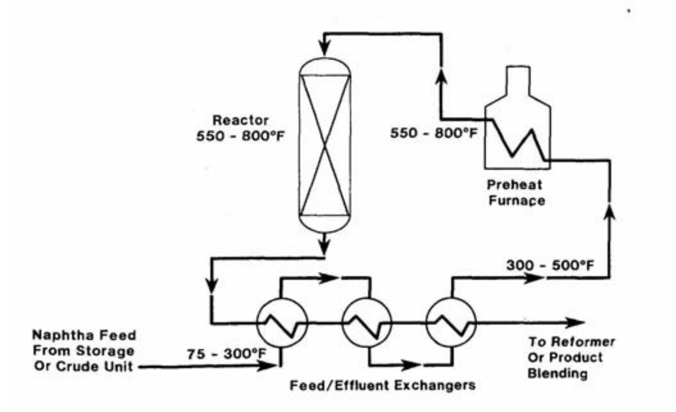


Fig. 2 Schematic of a Hydrotreater Unit (Leach et al., 1981)

The total fouling related expenses in the major refining units in USA alone are estimated to be approximately US$1.4 billion a year. The total fouling related costs for major industrialized nations are estimated to exceed US$4.4 billion annually (ESDU Item 00016, 2000).

Considering that the refinery fouling related costs represent a minor portion of the fouling related costs in all industries, the fouling mitigation technologies deserve greater attention.

**FOULING MITIGATION TECHNOLOGY**

The Tubular Heat Exchanger Manufacturers Association (TEMA) standards suggest fouling factors for several fluids based upon the asymptotic fouling model as described by Kern and Seaton (1959). In this model the competing fouling mechanisms lead to an asymptotic fouling resistance beyond which no further increase in fouling occurs. The asymptotic values are, therefore,

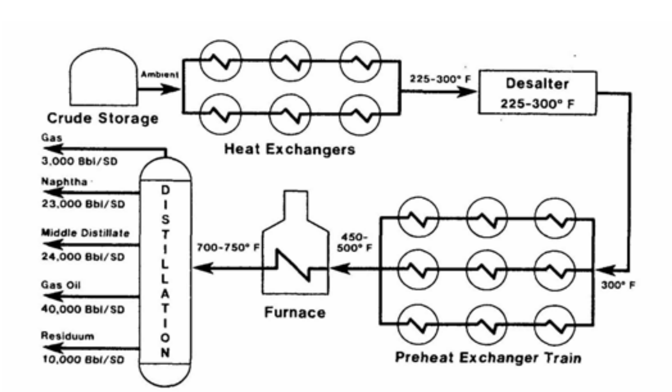


Fig. 1 Schematic of a Crude Unit (Leach et al., 1981)

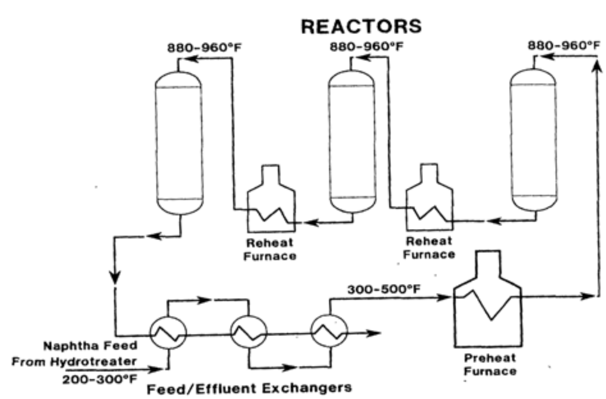


Fig. 3 Schematic of a Reformer Unit (Leach et al., 1981)

