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LOW FOULING CRUDE OIL PREHEATERS
SCRAP YOUR EXISTING CONVENTIONAL CRUDE OIL PREHEATERS, REPLACE THEM BY LOW FOULING HEAT EXCHANGERS AND SAVE MONEY

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ABSTRACT

In a time that crude oil prices are constantly higher than US$ 60 per barrel, low fouling heat exchangers can reduce total fouling cost in all crude oil preheat trains in the world with a throughput of 74 Mn bpd by 90%. For 2006, this is a reduction from approximately US$ 11 Bn to US$ 1.3 Bn and a saving on annual fouling cost of US$ 9.7 Bn. Besides this saving on fouling cost, substantial additional savings can be realized on energy by a more 'energy efficient' design of the crude oil preheat train.

The advantages of the low fouling exchanger have been achieved by novel, although already proven, heat transfer mechanisms for both the tube-side and the shell-side of the exchanger. The tube-side applies the circulation of solid particles, which ensures 'zero-fouling' in the tubes in combination with very high heat transfer film coefficients, whereas the shell-side applies Grid baffles also responsible for an excellent film coefficient and a low fouling factor. Combination of above technologies in one heat exchanger realizes clean overall heat transfer coefficients or k-values, which are approximately 200% higher than in conventional heat exchangers, while the fouling rates or fouling factors in low fouling exchangers can be reduced to less than 5% of values generally applied in conventional heat exchangers. The influence of these excellent results on additional pumping power requirements are marginal.

Low fouling exchangers are also characterized by their very compact design and vertical lay-out, which characteristics are responsible for a low weight and small plot area. Another advantage of the low fouling exchangers is the possibility to vary the crude oil throughput from 100% to less than 30% without losing its excellent heat transfer performance. In spite of the low fouling design, it is still possible that the shell-side might suffer from a slow build-up of fouling deposits. To avoid this, the low fouling heat exchanger can be designed in such a way that the bundle can be removed from the shell and sufficient distance between the tube rows allow for mechanical (hydro-blasting) cleaning using the standard available equipment.

As to investment cost of low fouling crude oil preheat trains versus savings, it should be mentioned that at crude oil prices of US$ 60 /barrel, the low fouling crude oil preheat train with a 100% back-up in low fouling heat transfer surface shows a 'Return Of Capital' (ROC) of approximately 6 months. If the existing conventional heat exchangers are used as back-up, then the ROC becomes less than 4 months.

In the case of an 'energy efficient' design and higher crude oil prices, these ROC's drop to less than 5 months and even less than 3 months respectively. However, if only the most problematic sections of the existing problematic crude oil preheat train are replaced by low fouling heat exchangers, the ROC's for these investments are further reduced and might come close to 2 months.

The conclusion is new crude oil preheat trains should be equipped with these low fouling exchangers and existing crude oil preheat trains or sections of these trains containing conventional heat exchangers, should be modified by replacing the conventional heat exchangers with low fouling exchangers.

INTRODUCTION

Conventional crude oil preheaters consist of shell and tube heat exchangers and use two severely fouling process streams, one in the tubes and one in the shell. The annual fouling cost of conventional crude oil preheat trains are staggering as a result of today's very high crude oil prices In an attempt to find a solution for these very high fouling cost, a novel design of a 'zero fouling' self-cleaning heat exchanger is described in Reference [1] as an alternative for the problematic fouling conventional crude oil preheaters. This 'zero fouling' self-cleaning exchanger applies a self-cleaning mechanism in the tubes of two vertical parallel bundles handling the fouling process streams, where the self-cleaning mechanism is created by the circulation of cleaning particles through the tubes of both bundles. For the transfer of heat between the bundles a small circulating flow of conditioned water is used as an intermediate fluid, a fraction of which evaporates on the outside of the tubes of the high temperature bundle and condenses on the outside of the tubes of the low temperature bundle.

In spite of the unique achievements of this novel design, i.e. truly 'zero-fouling', there are also some real disadvantages, which refer to the rather complex construction of the heat exchanger and the fact that using an intermediate liquid for the transfer of heat between two process streams, does have a serious negative effect on the installed heat transfer surface.

An alternative for this 'zero fouling' heat exchanger is a shell and tube heat exchanger where the fouling in the tubes remains indeed 'zero' because of the application of the self-cleaning heat transfer mechanism in the tubes, whereas in the shell another innovative heat transfer mechanism is applied, which very much improves the heat transfer film coefficient and dramatically lowers the fouling. The combination of both heat transfer mechanisms and the ideal synergy between both mechanisms results into the so-called 'low fouling' heat exchanger.

PRINCIPLE OF THE LOW FOULING CRUDE OIL PREHEATER

In Fig. 1, it is shown how liquid and cleaning particles are evenly distributed over all the vertical heat exchanger tubes, where these particles are carried through the vertical heat exchanger tubes by the liquid flow, separated from the liquid in a proprietary type of separator and returned through downcomer and control channel to the inlet channel, where the cycle is repeated. Inasmuch as the cleaning particles consist of cut metal wire with a diameter of 2 or 3 mm, and based on experiences involving many more severely fouling applications in industry, the cleaning action caused by the mild scouring of these particles is unquestionable and a guarantee for 'zero fouling' in the tubes in combination with an excellent heat transfer film coefficient.

The shell-side of the low fouling exchanger is equipped with multiple Grid baffles in series is shown in Fig. 2. Those baffles show a strong resemblance in performance with the recently developed EM baffles of Shell Global International and explained in the References [2] and [3]. The Grid baffles combine the advantages of low pressure drop, reduction of fouling and no tube vibrations. Many Grid baffles in series create a static mixing effect of the liquid in the shell between the tubes that explains their excellent heat transfer performance. The Grid baffled shell-side design often applies two-passes, where the flow in each pass is counter-current to the single-pass flow in the tubes. This two-pass design increases the longitudinal liquid velocity in the shell and, as a consequence, further increases the heat transfer film coefficient and reduces shell-side fouling.

FOULING RATES OF CONVENTIONAL AND LOW FOULING CRUDE OIL PREHEATERS

A fouling rate of an exchanger consists of the sum of the fouling rates for the tube-side and for the shell-side. What kind of fouling rate can we expect when we replace the conventional crude oil preheater by a low fouling crude oil preheater ?

If the total fouling rate of a conventional crude oil preheater with cross segmental baffles in the shell is expressed in percentages and equal to 100%, it is not unrealistic to assume a fouling rate for the tube-side equal to 67% and for the shell-side equal to 33%. These fouling rates are based on the assumption that the more severely fouling crude oil flows always through the tubes and the less severely fouling hydrocarbons through the shell of the exchanger. It has already been mentioned that the circulation of cleaning particles in the tubes of a low fouling heat exchanger reduces any fouling rate in the tubes of this heat exchanger to zero. Therefore the average fouling rate for the tube-side of a conventional heat exchanger of 67% will be reduced to 0% by the low fouling exchanger.

From the experiences with the EM baffles, it was found that when applying these baffles, the shell-side fouling rate can be reduced by approximately 50% in comparison with the shell-side fouling rate for conventional exchangers equipped with cross segmental baffles in the shell. Because of similarities between the EM baffle and the Grid baffle, it is very likely that this reduction of 50 % also applies to the Grid baffle and, therefore, the shell-side fouling rate of 33% should not only be reduced to 16.5% for the EM baffled configuration, but also for the Grid baffled configuration. For the low fouling exchanger with Grid baffles, an even larger reduction in shell-side fouling rate is possible, as, according to Reference [4] this fouling rate may be inversely proportional to a representative shell-side velocity, according to the relation:

$$\text{Fouling Rate} = [\text{Constant}] \times [\text{Representative Velocity}]^{-0.67}$$

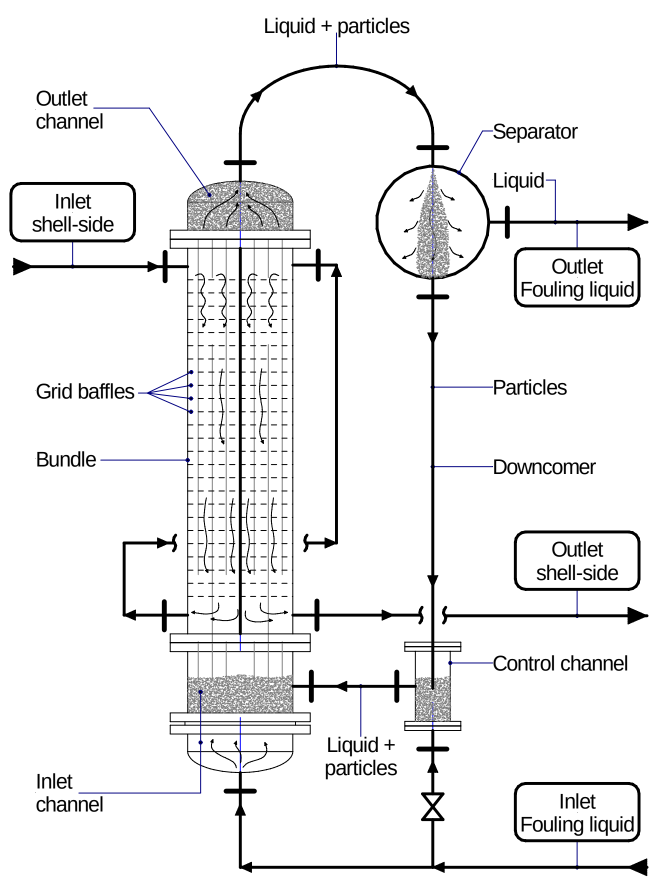


Fig. 1: Principle self-cleaning heat exchanger with one pass for the tube-side and two pass for the shell-side.

