Cost savings of ‘zero-fouling’ crude oil preheaters

Unique configurations of proven self-cleaning fluidized bed heat exchangers virtually eliminate fouling in this application

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A new way to make crude oil preheat trains more efficient is by employing “zero-fouling” heat exchangers. If all crude oil preheat trains in the world were equipped with zero-fouling exchangers, an annual savings of approximately $9.5 billion could be realized, assuming a crude price of $30/barrel.

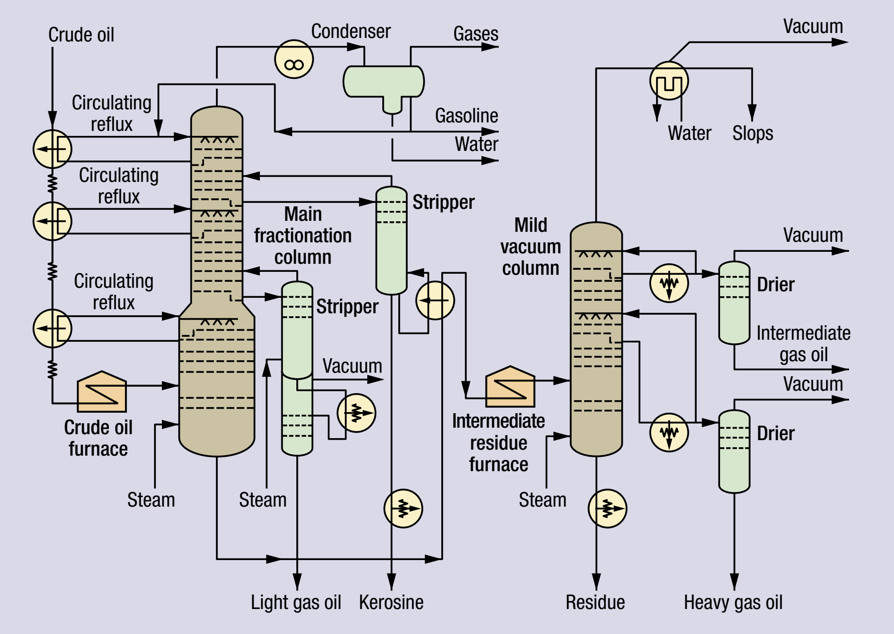

FIG. 1 Modern crude distillation unit.

Understanding fouling. Crude oil preheaters play an essential role in crude oil distillation. Fig. 1 shows the function and location of these crude oil preheaters in the distillation process. The cold crude is heated to the furnace inlet temperature by either:

- Exchanging heat between the crude oil and residue
- Exchanging heat between the crude oil and the circulating reflux of the main fractionating column.

In most cases, crude oil preheaters must cope with two severely fouling process streams:

- Crude oil in the tubes
- Residue or the circulating reflux in the shell.

Fouling of the crude oil preheat train is a major economic problem. According to Pugh, Hewitt and Muller-Steinhagen,[1] the annual costs associated specifically with crude oil fouling in preheat trains worldwide were estimated to be $4.5 billion in 1995.

Because of the large cost and environmental impact caused by fouling in crude preheat trains, a Crude Oil Fouling Working Party has been formed. This Working Party (Table 1) intends to recommend and coordinate initiatives among its members to create a better understanding of state-of-the-art fouling mitigation strategies. The initiatives of the Working Party have already resulted in developing a “User Guide” with novel heat exchanger software for analyzing crude oil preheat train fouling.

Table 1. Crude oil fouling working party member companies, 1999/2001

Refinery operators	
BP Amoco (UK)	TotalFinaElf (France, UK, US)
Conoco (UK)	ExxonMobil/Esso (US, UK)
Koch Industries (US, Mexico)	Marathon Oil Company (US)
Shell (The Netherlands)	Equilon (Shell/Texaco) (US)
Statoil (Norway)	Texaco (UK, US)

The Working Party has centered its efforts on existing fouling mitigation methods. However, the new zero-fouling technology goes beyond mitigation of fouling to the actual elimination of fouling. It will be shown that zero-fouling crude oil preheat systems can realize considerable cost savings as a result of energy savings, improved throughput and reduced maintenance and cleaning expenses. In addition, these exchangers allow the engineer to design closer approach temperatures that would raise the feed temperature to the furnace, thus reducing fuel required by the furnace.