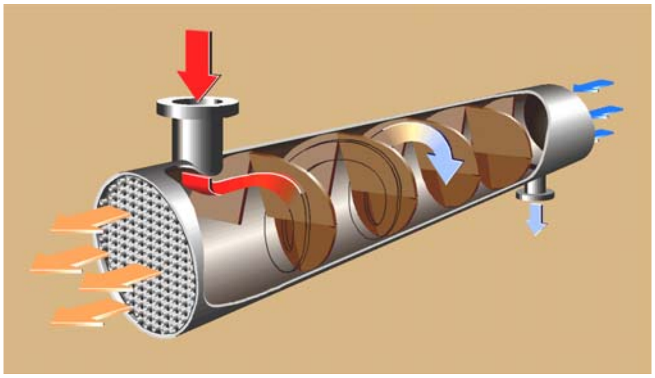

Fig. 4 HELIXCHANGER Heat Exchanger

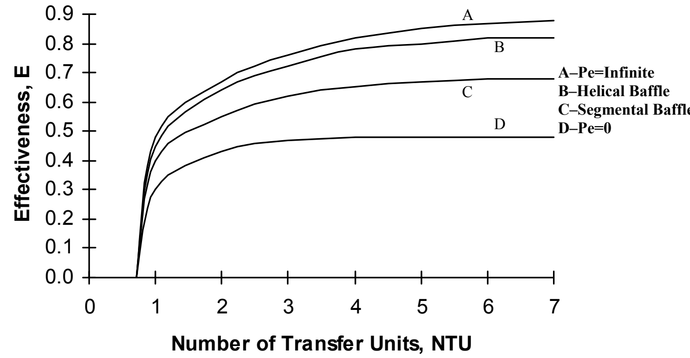


Fig. 6 Heat exchanger effectiveness for different geometries

recommended as the design fouling factors in the TEMA standards. This approach does not particularly address the fouling phenomenon such as that at the "hot" end of a crude preheat train, since fouling there does not exhibit the asymptotic behavior.

Ebert and Panchal (1997) have presented a fouling model that is expressed as the average (linear) fouling rate under given conditions as a result of two competing terms, namely, a deposition term and a mitigation term.

Fouling Rate = (deposition term) - (anti-deposition term)

$$\frac{dR_f}{dt} = \alpha \,\mathrm{Re}^{\beta}\, \mathrm{Pr}^{\delta} \exp\left(\frac{-E}{RT_{film}}\right) - \gamma\tau_w \qquad (1)$$

where α, β, γ and δ are parameters determined by regression, $\tau_w$ in the shear stress at the tube wall and $T_{film}$ is the crude film temperature ( average of the local bulk crude and local wall temperatures).

The relationship in Eq. (1) points to the possibility of identifying combinations of temperature and velocity below which the fouling rates will be negligible. Ebert and Panchal (1997) present this as the "threshold condition".

The model in Eq. (1) suggests that the heat exchanger geometry, which affects the surface and film temperatures, velocities and shear stresses, can be effectively applied to maintain the conditions below the "threshold conditions" in a given heat exchanger.

In a Helixchanger heat exchanger, the quadrant shaped baffle plates are arranged at an angle to the tube axis in a sequential pattern, creating a helical flow path through the tube bundle. See Fig. 4. Baffle plates act as guide vanes rather than forming a flow channel as in conventionally baffled heat exchangers. Uniformly higher flow velocities achieved in a Helixchanger heat exchanger offer enhanced convective heat transfer coefficients. See Fig. 5.

Helical baffles address the thermodynamics of shellside flow by reducing the flow dispersion primarily responsible for reducing heat exchanger effectiveness. Least dispersion (high Peclet numbers) achieved with the helical baffle arrangements approach that of a plug flow condition resulting in high thermal effectiveness of the heat exchanger (Kral et al., 1996). See Fig. 6.