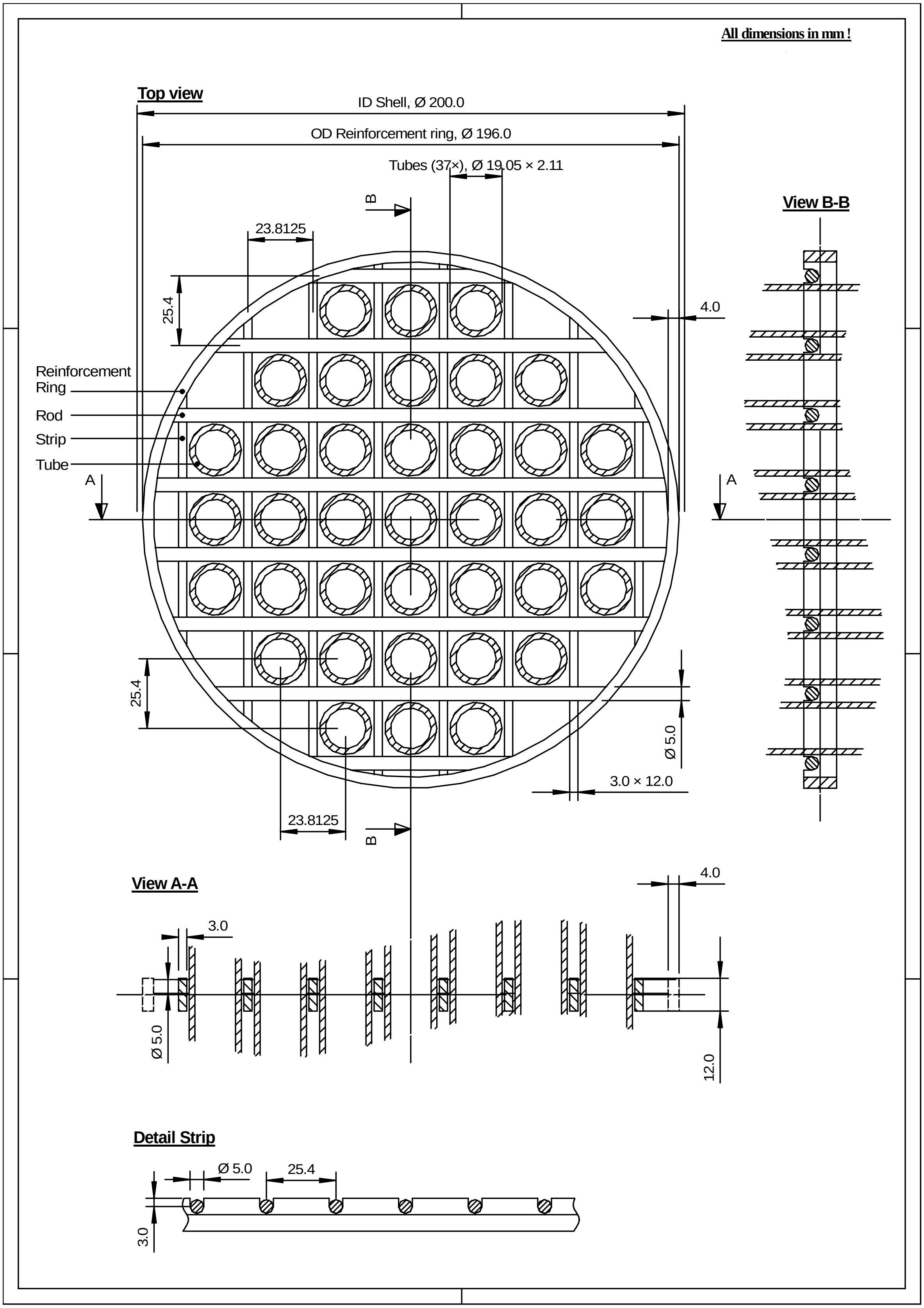


Fig. 2: Example of Grid baffle consisting of “Rods” and “Strips” laying in one plane.

This means that if the velocity increases by a factor 3, the fouling rate decreases by a factor 2. More information about this velocity influence is given in Reference [5].

For the low fouling heat exchanger with Grid baffles, which indeed can apply rather high shell-side velocities, the EM baffle fouling rate of 16.5% may be further reduced to approximately 4%, which actually means a reduction of the total fouling rate for a conventional heat exchanger of 100% to only 4% or even less for a low fouling exchanger.

Table 1 summarizes the fouling rates for the various types of crude oil preheaters.

Table 1: Fouling rate for various types of crude oil preheaters

Type of heat exchangers	Units	Fouling rate in % of total fouling rate for conventional heat exchangers		
		Tube-side	***Shell-side***	***Total***
Conventional heat exchanger with cross segmental baffle	%	67	33	100
Conventional heat exchanger with EM-baffle	%	67	16.5	83.5
Low fouling heat exchanger	%	0	4	4

Table 2: Significant process and design parameters low fouling and conventional crude oil preheater for 100,000 bpd.

	Units	Low fouling HEX	Conventional HEX
Crude oil flow	m^3/h	660	660
Density crude oil	kg/m^3	750	750
Diameter tubes	mm	19.05 × 2.11	25.4 × 2.77
Diameter shell	mm	500 to 700	1,000 to 1,300
Number of passes tube-side	-	1	2
Velocity in tubes	m/s	2.5 to 3.5	~1.5
Number of passes shell-side	-	1, 2 or 4	1 to 2
Longitudinal velocity shell-side	m/s	1.0 to 3.0	n.a.
Film coefficient tube-side	$W/(m^2{\cdot}K)$	2,000 to 4,000	~1,200
Film coefficient shell-side	$W/(m^2{\cdot}K)$	3,000 to 5,000	~1,200
Clean k-value	$W/(m^2{\cdot}K)$	1,000 to 1,600	~500
Fouling rate	$m^2{\cdot}K/J$	$[0.05 \text{ to } 0.1]\times10^{-10}$	$[1.0 \text{ to } 4.0]\times10^{-10}$
Thermal length, $\Delta T/\Delta T_{log}$	-	0.6 to 1.0	~0.7
Tube length	mm	6,000 to 9,000	~8,000
Total height / length	mm	8,000 to 11,000	8,000 to 10,000

IMPORTANT DESIGN PARAMETERS FOR LOW FOULING CRUDE OIL PREHEATERS AND CONSEQUENCES

The most significant process and design parameters for a low fouling heat exchanger and a conventional heat exchanger of an average crude oil preheat train with a throughput of 100,000 bpd are shown in Table 2.

From this table, it can be concluded that low fouling exchangers are very compact with shell diameters between 500 mm and 700 mm and heights varying from 8 m to 11 m for tube lengths of 6 m to 9 m. Such dimensions always result in a very low weight and small plot area for the installed exchanger.

It should be attractive to make the crude oil preheat train more thermally efficient than the conventional heat exchanger trains to save energy supplied in the furnace. If higher efficiency is targeted, the thermal length of the low fouling exchanger ΔT / ΔT_{log} may be increased by 50% or even more. This increase also affects the tube length of the exchanger. However, even though the resulting values for tube length, total height and weight of the exchanger are larger, economics still favors designing for the higher efficiency. Therefore, it can be stated that these low fouling exchangers are also ideally suited for the design of energy efficient crude oil preheat trains as will be shown later in this article.

COMPARISON FOULING COST 'CONVENTIONAL' VERSUS 'LOW FOULING' CRUDE OIL PREHEATERS

Conventional heat exchangers in crude oil preheat trains of refineries suffer from severe fouling and, as will be shown later in this article, for 2005, these fouling cost exceeded US$ 10 Bn per year based on a world-wide crude oil production of 74 Mn barrels per day and a crude oil price of US$ 60 per barrel. The fouling cost can be divided into the following categories:

- Lost production.
- Extra energy cost.
- Maintenance.

As a first step in the evaluation of the benefits of 'low fouling' exchangers in crude oil preheat trains in comparison with conventional heat exchangers, it is essential to compare the fouling cost between both types of heat exchangers. Therefore, it is necessary to compare the deterioration of the overall heat transfer coefficients (k-values) due to fouling as a function of time for both types of exchangers, also referred to as the transients of the k-values.

Fig. 3 shows the deterioration of the k-value for a conventional heat exchanger HEX-1 and a low fouling heat exchanger HEX-2. The low fouling exchanger not only shows a much slower decrease of the k-value than the conventional heat exchanger due to its much lower fouling rate, but also a much higher clean k-value Y_1 compared to X_1 for the conventional exchanger.

The fouling cost for the conventional exchanger during a period of P months is related to the average k-value X_m over that period. If we choose for the low fouling exchanger an average k-value Y_m based on the expression:

$$Y_m = X_m / X_1 \times Y_1,$$

and expand the curve representing the deterioration of the k-value for the low fouling exchanger to such an extent that the surface:

$$O_2^* = O_1^*,$$

then, the first cleaning of the low fouling exchanger HEX-2 takes place after an operating period of Z months in comparison with the period of P months for the conventional heat exchanger.

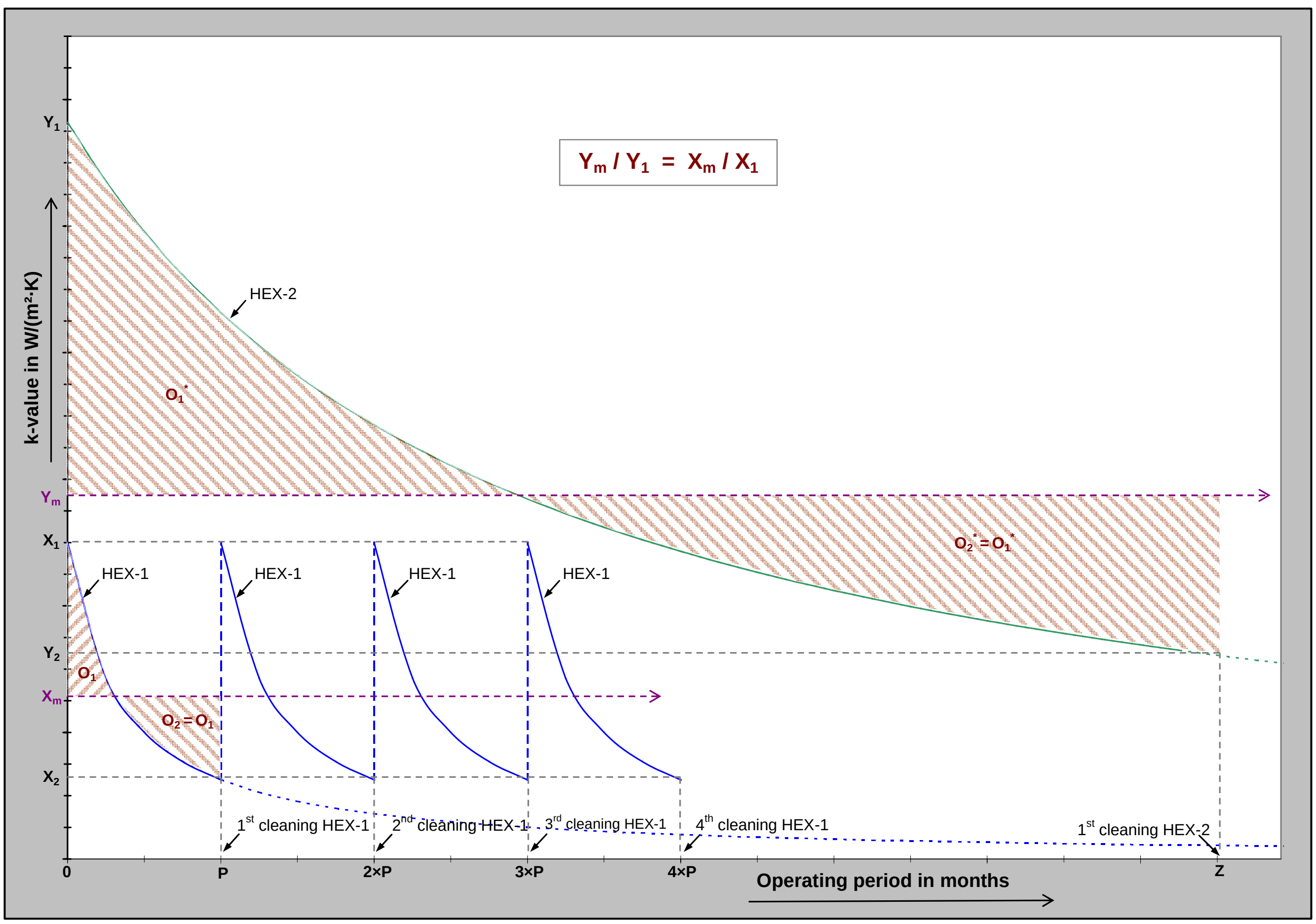


Fig. 3: Presentation overall heat transfer coefficients (k-value) transients for two heat exchangers HEX-1 and HEX-2 with a period between cleanings for HEX-1 of P months.