Zero fouling. A heat exchanger may be classified as zero fouling if it shows no measurable decrease in heat transfer coefficient over a several year continuous operating period.

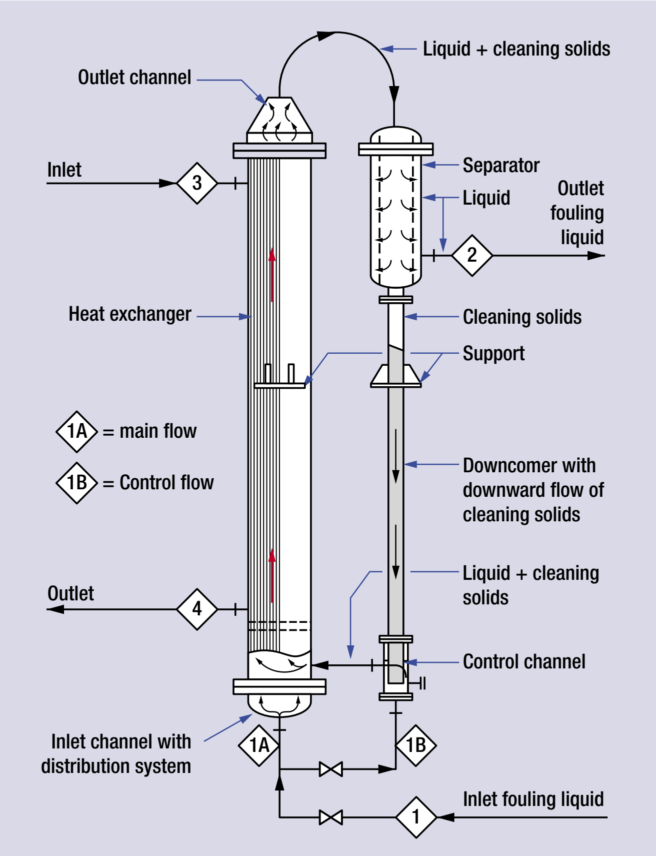

FIG. 2 The self-cleaning heat exchanger uses circulating fluidized solid particles in the tubes.

TABLE 2. Process and design data for conventional crude oil preheater

	Tube side	Shell side
	Process Data	
Medium	Crude oil	Hydrocarbon
Duty, kW	6,510	6,510
Number of heat exchangers in series	2	
Flow, m^3/h	500	308
Inlet temperature, °C	150	263
Outlet temperature, °C	175	225
Density, kg/m^3	750	800
Specific heat, J/kgK	2,500	2,500
Viscosity, mPas	1.0	2.0
Thermal conductivity, W/mK	0.1	0.1
Liquid velocity in tubes, m/s	1.2	NA
Fouling factor, m^2K/W	0.00175	0.00175
	Design data per heat exchanger	
Total number of tubes per shell	737	
Tube diameter, mm	25.4 x 2.7	
Tube length, mm	6,000	
Tube pitch, mm	36.75	
Number of passes tube side	2	
Number of passes shell side	1	
Design value overall heat transfer coefficient, k-value, W/m^2K	125	
Heat transfer surface per heat exchanger, m^2	350	
Total required heat transfer surface, m^2	700	

According to this definition, zero fouling of crude preheater exchangers is not currently achieved. The current state-of-the-art preheater exchanger train may attempt fouling mitigation by employing chemicals, in-tube mitigation devices and novel shell-side developments involving special types of baffles.

The zero fouling technology described in this article does not attempt to reduce fouling by using chemicals. Neither does it increase turbulence and, as a consequence, reduce wall temperatures for fouling mitigation. Instead, it is based on the concept of "let fouling happen," but remove the fouling deposits as they are being formed. The tube inside wall is cleaned by a mild and continuous scouring action of fluidized solid particles. The fluidized solid particles not only keep the surfaces clean, but they also break up the boundary layer, improving the heat transfer coefficient even at low fluid velocities.

