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'ZERO FOULING' SELF-CLEANING HEAT EXCHANGER

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ABSTRACT

Sometimes conventional shell and tube heat exchangers have to use two severely fouling process streams, one in the tubes and one in the shell. This paper presents the design of a self-cleaning heat exchanger applying the self-cleaning mechanism in the tubes of two parallel bundles handling the fouling process streams. For the transfer of heat between both 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.

This novel design which consists of two parallel bundles in one shell, experiences very high film coefficients at the outside surface of both tube bundles and does not suffer from any fouling. Therefore it is referred to as a 'zero fouling' self-cleaning heat exchanger.

In this paper, a conventional severely fouling crude oil preheater will be compared with a 'zero fouling' self-cleaning heat exchanger for the same service.

INTRODUCTION

A heat exchanger may be classified as 'zero fouling' if it services severely fouling media at both sides of the heat transfer surface and shows no measurable decrease in the heat transfer coefficient over a long continuous operating period that may last several years. According to this definition, 'zero fouling' of heat exchangers do not currently exist. The current state-of-the-art of dealing with severely fouling services in heat exchangers relates to various attempts of fouling mitigation by employing chemicals, in-tube mitigation devices and novel shell-side developments involving special types of baffles.

PRINCIPLE AND ACHIEVEMENTS

The 'zero fouling' mechanism 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 the tube-side as well as on the shell-side. 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 non-fouling heat transfer fluid is on the shell-side, such as condensing steam. The principle is shown in Figure 1 and is based on the circulation of 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

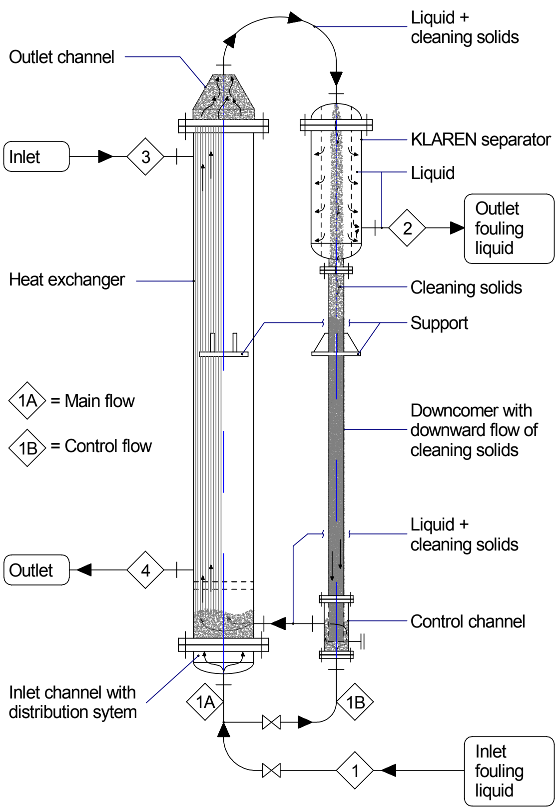

Figure 1: Principle of self-cleaning heat exchanger.

tube wall and remove any precipitated matter at an early stage.

Successfully operating self-cleaning (fluidized bed) heat exchangers have been applied in numerous highly fouling services, including the following:

1. Recirculated quench water containing tar globules and soot particles fouled conventional heat exchangers operating at fluid velocities in the tubes of 1.8 m/s to such an extent that the k-value dropped from 2,500 W/(m²·K) to 500 W/(m²·K) 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.
2. Waxy deposits reduced the k-values from 1,400 W/(m²·K) to 300 W/(m²·K) in only 4 to 5 days. A self-cleaning heat exchanger maintained a clean k-value of 1,700 W/(m²·K) indefinitely.
3. A waste-water stream could not be concentrated in a forced circulation evaporator because severe fouling reduced performance within a matter of hours. When this waste- water 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.
4. 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 the delivery of full-size self-cleaning reboilers to this client included a guarantee for continuous operation without fouling for a period of six years.
5. Natural and chemically untreated seawater has been heated to 125°C for a long period of time without any deterioration in heat transfer.

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

'ZERO-FOULING' SELF-CLEANING DESIGN

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

An interesting 'zero fouling' self-cleaning design is shown in Figure 2 and Figure 3. The hot fouling fluid is cooled by a very small circulating flow of conditioned water evaporating on the outer surface of the tubes, while the cold fouling fluid is heated by condensation of this produced water vapor on the outer surface of the parallel tube bundle.