Based on the above assumptions, it is evident that all fouling cost for the low fouling heat exchanger made in a period of Z months are equivalent to all fouling cost K_1 for the conventional heat exchanger made in a period of P months. However, the average fouling cost for the low fouling heat exchanger K_2 over a period of P months are then reduced to a fraction of the cost generated in the same period for the conventional exchanger and these average fouling cost for the low fouling exchanger K_2 during the period of P months can be expressed as follows:

$$K_2 = P / Z \times K_1, \text{ with } P \ll Z.$$

The questions then are:

- How many months between cleanings are represented by P and Z.
- What are the actual annual fouling cost K_1 for crude oil preheat trains equipped with conventional heat exchangers.

The answers to these questions will be given in the next paragraph.

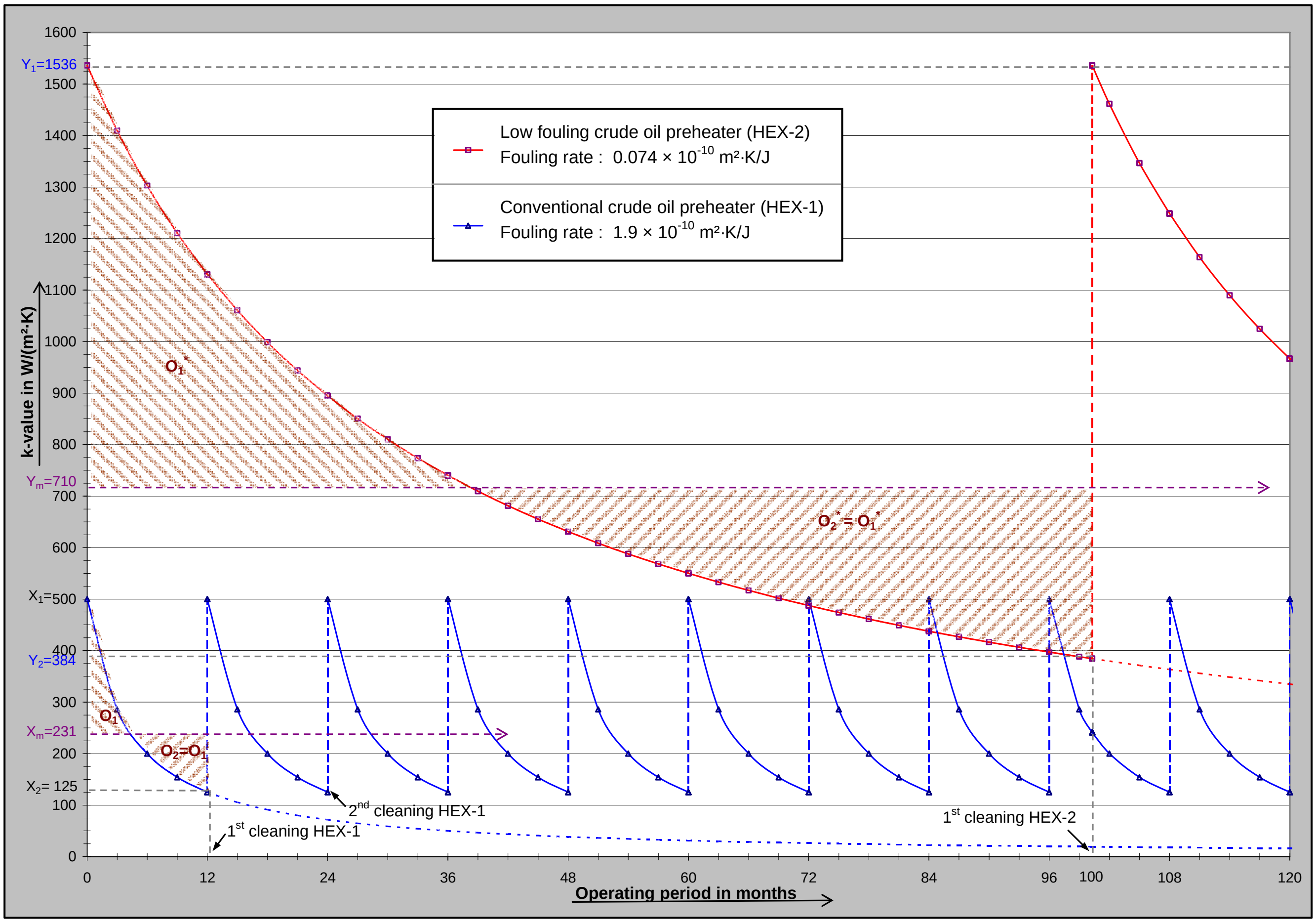


Fig. 4: Presentation real cases overall heat transfer coefficients (k-value) transients for two heat exchangers HEX-1 and HEX-2 with a period between cleanings for HEX-1 of 12 months.

COMPARISON REAL CASES 'CONVENTIONAL' VERSUS 'LOW FOULING'

From a comparison of the real transients for the k-values of crude oil preheaters shown in Fig. 4 (with indeed a much higher clean k-value for the low fouling heat exchanger than for the conventional exchanger and much lower fouling rates for the low fouling exchanger in comparison with the conventional exchanger) and with the help of the explanation given in Fig. 3, it follows that for a period P between cleanings for the conventional heat exchanger is equal to 12 months, and the period Z between cleanings for the low fouling exchanger becomes 100 months.

Fig. 5 shows that in the situation the conventional heat exchanger is cleaned twice a year, and again based on the assumptions of Fig. 3, the low fouling exchanger also requires two cleanings in a period of 100 months This actually means that the fouling costs for the conventional heat exchanger in a period of 12 months are again the same as the fouling costs for the low fouling exchanger in a period of 100 months.

In due course, the conclusions in this article obtained from the above presented real transients of the k-values are considered representative for the evaluation and the conclusions regarding the fouling cost of all crude oil preheat trains.

The References [6], [7] and [8] have played a significant role in the determination and validation of the annual fouling cost K_1 for all crude oil preheat trains in the world equipped with conventional heat exchangers. For 1992 the annual fouling cost for all refineries in the world, then processing a crude oil production of 60 Mn bpd at a crude oil price of US$ 13 per barrel, have been calculated as follows:

- Energy cost equal to US$ 1,000 Mn.
- Cost due to production loss equal to US$ 3,164 Mn.
- Maintenance cost equal to US$ 167 Mn.

As a consequence, the total annual fouling cost in 1992 amounted to:

US$ 4,331 Mn.

For the situation in 2005, a production increase from 60 Mn bpd in 1992 to 74 Mn bpd in 2005 has been taken into account. Further, during this period of 13 years (i.e.1992 up to and inclusive 2005) an annual inflation of 2% has been taken into account and the crude oil price has been increased from US$ 13 per barrel in 1992 to US$ 60 per barrel in 2005. Crude oil prices and production figures have been obtained with the help of Reference [9].

Using the above numbers, for 2005, the total annual fouling cost for all refineries in the world, processing the higher production at a higher crude oil price including annual inflation, increase as follows:

- Energy cost equal to US$ 5,692 Mn.
- Cost due to production loss equal to US$ 5,048 Mn.
- Maintenance cost equal to US$ 266 Mn.

Total annual fouling cost for 2005 for all refineries in the world operating crude oil preheat trains equipped with conventional heat exchangers are:

$$K_1 = \text{US\$ } 11{,}006 \text{ Mn}$$

or

$$\underline{K_1 = \text{US\$ } 11.0 \text{ Bn.}}$$

Taking into account the above mentioned values for P = 12 and Z = 100, the average annual fouling cost for all crude oil preheat trains equipped with low fouling exchangers become:

$$K_2 = 12 / 100 \times \text{US\$ } 11{,}006 \text{ Mn}$$

or

$$\underline{K_2 = \text{US\$ } 1{,}321 \text{ Mn.}}$$

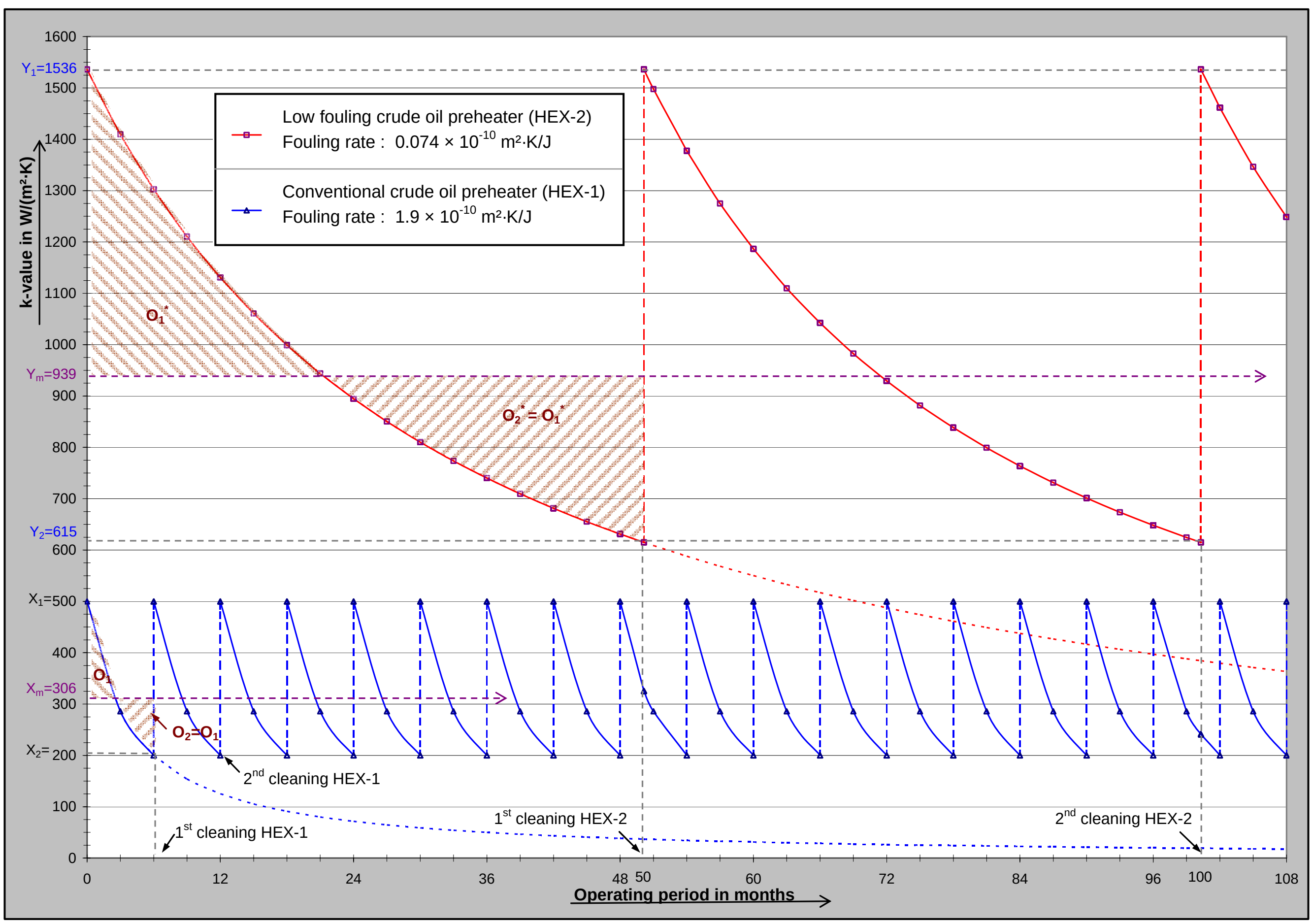


Fig. 5: Presentation real cases overall heat transfer coefficients (k-value) transients for two heat exchangers HEX-1 and HEX-2 with a period between cleanings for HEX-1 of 6 months.