A truly zero-fouling heat exchanger must have zero fouling on both the tube and shell sides. The zero-fouling heat exchanger explained in this article is derived from the well-known self-cleaning fluidized bed heat exchange technology where the self-cleaning action is only employed in the tubes. Often a nonfouling heat transfer fluid such as condensing steam is on the shell side. The principle is shown in Fig. 2 and is based on circulating fluidized solid particles in the tubes. Usually the particles are cut metal wire with a diameter of 2 to 3 mm and cut to a length equal to the wire diameter. These particles impose a mild scouring action on the inner tube wall and remove any precipitated matter at an early stage. Successfully operating self-cleaning (fluidized bed) heat exchangers have been applied to numerous highly fouling fluids including:

- Recirculated quench water containing tar globules and soot particles fouled conventional heat exchangers operating at liquid velocities in the tubes of 1.8 m/s to such an extent that the k-value dropped from 2,500 W/m^2K to 500 W/m^2K in only 4 to 5 weeks. A self-cleaning heat exchanger maintained clean heat transfer coefficient values indefinitely. An inspection after 30 months of operation revealed clean and shiny tubes.
- Waxy deposits reduced the k-values from 1,400 W/m^2K to 300 W/m^2K in only 4 to 5 days. A self-cleaning heat exchanger maintained a clean k-value of 1,700 W/m^2K indefinitely.
- A wastewater stream could not be concentrated in a forced circulation evaporator because severe fouling reduced performance within a matter of hours. When this wastewater was concentrated in an evaporator employing a self-cleaning heat exchanger, the heat transfer rate showed no deterioration. An inspection after more than two years of operation revealed clean and shiny tubes.
- The largest oil stabilization plant in the world suffered from severely fouling reboilers that required cleanings every four weeks. A test with a self-cleaning heat exchanger was so successful that the official proposal for delivery of full-size self-cleaning reboilers to this client came with a guarantee of continuous operation of six years without fouling.
- Natural and chemically untreated seawater has been heated to 125°C for a long period without any deterioration in heat transfer.

A frequently asked question is, "Does the self-cleaning heat exchange principle cause excessive wear of the tubes and clean-

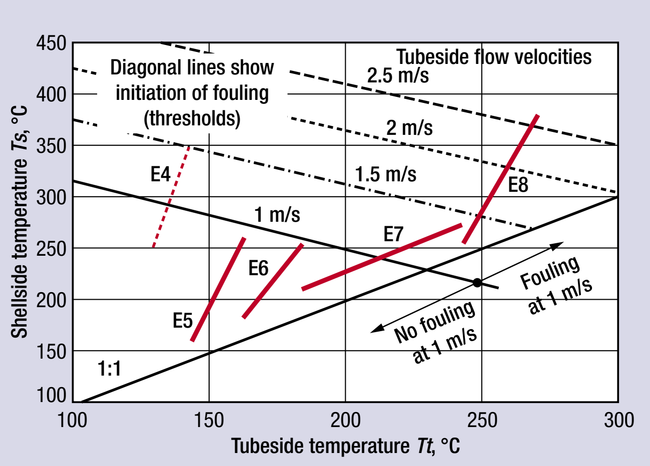

FIG. 3 Example temperature field plot for a crude preheat train.

ing particles?” The answer is no. The wear rate is essentially zero because the fluid velocity is low. Accurate weight loss measurements of fluidized particles reveal a wear rate loss of less than 1 wt% per year. A similar wear rate is experienced by the tubes.

Transition of conventional fouling crude preheaters into a zero-fouling configuration. Table 2 presents information of a typical conventional shell-and-tube crude preheater. The data presented in this table represent a fair example that has been obtained by averaging data from different refineries.

According to the design rules in the previously mentioned User Guide, and also explained in Fig. 3 and Reference 1, the crude preheater as presented in Table 2 would be predicted not to foul in the tubes because the velocity in its tubes is higher than 1.0 m/s and the tube-side bulk crude temperatures are lower than the critical values. In spite of these predictions, the crude preheater of Table 2 suffers from severe fouling. This example clearly shows that in spite of using the best correlated predictors, accuracy of predicting fouling remains questionable because too many variables can influence fouling. One important independent variable is the type of crude to be processed in the distillation system.