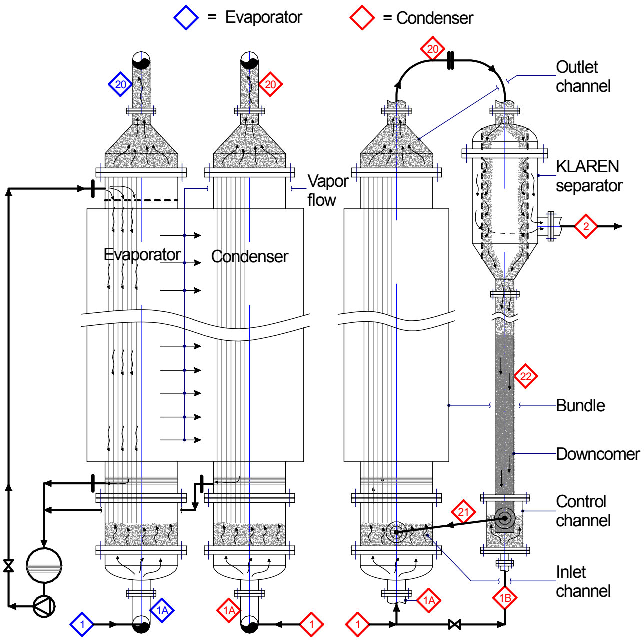

Figure 2: 'Zero fouling' self-cleaning heat exchanger employing an evaporator and condenser in one shell.

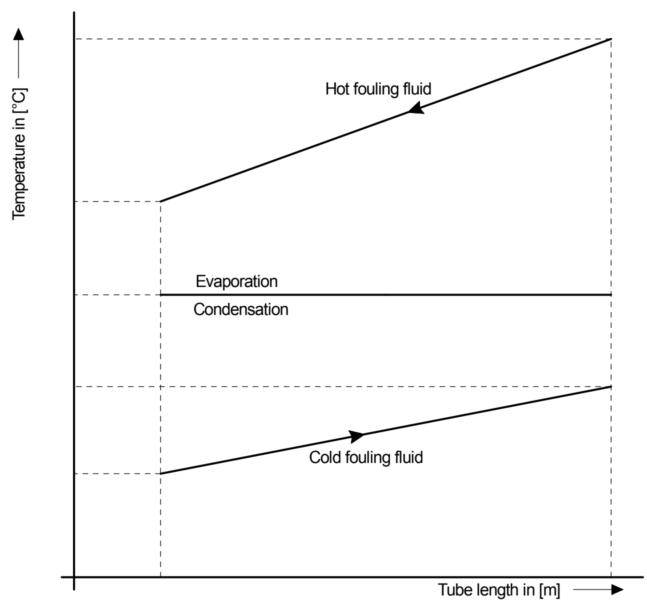

Figure 3: Temperatures referring to the design of Figure 2.

When the outlet temperature T_2 of the cold fouling fluid as shown in Figure 4 approaches the outlet temperature T_3 of the hot fouling fluid, 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 Figure 5. 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

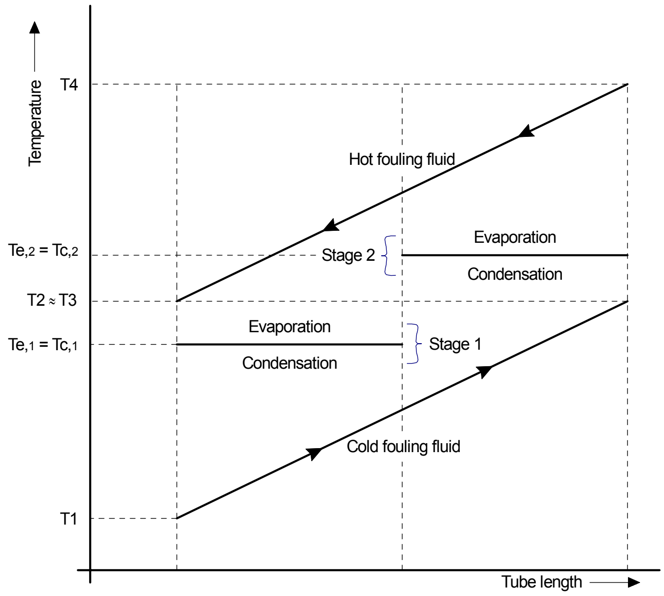

Figure 4: Typical temperature for multi-stage design.

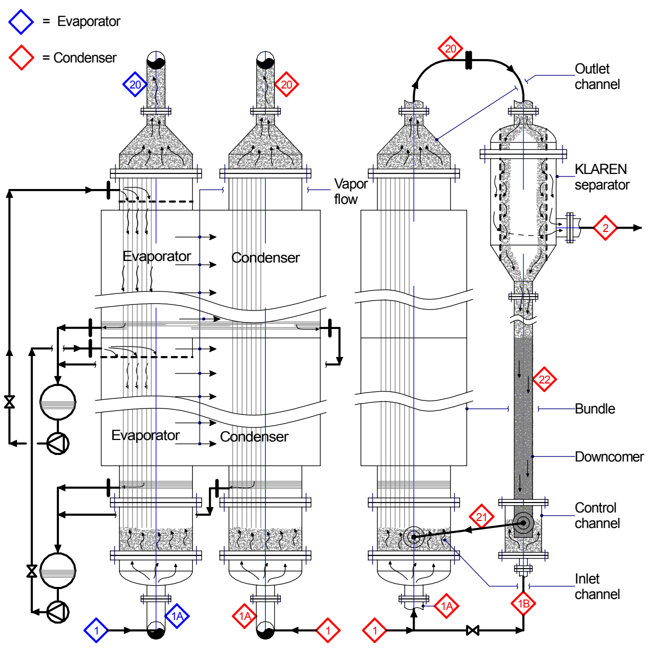

Figure 5: Multi-stage 'zero fouling' self-cleaning heat exchanger employing an evaporator and condenser in one shell.