SAVINGS ON FOULING COST BY THE INTRODUCTION OF LOW FOULING EXCHANGERS IN CRUDE OIL PREHEAT TRAINS

Replacing all conventional exchangers in the crude oil preheat trains by low fouling exchangers gives the following potential average annual saving Л in fouling cost:

$$Л = K_1 - K_2$$
$$= \text{US\$ } 11{,}006 \text{ Mn} - \text{US\$ } 1{,}321 \text{ Mn}$$
$$= \text{US\$ } 9{,}685 \text{ Mn}$$

or

$$\underline{Л = K_1 - K_2 = \text{US\$ } 9.69 \text{ Bn.}}$$

This saving applies to all crude oil preheat trains equipped with low fouling exchangers and processing the daily production in the world equal to 74 Mn bpd.

If these savings are related to a typical refinery crude oil processing preheat train with a throughput of 100,000 bpd, these savings $Л_{ref}$ amount to:

$$Л_{ref} = \text{US\$ } 9.69 \text{ Bn} / 740 = \text{US\$ } 13{,}094{,}595$$

or

$$\underline{Л_{ref} = \text{US\$ } 13.09 \text{ Mn.}}$$

For a real understanding of the meaning of these savings, it is necessary to implement the installation of the low fouling heat exchangers in a crude oil preheat train processing 100,000 bpd and compare these savings with the required investment costs for this new configuration preheat train equipped with low fouling exchangers.

INSTALLATION OF LOW FOULING HEAT EXCHANGERS IN A CRUDE OIL PREHEAT TRAIN

Fig. 6 shows an average, although simplified, 'state-of-the-art' crude oil preheat train processing 100,000 bpd that corresponds to a crude oil flow of 660 m³/h. The term 'state-of-the-art' refers to a train with a temperature increase of the crude in the furnace from 271 °C to 380 °C. Later in this article we will discuss a more 'energy efficient' crude oil preheat train with a temperature increase of the crude in the furnace from 298 °C to 380 °C. It should be noted that all different kinds of fouling cost or fouling costs definitions subject of discussion in this article relate to the heat exchangers in the section of the crude oil preheat train downstream the desalter. For the section of the crude oil preheat train upstream the desalter, the fouling cost are considered negligible.

Using the example shown in Fig. 6 and with the help of Reference [6], a simplified example for tube-side and shell-side temperatures of the exchangers Ex4 up to and inclusive Ex8 and the average values for the physical properties of both process streams, have been presented in Fig. 7. From the Figures 6 and 7, it is possible to prepare Fig. 8, which simulates the performance of the original crude oil preheat train consisting of multiple exchangers in series, by just one large heat exchanger with a ΔT_{log} = 37.4 °C, an average

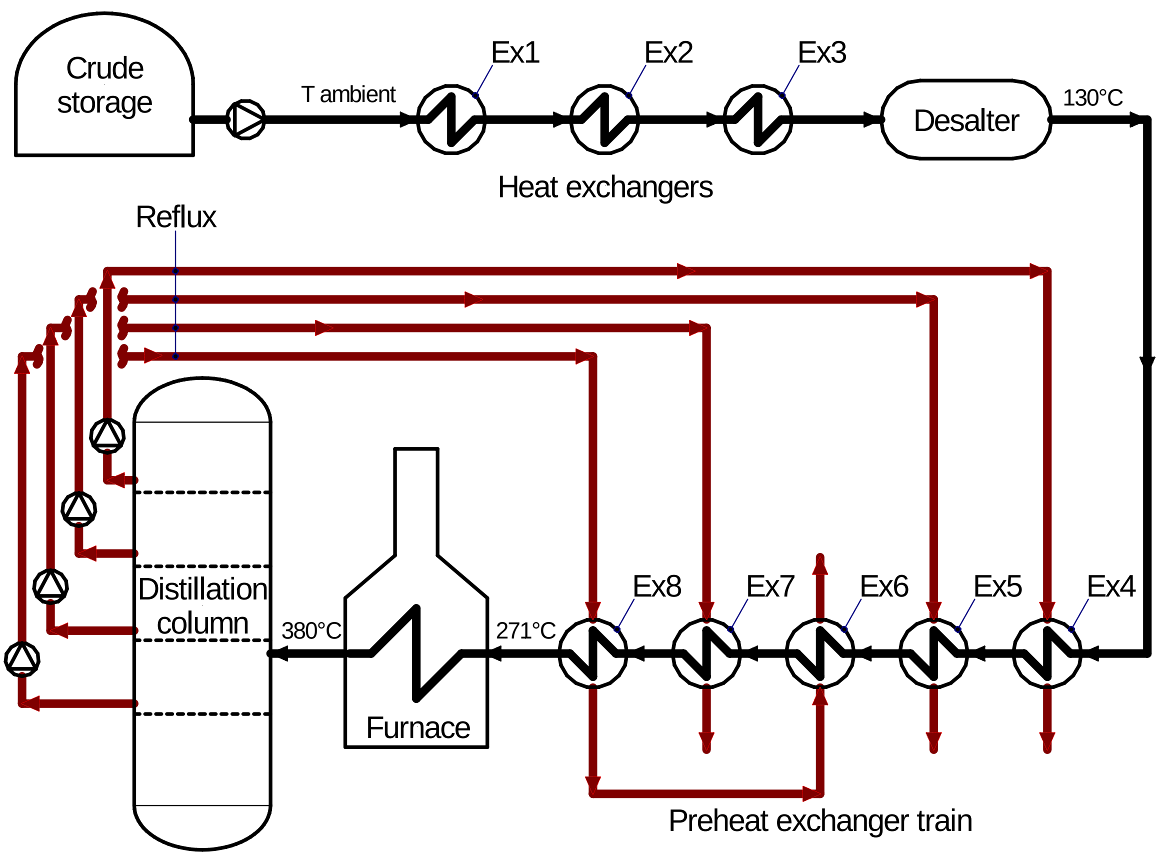


Fig. 6: Simplified flow diagram crude oil preheaters upstream distillation column.

shell-side flow of hydrocarbons equal to 359 m³/h and an outlet temperature of the hydrocarbons of 137.2 °C. The linear temperature profiles in Fig. 8 are, of course, a simplification of the real profiles.

Considering the situation presented in the Figures 6, 7 and 8 as an example representative for our evaluation of all crude oil preheat trains processing a throughput of 100,000 bpd, equipped with low fouling exchangers and assuming a clean k-value of 1,536 W/(m²·K), it is possible to calculate the installed heat transfer surface F_{low} for the single low-fouling-heat-exchanger, which then yields:

$$F_{low} = (660 / 3{,}600 \times 750 \times 2{,}500 \times 141) / (1{,}536 \times 37.4) = 844 \text{ m}^2.$$

In order to create an accurate estimate for the investment costs of a low fouling crude oil preheat train, the single large low-fouling-heat-exchanger train has been broken up into five smaller low fouling exchangers in series with the same thermal length ΔT / ΔT_{log} for each heat exchanger, which then becomes:

$$\Delta T / \Delta T_{log} |_{Ex4,Ex5,Ex6,Ex7,Ex8} = (141 / 5) / 37.4 = 28.2 / 37.4 = 0.754$$

The effect of these equal ‘thermal lengths’ for each heat exchanger on the simplified temperature diagram of Fig. 8 is shown in Fig. 10.

As it has also been assumed that for all five heat exchangers equal physical properties, volume flows, tube diameters and velocities in the tubes and in the shell for the crude oil and the hydrocarbons apply, the consequences of equal thermal length for all heat exchangers is that all five heat exchangers should also have the same tube length, number of tubes and heat transfer surface. As a matter of fact, all five low fouling heat exchangers are identical, which very much simplifies our evaluation for the total installation cost.