From an example presented by Van Nostrand, Leach and Haluska,[2] over a period of 12 to 18 months the heat transfer coefficient (*k*-value) of a crude preheater decreases by a factor 2 to 3. This decline in *k*-value of crude preheaters is caused by fouling on the shell side as well as on the tube side. Since the fluids on both sides of the exchanger have very low thermal conductivities, the *k*-value of a crude preheater is rather insensitive to fouling. Typically, the preheater heat transfer coefficient falls by 30–50% over a period of 12 to 18 months due to fouling. This rate is considered to be a very mild fouling situation for the application of self-cleaning heat exchangers. Typically, self-cleaning exchangers serve highly fouling fluids that normally would require conventional exchangers to be cleaned every few weeks. Therefore, it can be concluded that self-cleaning heat exchangers can easily prevent fouling when processing crude oil.

Because self-cleaning heat exchangers clean the inner surface of the tubes, the newly proposed zero-fouling heat exchanger is actually two self-cleaning heat exchangers in parallel with the fouling process streams passing through their tubes. Additionally, a clean intermediate shell-side fluid operating in the shell of both exchangers transfers the heat between both bundles.

TABLE 3. Process and design data for both parallel operating self-cleaning heat exchangers

	Evaporator (cooling hydrocarbon)	Condenser (heating crude oil)
Duty, kW	6,510	6,510
Flow, m^3/h	308	500
Inlet temperature, °C	263	150
Outlet temperature, °C	225	175
For physical properties, see Table 2.		
Total number of tubes	494	515
Tube diameter, mm	19.05 x 2.11	19.05 x 2.11
Effective tube length, mm	3,800	3,800
Liquid velocity in tubes, m/s	1.0	1.56
Particle size ($1/d = 1.0$), mm	3.0 (cut metal wire)	3.0 (cut metal wire)
Bed porosity, %	92	97
Tube-side fouling factor, m^2K/W	0.0	0.0
Shell-side fouling factor, m^2K/W	0.0	0.0
Heat transfer coefficient, W/m^2K	1,306	1,504
Condensation/evaporation temperature, °C	199.5	199.5
Log. temperature difference, °C	44.5	37.0
Heat transfer surface, m^2	112	117
Total required heat transfer surface, m^2	**112 + 117 = 229**	

TABLE 4. Conventional design versus zero-fouling design

		Zero-fouling	
	Conventional	Evaporator (hydrocarbon)	Condenser (crude oil)
Number of shells in series	2	1	1
Diameter shell, mm	1,200	700	700
Diameter tubes, mm	25.4 x 2.7	19.05 x 2.1	19.05 x 2.1
Tube length, mm	6,000	3,800	3,800
Number of passes tube side	2	1	1
Number of passes shell side	1	1	1
Installed heat transfer surface, m^2	700	112	117
Design *k*-value, W/m^2K	125	1,306	1,504
Removable tube bundle	Yes	No	No
Positioning heat exchanger	Horizontal	Vertical	Vertical

A typical zero-fouling design is shown in Fig. 4. This design shows how two self-cleaning heat exchangers operate in parallel with clean conditioned water circulating through their shells. Fig. 5 shows the temperatures of the fouling liquids and the circulating conditioned water as a function of tube length.

The suggested zero-fouling design for the same application as specified in Table 2 is shown in Figs. 6 and 7. The hot liquid (hydrocarbon) is cooled by a very small circulating flow of conditioned water evaporating on the outer surface of the tubes, while the cold liquid (crude) is heated by condensation of this produced