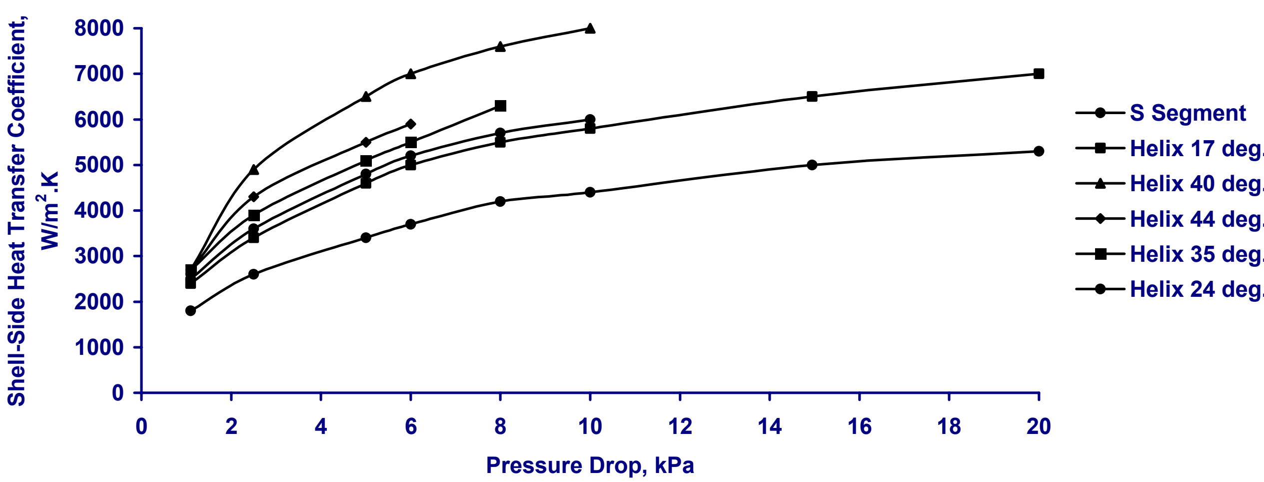


Fig. 5 Measured heat transfer coefficient versus pressure drop on shellside for various baffle systems (Kral et al., 1996) (In Helix x deg., the helical baffles make an angle of x deg. with a plane normal to the tube-axis)

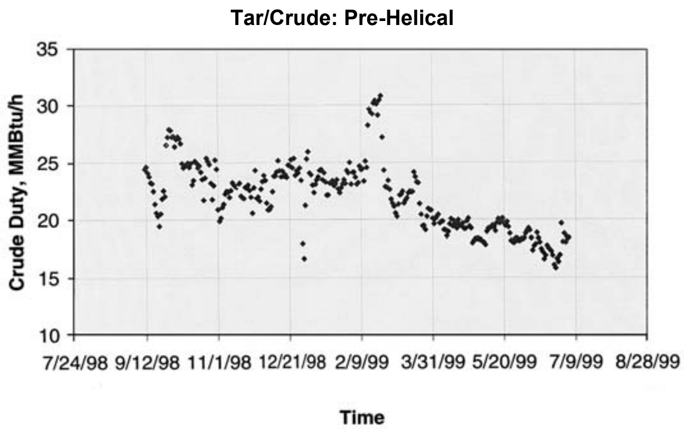


Fig. 7(a) Case 1: Performance of Segmental Bundles

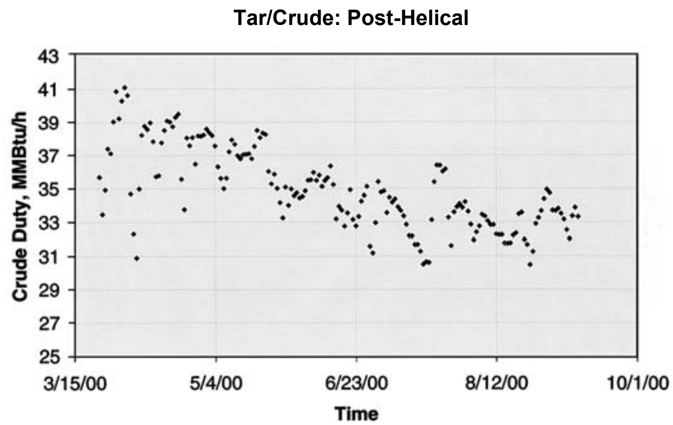


Fig. 7(b) Case 1: Performance of HELIX Bundles

Optimum design of a Helixchanger heat exchanger offers the following characteristics (Chunangad et al.,1998):

- Uniform flow velocities through the tube bundle offering uniform film and metal temperatures
- Elimination of backflow and eddies
- Shellside flow approaches plug flow conditions improving the temperature driving force
- Higher flow velocities are achieved with the same pressure drops, thereby improving shear stress at the heat transfer surface.
- Reduced shell size achieved with the Helixchanger heat exchanger, offers higher tubeside velocities as a secondary benefit in reducing the tubeside fouling rates as well.

All of the above characteristics achieved in a Helixchanger heat exchanger contribute significantly in lowering the fouling rates and maintaining higher performance over longer run cycles as compared to conventional heat exchangers.