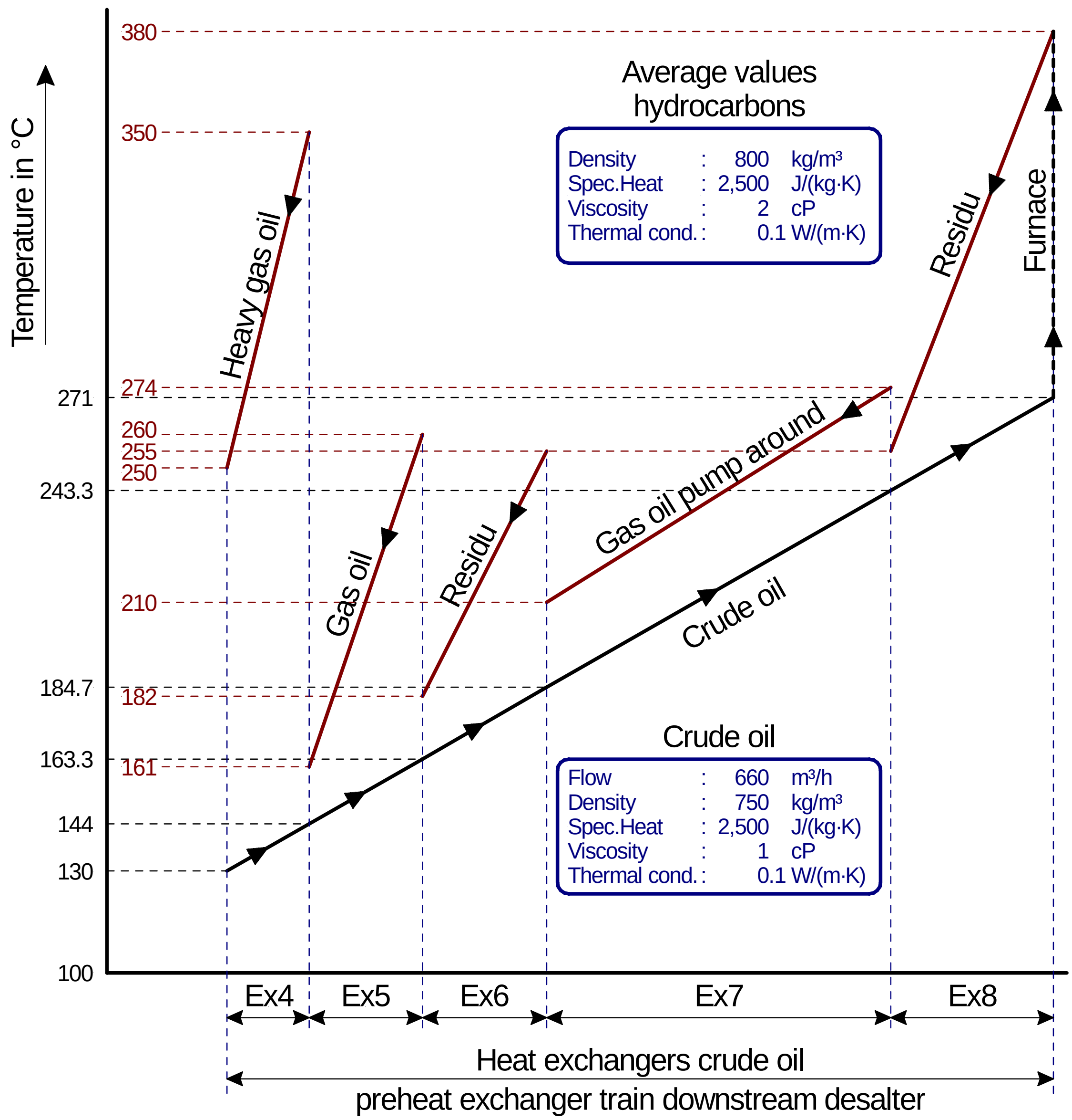


Fig. 7: Temperature diagram crude oil heaters in simplified model preheat train of Fig. 6.

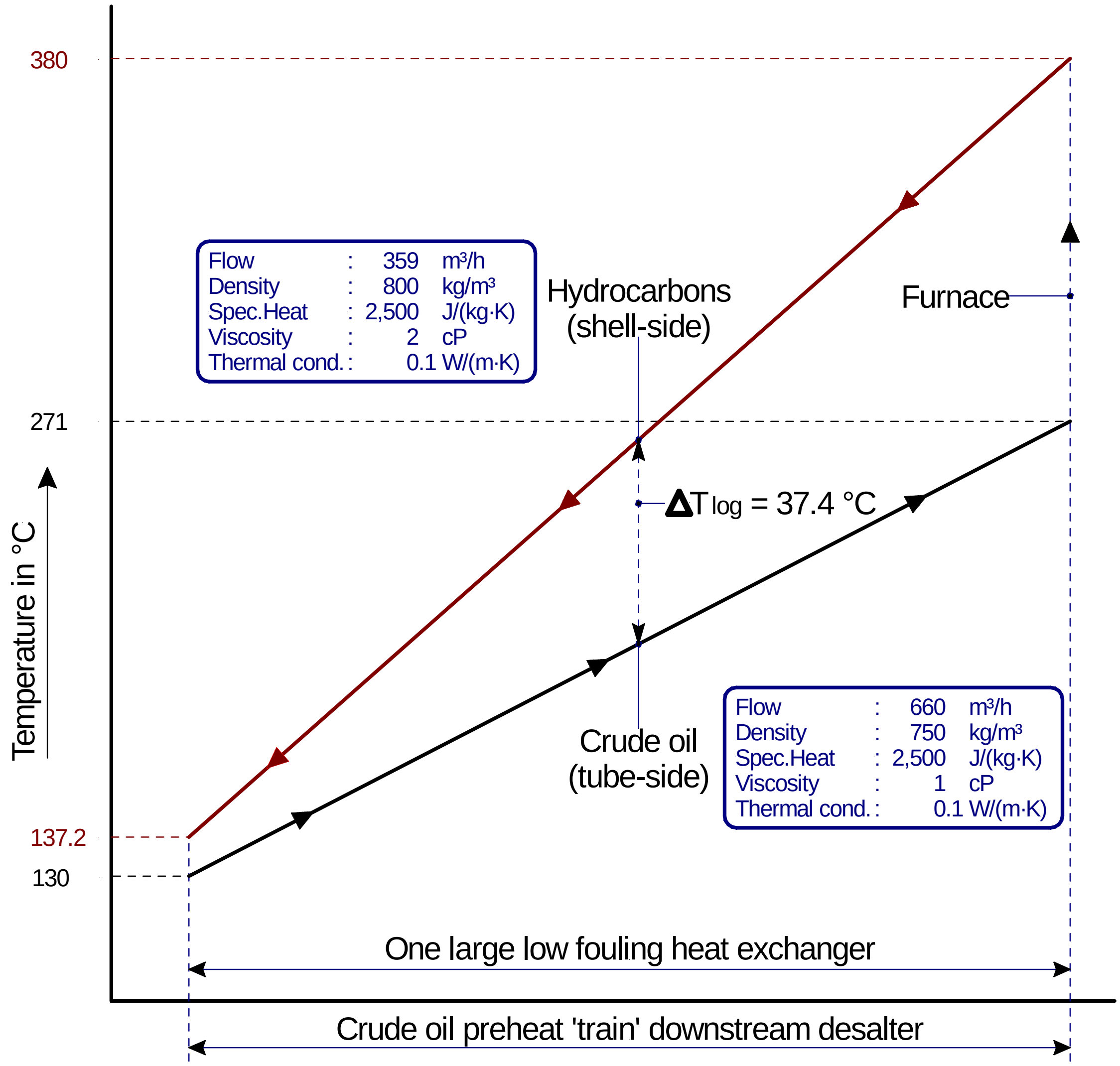


Fig. 8: Modified simplified temperature diagram crude oil preheat train with ΔT_{log} = 37.4 °C consisting of one large low fouling heat exchanger.

Based on the above assumptions for the low fouling exchangers, the heat transfer surface for each exchanger F_{Ex} becomes:

$$F_{Ex4} = F_{Ex5} = F_{Ex6} = F_{Ex7} = F_{Ex8} = 844 / 5 = 169 \text{ m}^2.$$

Table 3 gives a specification of one of these low fouling exchangers, while Fig. 9 gives an impression of how these exchangers should be installed in case of a 100% operating capacity without a back-up heat exchanger, and the situation that 2 × 100% operating capacity in series has been installed, one of which serves as back-up.

Table 4 specifies the investment cost for the various options of a 'state-of-the-art' low fouling crude oil preheat train with a throughput of 100,000 bpd. The following important conclusions from Table 4 deserve emphasis:

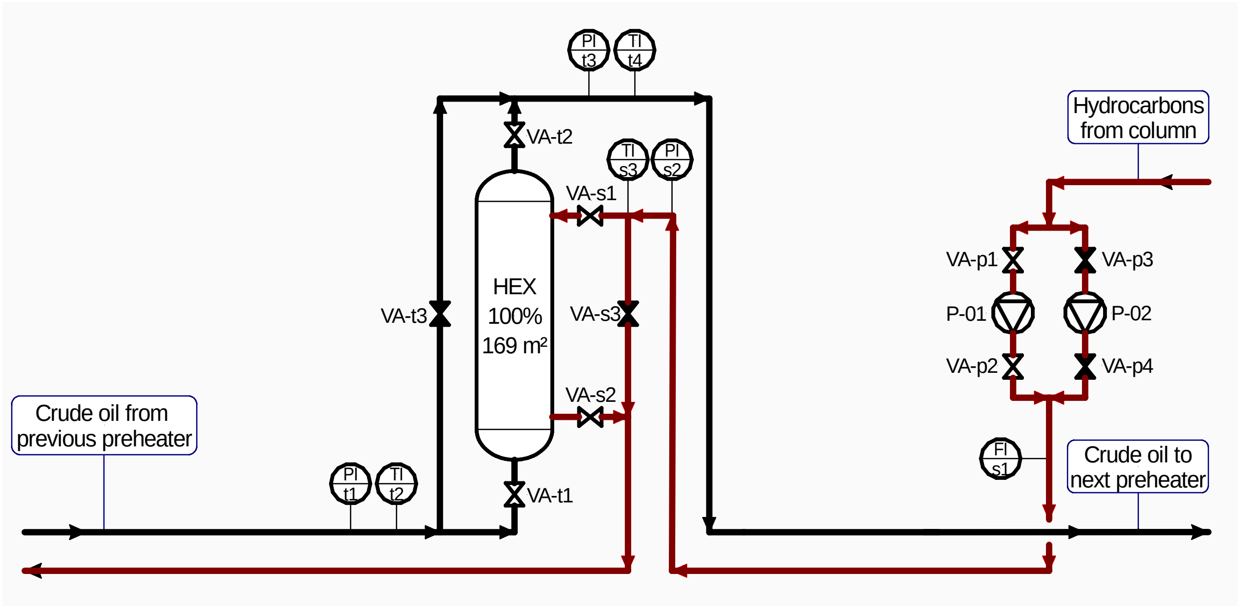
The total investment cost for a 'state-of-the-art' low fouling crude oil preheat train with 1 × 100% capacity in heat transfer surface and no back-up heat exchanger amounts to:

$$\underline{Д_{ref}^{*}\big|_{1\times100\%} = US\$\ 4.10\ Mn,}$$

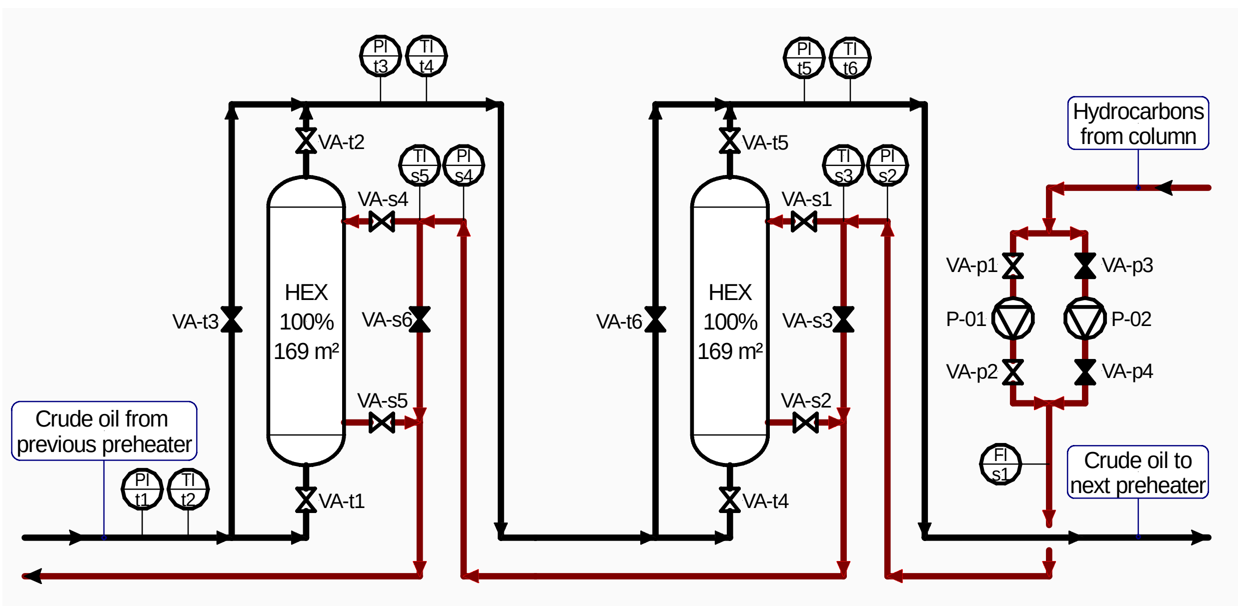
for similar 'state-of-the-art' low fouling crude oil preheat train with 2 × 100% capacity, i.e. equipped with 100% back-up heat exchanger, these investment costs amount to:

$$\underline{Д_{ref}^{*}\big|_{2\times100\%} = US\$\ 6.60\ Mn.}$$

These conclusions will also be used later in this report.