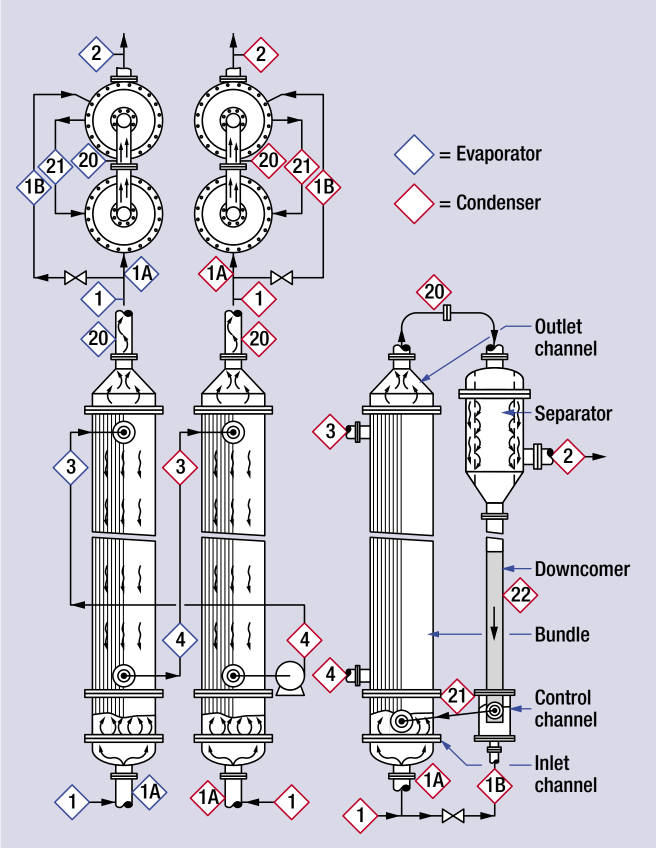

FIG. 4 Zero-fouling crude oil preheaters use two parallel self-cleaning heat exchangers with clean conditioned water circulating through their shells.

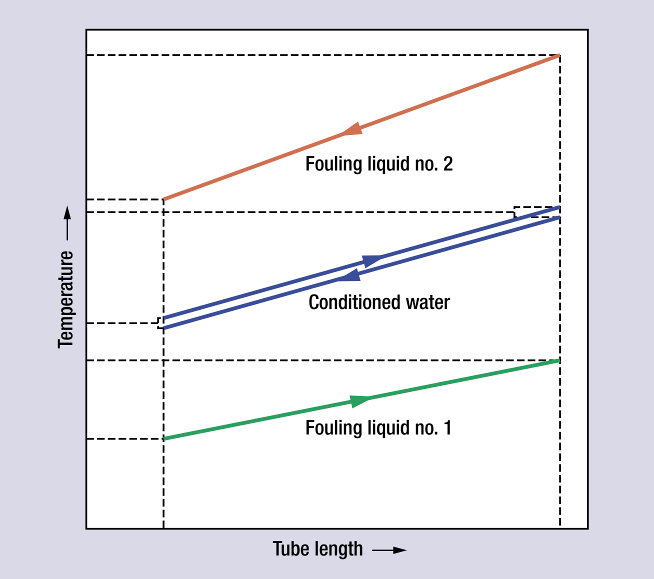

FIG. 5 Temperature referring to the design of Fig. 4.

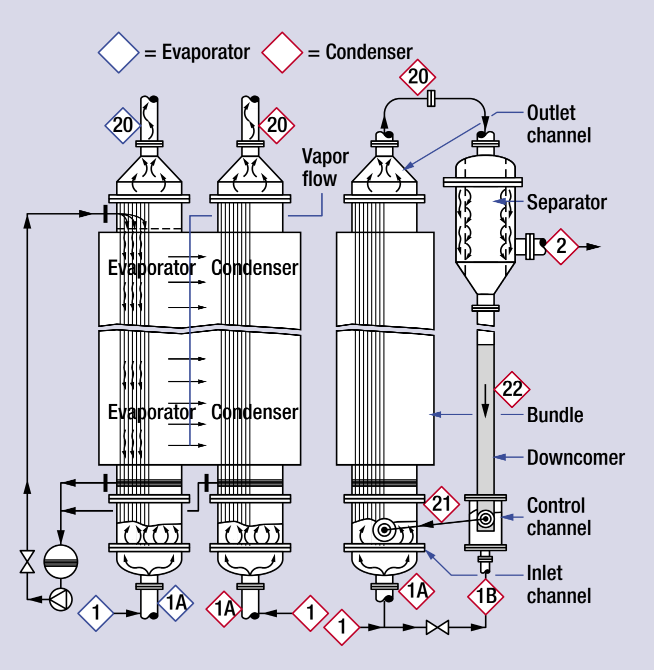

FIG. 6 Zero-fouling crude oil preheaters with an evaporator and condenser in one shell.

water vapor on the outer surface of the parallel tube bundle. Table 3 gives more information about this design and Table 4 compares some significant parameters for the conventional severely fouling design with the zero-fouling design.