## HELIXCHANGER HEAT EXCHANGER FEEDBACK

### Case 1: Crude Preheat Train, Refinery in USA

This application consists of two parallel trains of two exchangers in series. Desalted crude is preheated from about 450°F to 500°F in this exchanger with 680°F tar, before being sent to the crude furnace for further heating. It is an application highly susceptible to fouling. The existing segmental baffle exchangers required cleaning once per year. Fig 7 (a) shows the performance of these exchangers in the last operation cycle. After cleaning in mid-1998, the heat duty achieved in these exchangers varied from about 24 MMBtu/hr to 17 MMBtu/hr in mid-1999. The first set of HELIX bundles were installed in mid-1999. Fig 7 (b) shows the performance of these bundles after more than six months in operation. Between Mar-2000 and Sep-2000, the heat duty achieved in these bundles varied from 37 MMBtu/hr. to 33 MMBtu/hr. In mid-2001, the average heat duty achieved in the HELIX bundles was 29MMBtu/hr. As evident, the HELIX bundles achieved, on average, more than 50% higher duty than the earlier segmental bundles. This was a result of the significantly reduced fouling accumulation on the heat transfer surface and the enhanced heat transfer performance achieved in the HELIX design. Evaluation of typical mid-2001 data on the HELIX bundles showed the total fouling resistance to be around 0.022 hr ft$^2$ °F/Btu, which was less than 50% of the fouling resistance observed in the segmental bundles. The higher average heat transfer performance of the HELIX bundles resulted in valuable savings in fuel cost in the downstream fired heater. Inspection of these bundles in early 2002 showed little fouling on the heat transfer surface. In summary, the HELIX bundles achieved two to three times longer operation run-lengths between cleaning than the earlier segmental bundles while achieving enhanced heat transfer performance. The feedback on the application has led to the specification of HELIX bundles in many crude preheat trains at different facilities of this processor.

### Case 2: Crude Unit, Refinery in Canada

Twenty-two HELIX units are in service at this refinery – fourteen in crude preheat service and eight in crude overhead condenser service.

Replacement HELIX bundles were offered targeting the original heat duty in the fourteen crude preheat exchangers. The earlier segmental bundles required cleaning once every

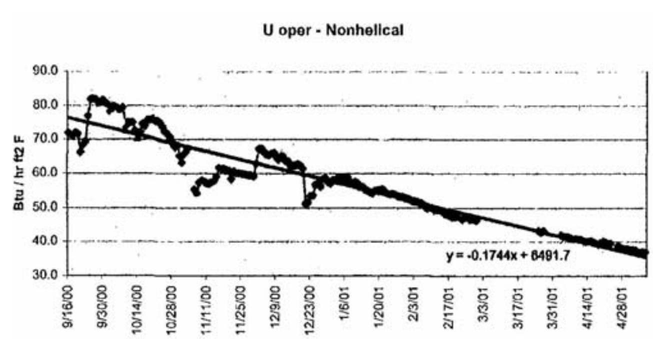


Fig. 8(a) Case 2: Performance of Segmental Bundles

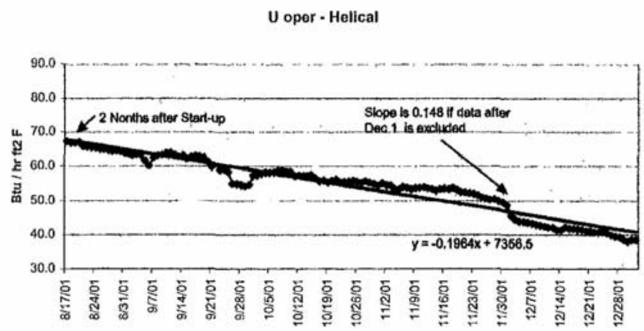


Fig. 8(b) Case 2: Performance of HELIX Bundles

year. As of Mar-2003, the HELIX bundles have demonstrated more than two years of continuous enhanced heat transfer performance. Fig 8 (a) & (b) shows sample data as variation of overall heat transfer coefficient with time between the segmental and the HELIX bundles, in the hottest four of the crude preheat exchangers. In this set of exchangers, crude is preheated from 370°F to about 475°F using 540°F heavy vacuum gas oil (HVGO). It is limited by temperature cross. The helical data in Fig 8 (b) after Dec 1 is to be excluded as it corresponds to a sudden 25% drop in crude flow rates combined with a 25°F drop in HVGO inlet temperature. Although it may be observed from the graphs that the HELIX bundles show marginal improvement in the drop in overall heat transfer coefficient with time in the initial stages, it has since achieved and sustained an asymptotic level of performance much higher than the performance level achieved in the earlier segmental bundles. The HELIX bundles are reportedly expected to achieve more than three years of continuous operation, thus increasing the run-length by three times.