A: Flow diagram low fouling preheater consisting of one shell (1×100%).



B: Flow diagram low fouling preheater consisting of two shells (2×100%) in series.

Fig. 9: Flow diagrams low fouling preheaters.

INFLUENCE OF PUMPING POWER ON SAVINGS

It has been shown that the savings on annual fouling cost in a 100,000 bpd crude oil preheat train by replacing conventional heat exchangers in this train by low fouling heat exchangers, amounts to:

$$\underline{JI_{ref} = US\$\ 13.09\ Mn.}$$

However, for a fair comparison it necessary to account for the pumping energy because the low fouling heat exchangers operate with a larger pressure drop in their shells due to the presence of the Grid baffles and, consequently, do need more pumping power. For the tube-side no extra pumping power is needed. Experience in real installations have shown that, in spite of better performance, the self-cleaning technology in the tubes employing the circulation of particles, never requires more pumping power than in conventional heat exchangers.

From Table 3 it can be derived that a complete crude oil preheat train for a throughput of 100,000 bpd and consisting of the five exchangers Ex4 up to and inclusive Ex8 in series, requires a pumping power for its shell-side flow of 5 × 66 = 330 kW. If we assume that 80% of this pumping power exceeds the shell-side pumping power required by the conventional preheaters, then, for 8,750 hours per year and a kWh price of US$ 0.125, this extra pumping power adds to the operating cost of the low fouling crude oil preheat train for the processing of the daily crude oil throughput of 100,000 bpd:

$$0.8 \times 330 \times 8{,}750 \times 0.125 = \text{US\$ } 288{,}750 \text{ or US\$ } 0.29 \text{ Mn.}$$

This reduces the net savings on fouling cost $Л_{ref,\ net}$ due to the installation of low fouling exchangers to:

$$Л_{ref,\ net} = \text{US\$ } 13.09\text{Mn} - \text{US\$ } 0.29 \text{ Mn} = \text{US\$ } 12.80 \text{ Mn.}$$

Table 3: Specifications low fouling crude oil preheaters (Ex4 up to and inclusive Ex8) for 100,000 bpd.

	Units	
Flow tubes (crude oil)	m³/h	660
Flow shell (hydrocarbons)	m³/h	359
Number of tubes	-	391
Tube diameter	mm	19.05 × 2.11
Tube length	mm	7,226
Tube pattern	-	rectangular
Tube pitch	-	1.33 × 1.25
Inner shell diameter	mm	590
Total heat exchanger surface	m²	169
Number of passes tube-side	-	1
Number of passes shell-side	-	2
Baffle configuration shell-side	-	Grid
Diameter cleaning particles	mm	3
Material cleaning particles	-	C.St.
Liquid velocity tubes	m/s	2.70
Longitudinal liquid velocity shell	m/s	1.23
Clean k-value	W/(m²·K)	1,536
Fouling rate	m²·K/J	0.74×10^{-10}
Pressure drop tube-side	bar	0.75
Pressure drop shell-side	bar	4.5
Pump power tube-side (η=70%)	kW	20
Pump power shell-side (η=70%)	kW	66

ENERGY EFFICIENT DESIGN TO INCREASE NET SAVINGS

One of the possibilities to increase net savings is the modification of crude oil preheat trains equipped with low fouling heat exchangers into a more 'energy efficient' configuration. For example, the reduction of the heat input of the furnace would save a considerable amount of energy.

Fig. 11 shows the situation where the heat input into the furnace is reduced by 25%. This means that in comparison with the 'state-of-the-art' situation in Fig. 8 the inlet temperature of the furnace is increased from 271 °C to 298 °C, while the outlet temperature remains 380 °C. This more 'energy efficient' design requires a larger surface for the crude oil preheaters Ex4 up to and inclusive Ex8 as these heat exchangers have to recover more heat from the shell-side hydrocarbons to heat the crude from 130 °C to 298 °C. However, this larger heat recovery has to be performed at a smaller logarithmic temperature difference which has been reduced from the original situation shown in Fig. 8 with ΔT_{log} = 37.4 °C to the new situation shown in Fig. 11 with ΔT_{log} = 30.7 °C.

The consequences of the changes in the temperatures of Fig. 8 into the temperatures shown in Fig. 11 are an increase in the thermal length $\Delta T / \Delta T_{log}$ of the crude oil preheaters Ex4 up to and inclusive Ex8 from 141 / 37.4 = 3.77 to 168 / 30.7 = 5.47. As a matter of fact, this increase in thermal length by a factor 5.47 / 3.77 = 1.45 means that the heat transfer surfaces of the preheaters Ex4 up to and inclusive Ex8 have been increased by this factor from 844 m² to 1.45 × 844 = 1,224 m². This also applies to the tube length of these exchangers that has been increased from 7,226 mm to 1.45 × 7,226 = 10,478 mm. More heat transfer surface means higher investment cost for the exchangers and longer tubes means larger pressure drops on both the tube-side and the shell-side.

In Fig. 11, the outlet temperature of the hydrocarbons has not been changed in comparison with its value in Fig. 8. Although, this temperature influences the new ΔT_{log} and the flow of hydrocarbons which now increases from 359 m³/h to 428 m³/h, it is assumed that this rather arbitrary decision has much influence on the overall results of this evaluation.

In the text below, the energy savings will be calculated and will be compared with the increased investment cost for the exchangers and the extra costs for higher pumping power requirements.

Table 4: Dimensions, weight, area and cost for low fouling exchangers for a crude oil throughput of 100,000 bpd.

	Units	**Low fouling 1×100%**	**Low fouling 2×100%**
Total number of shells in series	-	1	2
Tube length per shell	mm	7,226	7,226
Total height / length per shell	mm	9,750	9,750
Diameter shell	mm	590	590
Total heat transfer surface	m²	169	338
Total cost heat exchanger(s)	US$	225,000	450,000
Pumps including E-motors for shell-side flow	US$	150,000	150,000
Contribution for pumps including E-motors for tube-side flow	US$	30,000	30,000
Civil works, steel support construction, insulation and installation	US$	100,000	150,000
Valves	US$	70,000	130,000
Instrumentation	US$	60,000	100,000
Extra valves low fouling exchanger	US$	25,000	50,000
Total cost	US$	660,000	1,060,000
Contingencies 25% of total cost	US$	160,000	260,000
Total cost of completely installed heat exchanger	US$	820,000	1,320,000
Total cost per m² of surface completely installed heat exchanger for 100,000 bpd	US$/m²	4,852	3,905
Total cost of completely installed crude oil preheat train for 100,000 bpd	US$	5 × 820,000 = 4.1×10^6	5 × 1,320,000 = 6.6×10^6

Enernergy savings

Considering the situation that in case of a more 'energy efficient' crude oil preheat train, the original temperature increase of the crude oil in the furnace can be reduced from (380 – 271) = 109 °C to (380 – 298) = 82 °C, this would save energy equivalent to the heating of the crude in the furnace over a temperature difference of 27 °C. For all crude oil preheat trains in the world processing a throughput of crude oil of 100,000 bpd or 660 m³/h and assuming a thermal efficiency of the furnace of 90%, these additional savings $Л_{add, ref}$ amount to:

$$Л_{add, ref} = \{8{,}750\ [\text{hours/year}] \times 660\ [\text{m}^3/\text{h}] \times 750\ [\text{kg/m}^3] \times 2{,}500\ [\text{J/(kg·K)}] \times 27\ [°\text{C}]\} / 0.9\ [\text{thermal efficiency furnace}] = 3.25\times10^{14}\ \text{Joules/year}.$$

This is also equal to:

$$Л_{add, ref} = 3.1\times10^{11}\ \text{Btu/year}$$

or

$$\text{Л}_{\text{add, ref}} = 3.1\times10^{5} \text{ Mn Btu/year.}$$

Assuming that a barrel crude costs US$ 60, the cost of heating oil for industry is approximately US$ 12.5 /million Btu and, therefore, the annual savings realized in the furnace by reducing the temperature increase of the crude oil in the furnace by 27 °C amount to:

$$\text{Л}_{\text{add, ref}} = 3.1\times10^{5} \times 12.5 = \text{US\$ } 3{,}875{,}000$$

or

$$\underline{\text{Л}_{add,\,ref} = \text{US\$ 3.88 Mn.}}$$

Higher investment cost for heat exchangers

It has been shown above that the more ‘energy efficient’ crude oil preheat train for a throughput of 100,000 bpd and equipped with low fouling heat exchangers, requires 1,224 m² of surface instead of 844 m². This corresponds with an increase in surface of (1,224 – 844) = 380 m².

It is a reasonable estimate that this rather simple and cheap extra heat transfer surface, which consists only of an extension of the shell with tubes and of the downcomer, costs approximately US$ 500 /m². As a consequence, for a throughput of 100,000 bpd, and only 380 m² of extra surface, this increase in heat transfer surface only cost US$ 190,000.