In comparison, the zero-fouling design requires only 33% of the heat transfer surface of the conventional crude preheater. If the same surface area were to be installed in the zero-fouling exchangers as in conventional exchangers, more energy would be recovered in the preheat train. This energy savings could result in up to 50% of the energy input to the furnace. For the example given in Table 3, the tube length of 3.8 m would increase to approximately 10 m for the higher energy recovery design. Furthermore, employing smaller tube diameters, smaller particles and lower liquid velocities could reduce this tube length to approximately 7.5 m.

Any attempt to achieve the higher furnace inlet temperature and the resulting savings with conventionally designed preheater exchangers is not practical. It would require an increase of the already very large severely fouling heat transfer surface by a factor of three. The additional heat transfer surface would need to operate in a higher temperature region, causing these exchangers to suffer from an even higher fouling rate.

Other zero-fouling design configurations.

Multistage design. When the outlet temperature, T_2, of the preheated crude oil stream as shown in Fig. 8 approaches the outlet temperature, T_3, of the hydrocarbon, it is necessary to apply evaporation/condensation of the conditioned water at two or more temperature levels. The consequences of this design are shown in Fig. 9. This requires a horizontal separation of the shell, where each shell compartment operates at a different temperature and saturation pressure. The more stages, the higher the average value for the logarithmic temperature differences of the various compartments, reducing the total installed heat transfer surface.

The recommended number of stages follows from a cost optimization. More stages require more small circulation pumps for the conditioned water loop and more auxiliaries like small storage vessels for the conditioned water and connecting piping. For

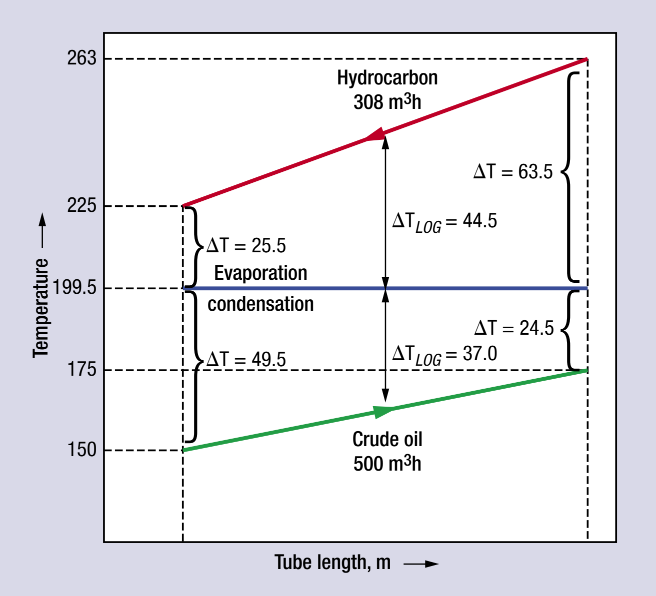

FIG. 7 Temperature referring to the design of Fig. 6.

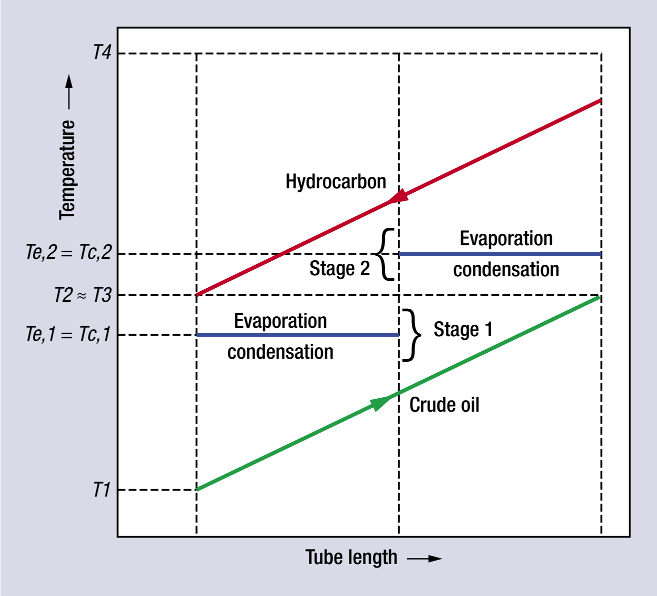

FIG. 8 Typical temperatures for multistage design.

example, a two-stage configuration requires two small circulation pumps each with only half the flow and pump head as required for the one-stage configuration.