The crude overhead condenser application consists of four parallel trains of two shells in series. 50% capacity upgrade was offered for this service using helical baffles in low-finned tube bundles within limited shellside pressure drop. The plant has confirmed achieving the capacity upgrade and has reported, as of Mar-2003, more than two years of successful continuous operation with these HELIX bundles. Earlier segmental bundles required two to three times cleaning in this time period. The HELIX bundles have achieved significantly enhanced heat transfer performance and have sustained this performance for a long period of time. Three to four times longer run-length has already been achieved with these bundles.

**Case 3: Feed/Effluent Exchangers, Hydrotreater Unit, Refinery in the Netherlands**

This application consists of four 'BEU' (TEMA type) shells in series. The reactor effluent condenses in the tube while the feed vaporizes on the shellside. The existing segmental bundles experienced severe shellside fouling requiring cleaning twice per year. Replacement HELIX bundles were supplied for this application. They were installed in 1998. Fig 9 (a) and (b) show photographs of the hottest and coldest HELIX bundles after one year in operation. Insignificant fouling was observed in the COLD bundle while uniform scale type of fouling was observed on the heat transfer surface in the HOT bundle. The run-length of this unit has been extended by three to four times with the HELIX bundles, as reported by the processor. These bundles have achieved 25% larger throughput within limiting hydraulic constraints. It was also reported that the significantly enhanced heat transfer performance of the HELIX bundles have provided substantial additional savings by not requiring downstream heater modifications.

**Case 4: Feed/Effluent Exchanger, Unifining-Platforming Unit, Refinery in Italy**

This feed/effluent exchanger is a four shells-in-series unit with feed vaporizing on the shellside and effluent condensing in the tubes. The existing segmental-baffled bundles experienced severe uneven fouling, requiring cutting of the shell for access to the bundle. Fig 10 (a) shows the heavily fouled segmental bundle inside the half-cut shell. A replacement HELIX bundle was installed in the


Fig. 9(a) Case 3: Coldest HELIX Bundle

Fig. 9(b) Case 3: Hottest HELIX Bundle

Fig. 10(a) Case 4: Segmental Bundle with Heavy Fouling

Fig. 10(b) Case 4: HELIX Bundle with Uniform Fouling

second hottest shell of this unit in year 2000. Fig 10 (b) shows the photograph of the U-bend end of this HELIX bundle, with uniformly distributed fouling over the heat transfer surface. Significant cost savings have been achieved by the application of the HELIX bundle in this unit, by its reliable operation, its reduced fouling characteristics and its consistent enhanced heat transfer performance.

## CONCLUSIONS

Heat exchanger fouling has been very costly for the industry both in terms of capital costs of heat exchanger banks as well as operation and maintenance costs associated with it.

The HELIXCHANGER heat exchanger, when applied in typically fouling services, has proven to be very effective in reducing the fouling rates significantly. Three to four times longer run-lengths are achieved between bundle cleaning operations.

Proper attention is required in designing the heat exchangers placed at the hot end of crude oil pre-heat operations where temperatures and velocity thresholds are highly dependent on heat exchanger geometry. The helical baffle design offers great flexibility in selecting the optimum helix angles to maintain the desired flow velocities and temperature profiles to keep the conditions below the "fouling thresholds".

## NOMENCLATURE

| | |
|---|---|
| E | activation energy, J/mol K |
| Pr | Prandtl number |
| R | gas constant, J/mol K |
| Re | Reynolds number |
| $R_f$ | fouling resistance, $m^2$ K/kW |
| t | time, s |
| T | temperature, K |
| $\alpha$, $\beta$, $\gamma$, $\delta$ | constants in Eq. (1) |
| $\tau_w$ | Wall shear stress, Pa |

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