This extra heat transfer surface increases the investment costs for the ‘energy efficient’ (i.e. the temperature increase in furnace from 298 °C to 380 °C) low fouling crude oil preheat trains with a throughput of 100,000 bpd to:

$$\underline{\text{Д}_{ref}^{**}\big|_{1\times100\%} = \text{US\$ 4.10 Mn + US\$ 0.19 Mn}}$$
$$\underline{= \text{US\$ 4.29 Mn}}$$

and

$$\text{Д}_{\text{ref}}^{**}\big|_{2\times100\%} = \text{US\$ 6.60 Mn} + 2 \times \text{US\$ 0.19 Mn} = \text{US\$ 6.98 Mn.}$$

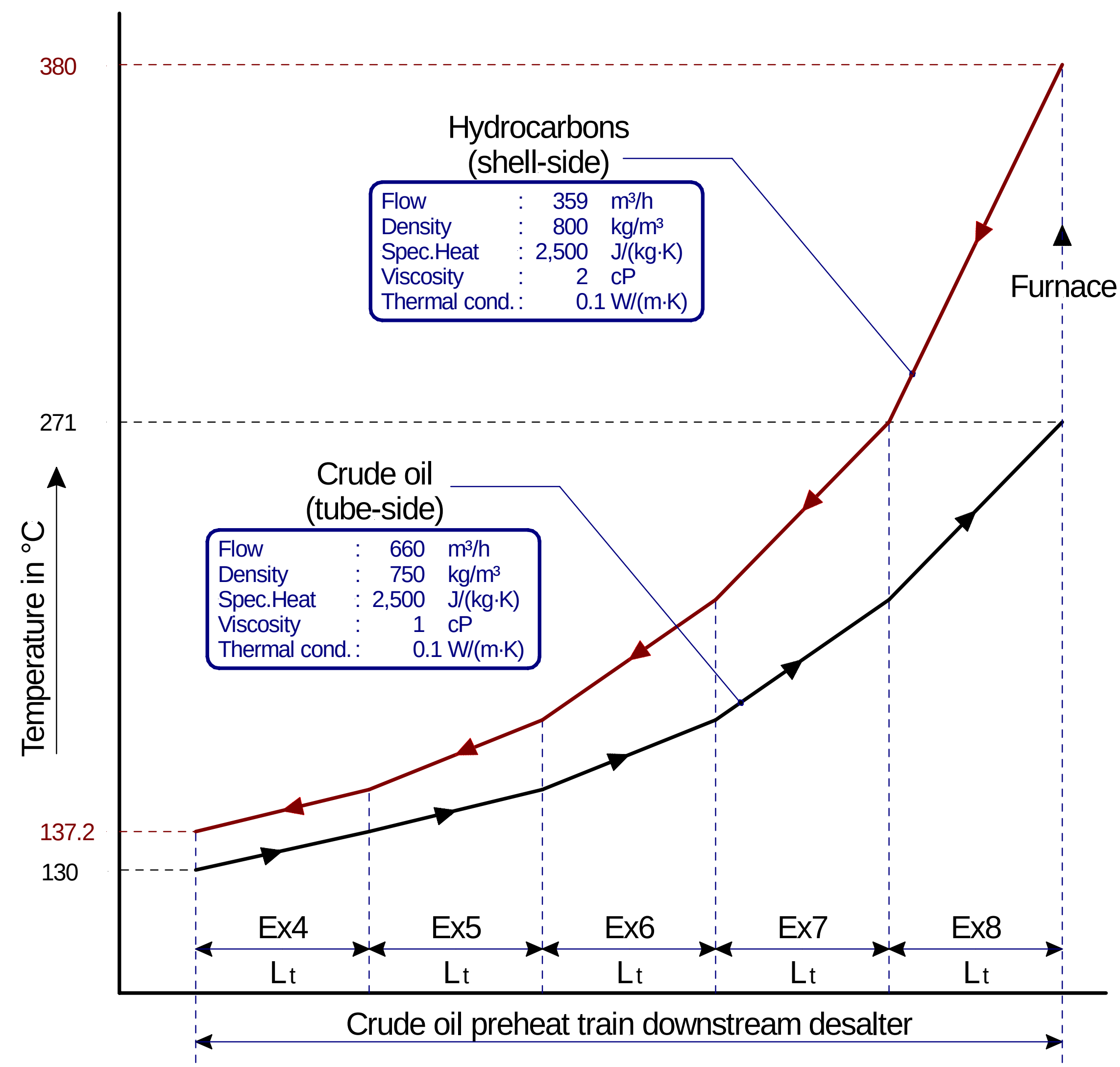


Fig. 10: Example temperatures curves for heat exchangers Ex4 up to and inclusive Ex8 with equal tube length L_t and equal thermal length $\Delta T/\Delta T_{log} = 0.752$.

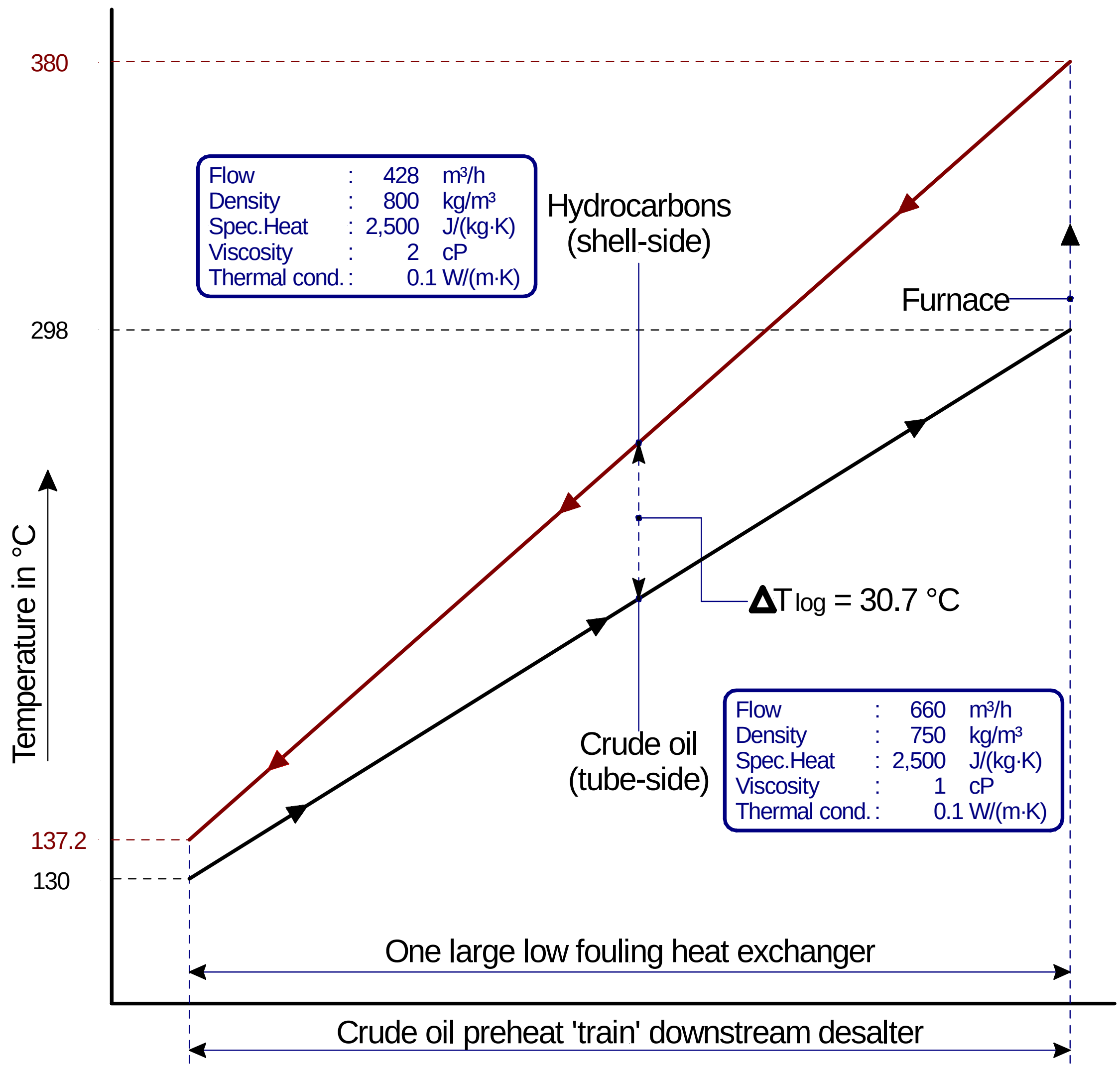


Fig. 11: Modified simplified temperature diagram of crude oil preheat train with ΔT log = 30.7 °C consisting of one large low fouling heat exchanger.

Higher pumping cost

Table 3 has shown that for the old situation involving a throughput of 100,000 bpd, the pumping power for the tube-side totals 5 × 20 kW = 100 kW and for the shell-side 5 × 66 = 330 kW.

For the tube-side, the pumping power is directly proportional to the tube length and because the tube length has increased by a factor 1.45, this also applies to the required pumping power which now becomes 1.45 × 100 = 145 kW. However, this means that the new ‘energy efficient’ design of the crude oil preheat train adds only 45 kW to the extra tube-side pumping cost. For a throughput of 100,000 bpd and an electricity price of US$ 0.125 kW/h, the annual total extra cost for the tube-side pumping power amounts to:

$$45 \times 0.125 \times 8{,}750 = \text{US\$ } 49{,}219.$$

For the shell-side, the extra pumping power required by the more energy efficiently designed crude oil preheat train with a throughput of 100,000 bpd is directly proportional to the ratio of the tube lengths and the square of the ratio of the shell-side flows, according to the expression:

$$1.45 \times (428 / 359)^2 \times 330 - 330 = 350 \text{ kW}.$$

The annual cost for this extra pumping power, again for a throughput of 100,000 bpd and an electricity price of US$ 0.125 kW/h yields:

$$350 \times 0.125 \times 8{,}750 = \text{US\$ } 382{,}813.$$

The total electricity cost for the extra pumping power for both the tube-side and the shell-side amounts to:

$$\text{US\$ } 49{,}219 + \text{US\$ } 382{,}813 = \text{US\$ } 432{,}032$$

or

US$ 0.43 Mn.

Conclusions

A more 'energy efficient' design of the crude oil preheat train as discussed above and presented in more detail in Fig. 11, produces the following annual additional net savings $Л_{add,\ ref,\ net}$ for a throughput on crude oil of 100,000 bpd:

$$Л_{add,\ ref,\ net} = \text{US\$ 3.88 Mn} - \text{US\$ 0.43 Bn} = \text{US\$ 3.45 Mn.}$$

We already realized a net saving:

$$Л_{ref,\ net} = \text{US\$ 12.80 Mn.}$$

This creates a total net saving $Л_{tot,\ ref,\ net}$ for this more 'energy efficient' design:

$$Л_{tot,\ ref,\ net} = Л_{add,\ ref,\ net} + Л_{ref,\ net} = \text{US\$ 3.45 Mn} + \text{US\$ 12.80 Mn}$$

or

$$\underline{Л_{tot,\ ref,\ net} = \text{US\$ 16.25 Mn.}}$$

Compare this total net saving with the slightly higher investment cost for the 'energy efficient' (i.e. temperature increase of the crude oil in furnace from 298 °C to 380 °C) low fouling crude oil preheat trains $Д^{**}$ as referred to above, which are required to make this total net saving possible, i.e.:

Low fouling crude oil preheat trains for 1 × 100% capacity in heat transfer surface:

$$\underline{Д_{ref}^{**}\,|_{1\times100\%} = \text{US\$ 4.29 Mn.}}$$

And low fouling crude oil preheat trains for 2 × 100% capacity, i.e. with 100% back-up heat transfer surface:

$$\underline{Д_{ref}^{**}\,|_{2\times100\%} = \text{US\$ 6.98 Mn.}}$$

INFLUENCE OF CRUDE OIL PRICE ON NET SAVINGS AND INVESTMENT COST

Table 5 presents the influence of the crude oil price per barrel on the total net annual savings and the investment cost for crude oil preheat trains for a throughput of 100,000 bpd. In this evaluation the following electricity prices have been used:

- US$ 0.100 /kWh for US$ 45 /barrel,
- US$ 0.125 /kWh for US$ 60 /barrel,
- US$ 0.150 /kWh for US$ 75 /barrel,
- US$ 0.175 /kWh for US$ 90 /barrel.