Flow variation. Many conventional fouling-prone exchangers that serve fouling liquids are designed for a 3 × 50% capacity with 2 × 50% in operation and 1 × 50% as a spare capacity in case one of the 2 × 50% operating units is forced out of service.

For the zero-fouling configuration of the crude oil preheaters, the 2 x 50% units are sufficient and can be designed to handle flow variations from 100% to 35% while still maintaining zero fouling. When using 2 × 50% zero-fouling units in parallel, the tube bundles for both process streams are installed in only one shell. This design is shown in Fig. 10 and consists of two parallel evaporators and two parallel condensers. Each evaporator and condenser handles 50% of the flow.

A clever alternate design has the parallel bundles for the evaporators and for the condensers using only one separator, downcomer and control channel. The cleaning particles are fed into the inlet channels of the bundles for both the evaporators and the condensers. A special valve arrangement makes it possible to isolate the tube bundle from the process for inspection and/or repairs of the tube side.

Total potential cost savings of zero-fouling crude preheat trains. The estimate of the total potential cost savings that could be achieved with zero-fouling crude preheat trains include:

- The savings on the directly related fouling costs including:
  - ▶ Energy costs and environmental impact
  - ▶ Production loss during shutdowns due to fouling
  - ▶ Capital expenditure for excess surface area of heat exchangers
  - ▶ Maintenance costs.
- The savings that can be achieved by operating a thermally more efficient crude preheat train from the point of view of better heat recovery that reduces furnace heat input.

Savings on the directly related fouling cost. To estimate the savings on fouling cost, it is essential to know the history of the related fouling cost. In 1995, the annual cost caused by fouling in crude preheat trains worldwide was estimated at $4.5 billion.[1] For 2005, this cost would have increased by approximately 20% as a result of a 2% annual growth in the production of crude to approximately $5.4 billion. Assuming that the cost for 1995 was based on a crude price of $20/barrel, whereas a crude price of at least $30/barrel is conservative for 2005, and also assuming that some of the increase in the crude price directly influences the fouling cost, the related fouling cost for 2005 will be at least 20% higher—giving an approximate total cost of $6.75 billion.

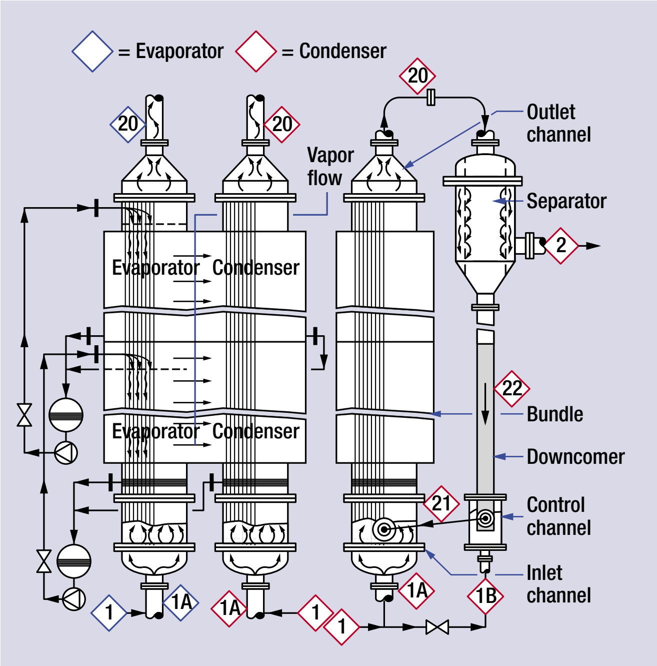

FIG. 9 Multistage zero-fouling crude oil preheater with an evaporator and condenser in one shell.

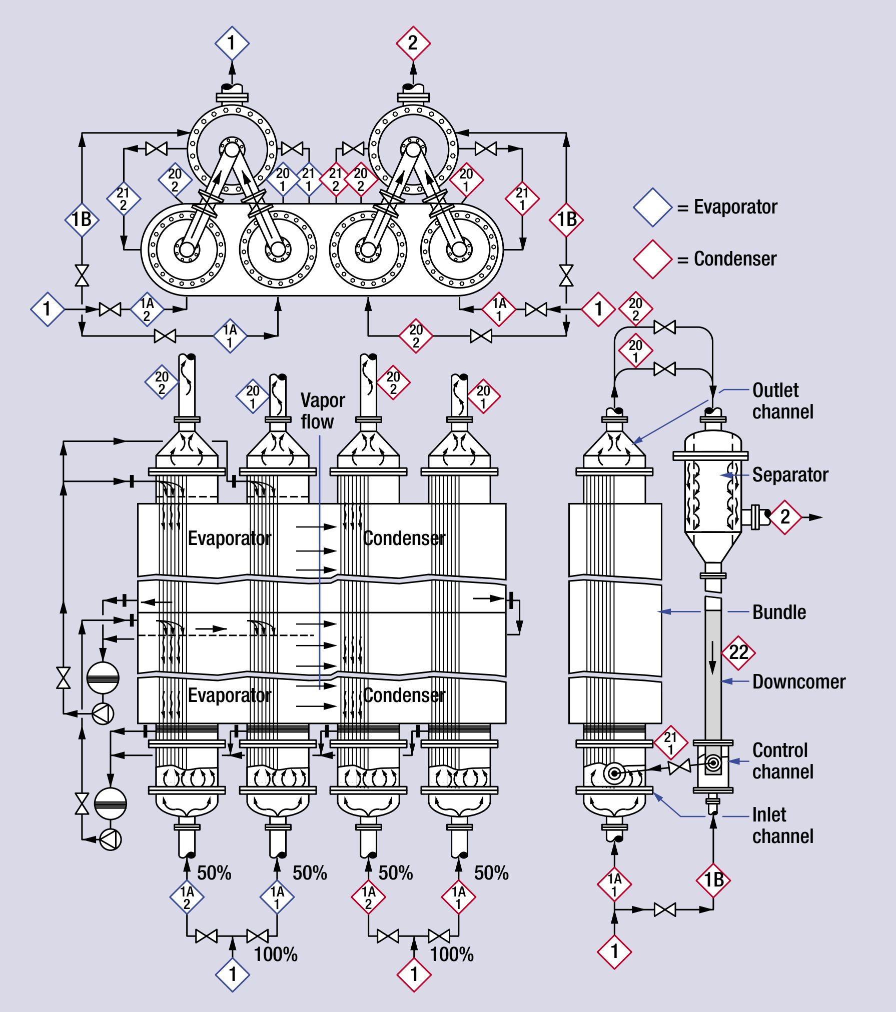

FIG. 10 Zero-fouling crude oil preheater with 2 x 50% flow capacity in one shell.

Savings of a thermally more efficient preheat train. From various references, among them Reference 2, it can be concluded that moderately fouled existing preheater trains require the temperature rise of crude oil in the furnace to be approximately 120°C. If a more efficient zero-fouling preheat train is used, this temperature difference can be reduced to approximately 60°C. In that case, the annual savings in fuel for the furnace amount to approximately $3.0 billion. This estimate is based on a worldwide production of crude of 80 million bpd at an estimated price of $30/barrel.

Total savings. Based on these assumptions, the total annual worldwide savings that could be realized by applying the zero-fouling technology would be a staggering $9.75 billion. Of course, this is an absolute maximum and would require all available complete crude preheat trains in the world to be converted into the zero-fouling configuration.

The incentives to introduce new crude preheat train technology will likely be stronger for new facilities than for existing ones. Existing crude processors may focus on introducing this new technology on other fouling exchangers in addition to their crude preheat train.

This self-cleaning heat exchange technology has already produced very large savings in industrial processes that suffer from severely fouling heat exchangers as explained in References 3, 4, 5 and 6. Since the fouling rate of crude oil preheaters is only moderate, zero fouling would be easily maintained. **HP**

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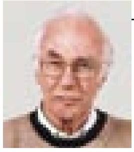

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