It is evident that an 'energy efficient' design increases the total net annual savings which now consists of savings on fouling cost and savings on the energy input of the furnace. The investment costs for this 'energy efficient' design of the low fouling installation do not differ much from the 'state-of-the-art' design, because rather inexpensive heat transfer surface has to be added and, therefore, an 'energy efficient' design does indeed further increase the difference between savings and investment cost, particularly, at high crude oil prices.

The change in design from 'state-of-the-art' to 'energy efficient' increases the tube length of the exchangers Ex4 up to and inclusive Ex8 by a factor 1.45 and the total height of the exchangers from approximately 10 m to 13 m. These are only modest heights for this type of low fouling exchangers, and even larger heights would not be a problem, which means that there are possibilities to even further increase the energy efficiency of low fouling crude oil preheat trains.

For a crude oil preheat train equipped with conventional heat exchangers, it is not that easy to benefit from an 'energy efficient' design. These already poor performing heat exchangers will require much more heat transfer surface, more plot area and the higher crude oil outlet temperatures of the preheat train will dramatically increase fouling at the high temperature end of the train and, as a consequence, their much higher fouling cost very likely neutralizes any possible savings realized with the 'energy efficient' design, if not worse.

IMPLEMENTATION OF THE LOW FOULING HEAT EXCHANGERS IN CRUDE OIL PREHEAT TRAINS OF REFINERIES

The results of Table 5 make it clear that any new crude oil preheat train should be equipped with low fouling exchangers and not with conventional exchangers for the following reasons:

- Dramatic reduction in fouling cost in comparison with conventional exchangers.
- Low fouling exchangers offer possibilities for a more energy efficient design.

However, the advantages of this low fouling exchangers go even further. There is economical justification to replace existing conventional heat exchangers in crude oil preheat trains by low fouling heat exchangers.

When this new heat exchange technology is implemented in an existing installation equipped with exchangers based on the conventional technology, then the most attractive way to proceed, is to use the new technology with all its benefits for the daily operation and employ the existing installation as back-up. This, of course, reduces the required investment cost for the new technology, which now does not need any back-up low fouling heat transfer surface and is referred to in Table 5 as 'investment costs (1 × 100%)'.

For a 'state-of-the-art' crude oil preheat train with a throughput of 100,000 bpd and a crude oil price of US$ 60 per barrel, the net annual saving amounts to:

$$Л_{ref,\ net} = \text{US\$ 12.80 Mn,}$$

versus investment cost (1 × 100%) of only:

$$Д_{ref}^{*}\,|_{1\times100\%} = \text{US\$ 4.10 Mn,}$$

which corresponds with a 'Return Of Capital' (ROC) of less than four months. At higher crude oil prices, this ROC improves to approximately three months and in case of an 'energy efficient' design of the low fouling crude oil preheat train to even less than two-and-a-half month. In this evaluation, the investment cost for the connecting piping and accessories between the low fouling exchangers and the conventional exchangers has not been taken into account, which, of course, is necessary to be able to use the conventional exchangers as back-up, when necessary.

For a low fouling crude oil preheat train with a 100% back-up of low fouling heat exchange surface (i.e. 2 × 100%), the investment cost increases, while net annual savings remain the same. However, the ROC is still excellent and varies from approximately seven months to less than five months.

Table 5: Comparison savings, investment cost and return of capital (ROC) low fouling for a crude oil preheat train with a throughput of 100,000 bpd as a function of the crude oil price.

Case	Description	Symbol	Units	**Crude oil price in US$ / barrel**			
				45	**60**	**75**	**90**
1	Net annual savings State-of-the-art design 1)	$\text{Л}_{ref\,net}$	US$	11.17×10^6	12.80×10^6	14.43×10^6	16.06×10^6
2	Net annual savings Energy efficient design 2)	$\text{Л}_{tot,\,ref\,net}$	US$	13.74×10^6	16.25×10^6	18.76×10^6	21.28×10^6
3	Investment cost (1×100%) State-of-the-art design 1)	$\text{Д}_{ref}^{*}\|_{1\times100\%}$	US$	4.10×10^6	4.10×10^6	4.10×10^6	4.10×10^6
4	Investment cost (2×100%) State-of-the-art design 1)	$\text{Д}_{ref}^{*}\|_{2\times100\%}$	US$	6.60×10^6	6.60×10^6	6.60×10^6	6.60×10^6
5	Investment cost (1×100%) Energy efficient design 2)	$\text{Д}_{ref}^{**}\|_{1\times100\%}$	US$	4.29×10^6	4.29×10^6	4.29×10^6	4.29×10^6
6	Investment cost (2×100%) Energy efficient design 2)	$\text{Д}_{ref}^{**}\|_{2\times100\%}$	US$	6.98×10^6	6.98×10^6	6.98×10^6	6.98×10^6
7	ROC 3) applies to 'Case 1' and 'Case 3'	-	months	4.4	3.8	3.4	3.1
8	ROC 3) applies to 'Case 1' and 'Case 4'	-	months	7.1	6.2	5.5	4.9
9	ROC 3) applies to 'Case 2' and 'Case 5'	-	months	3.7	3.2	2.7	2.4
10	ROC 3) applies to 'Case 2' and 'Case 6'	-	months	6.1	5.2	4.5	3.9

1) Heating crude oil in furnace from 271 °C → 380 °C or ΔT = 109 °C
2) Heating crude oil in furnace from 298 °C → 380 °C or ΔT = 82 °C
3) ROC means Return Of Capital

FLEXIBILITY IN DESIGN AND OPERATION OF THE LOW FOULING EXCHANGER

The correlations for the heat transfer film coefficients in the tubes and in the shell are sufficiently accurate and well understood. This means that it is very well known how to influence these film coefficients to achieve the best overall heat transfer coefficient or k-value for a particular low fouling heat exchanger design. Considering the fact that the vertical low fouling exchangers have only a limited height, there is still enough room for over dimensioning of the exchangers, when necessary.

An important question in heat exchanger design is always the point of flow variation and its consequences on fouling. The tube-side flow using the circulation of cleaning particles at a velocity of 2.70 m/s can be reduced, while maintaining circulation of particles, to approximately 0.7 m/s. Even at this low velocity an excellent heat transfer film coefficient and 'zero' fouling of the tube-side surface is still guaranteed. If necessary, cleaning particles can also be used intermittently. The shell-side flow can be lowered without restrictions, although, at lower velocities, the heat transfer film coefficient will decrease and the fouling rate will increase.

Finally, it has already been mentioned that in case of the low fouling exchangers the bundle can be removed from the shell for cleaning and that the rectangular tube pattern allows for sufficient spacing between the tube rows to clean the outside of the tubes mechanically (hydro-blasting) with standard available cleaning equipment.

CONCLUSIONS

The low fouling heat exchanger is a unique piece of heat transfer equipment which can be used to battle severe fouling problems in shell and tube exchangers and, particularly, in crude oil preheaters.

For example, it has been shown that the fouling cost in all crude oil preheat trains in the world with a total throughput of 74 Mn bpd can be reduced by 90% when all conventional heat exchangers in crude oil preheat trains are replaced by low fouling heat exchangers. For 2006, this is a reduction in fouling cost from approximately US$ 11 Bn to US$ 1.3 Bn and a saving on fouling cost of US$ 9.7 Bn. The design and characteristics of this low fouling heat exchanger makes it also possible to operate these exchangers at higher crude oil temperatures, which then creates substantial additional savings on energy through a reduction of the heat input into the furnace.

The above mentioned benefits have been achieved by novel, although already proven, heat transfer mechanisms for both the tube-side and shell-side:

The tube-side applies the circulation of solid particles through the tube, which assures 'zero- fouling' in the tubes in combination with very high heat transfer film coefficients, while the shell-side applies Grid baffles also responsible for an excellent film coefficient and low fouling factor. Combination of above technologies in one heat exchanger creates clean overall heat transfer coefficients, or k-values, which are approximately 200% higher than in conventional exchangers, while the fouling rates or fouling factors in low fouling exchangers can be reduced to less than 5% of values generally applied in conventional heat exchangers. The influences of these excellent results on additional pumping power requirements are marginal.

Low fouling exchangers are also characterized by their very compact design, as a result of the small tube diameters, the high liquid velocities in the tubes and in the shell and excellent clean heat transfer coefficients or k-values. This compact design is also responsible for a low weight and small plot area. Another advantage of the low fouling exchangers is their flexibility in operation, i.e. flow variation in the tubes employing the (continuous or intermittent) circulation of cleaning particles from 100% to less than 30%, without losing its excellent heat transfer performance.

In spite of the low fouling design, it is still possible that the shell-side might suffer from a slow build-up of fouling deposits. However, it is possible to design the low fouling exchangers with tube bundles with sufficient distance between the tube rows, while the bundles can be removed from the shell and then can be cleaned with the standard available (hydro-blasting) equipment.

Of course, much has been mentioned in this article about investment cost versus savings. It should be emphasized that even in case of crude oil prices of US$ 45 /barrel and a 'state-of-the-art' design of a crude oil preheat train including the availability of 100% back-up low fouling heat transfer surface, the return on investment is approximately 7 months. If the existing conventional exchangers are used as back-up, then the 'Return Of Capital' (ROC) becomes far less than 5 months.

In case of an 'energy efficient' design and a crude oil price of US$ 90 /barrel these ROC's become respectively less than 4 months and even much less than 3 months.

If the attention is focused on replacing the most problematic sections of the crude oil preheat train by low fouling exchangers, then the ROC's for these particular sections, located at the high temperature end of the crude oil preheat train, could even be lower than 2 months for an 'energy efficient' design and a crude oil price of US$ 90 /barrel.

Therefore, the facts presented herein clearly leads to the conclusion that for economic reasons, governed by the laws of savings versus investment cost, any new crude oil preheat train should be equipped with these low fouling heat exchangers and existing conventional heat exchangers operating in crude oil preheat trains should be replaced with low fouling heat exchangers.

NOMENCLATURE

F	heat transfer surface, m²
k-value	heat transfer coefficient, W/(m²·K)
L_t	tube length, m
O	heat transfer surface, m²
X	heat transfer coefficient conventional HEX, W/(m²·K)
Y	heat transfer coefficient KLAREN HEX, W/(m²·K)
ΔT	Temperature difference across tubes, °C
ΔT_{log}	Mean log t Temperature difference across bundle, °C
η	efficiency, %
Л	potential average annual saving in fouling cost, US$ or Joules/year
K	Fouling cost, US$

Subscript

1	case 1
2	case 2
m	mean value
*	case …
low	Low fouling heat exchanger
Ex..	heat exchanger number
ref	reference crude oil preheat train processing 100,000 bpd

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