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 such as small storage vessels for the conditioned water and connecting piping. For example, a two-stage configuration requires two small circulation pumps each with only half the flow and pump head required for the one-stage configuration.

Another 'zero fouling' self-cleaning design applies two separate self-cleaning heat exchangers operate in parallel to a flow of clean conditioned water circulating through their shells. Figure 6 shows the temperatures of the fouling fluids and the circulating conditioned water as a function of tube length.

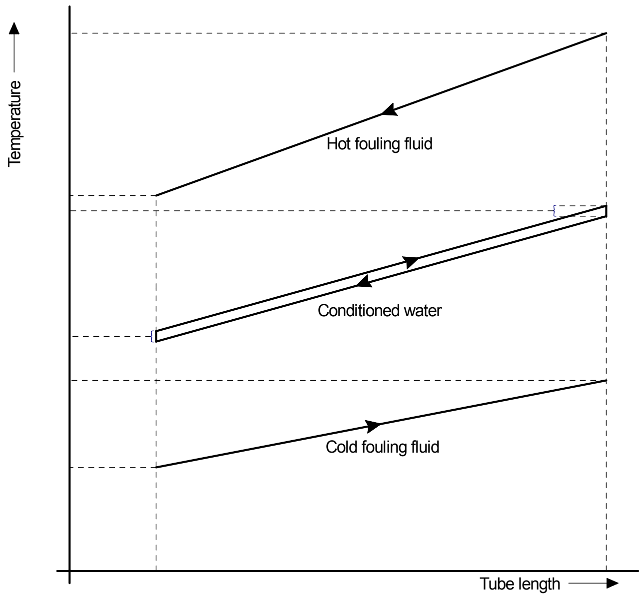

Figure 6: Temperatures referring to the design employing a circulating conditioned water flow between the shells.

COMPARISON BETWEEN A CONVENTIONAL FOULING CRUDE PREHEATER AND A 'ZERO FOULING' SELF-CLEANING CONFI-GURATION

Table 1 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.

Refineries often experience a reduction of the heat transfer coefficient (k-value) of their crude preheaters to 30% of its clean value in less than one year. 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 heat exchange surface have very low thermal

Table 1: Process and design data for conventional crude oil pre-heater.

	Unit	Process Data	
		Tube-side	*Shell-side*
Medium	-	Crude oil	Hydro carbon
Duty	kW	6,510	6,510
Number of heat exchangers in series	-	2	
Flow	m³/h	500	308
Inlet temperature	°C	150	263
Outlet temperature	°C	175	225
Density	kg/m³	750	800
Specific heat	J/(kg·K)	2,500	2,500
Viscosity	mPa·s	1.0	2.0
Thermal conductivity	W/(m·K)	0.1	0.1
Liquid velocity in tubes	m/s	1.2	n.a.
Fouling factor	m²·K/W	0.00175	0.00175
		Design data per heat exchanger	
Total number of tubes per shell	-	737	
Diameter of tubes	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/(m²·K)	125	
Heat transfer surface per heat exchanger	m²	350	
Total required heat transfer surface	m²	700	

conductivities, the k-value is rather insensitive to fouling and its rate of decline represents a very mild fouling situation for self-cleaning heat exchangers. Typically self-cleaning heat exchangers serve highly fouling fluids where conventional exchangers would require to be cleaned every few weeks. Therefore, it can be concluded that self-cleaning heat exchangers can easily prevent fouling if processing crude oil.

The ‘zero fouling’ self-cleaning design shown in Figure 2 and elucidated in Figure 3 is used in this comparison for the application as specified in Table 1. Figure 7 shows the temperatures as a function of the tube length. Table 2 gives more information about this design and Table 3 compares significant parameters for the conventional severely fouling design with the ‘zero fouling’ self-cleaning design.

Striking advantages are that the ‘zero fouling’ self-cleaning design requires only 33% of the heat transfer surface of the conventional crude preheater and that much longer operating periods can be achieved between inspections or cleanings. Plot area is less than that required for the conventional crude preheater and the total installation height is modest and can even be further reduced by smaller tube diameters and/or particles and lower fluid velocities in the tubes. Although not explained in this article, even the required pumping power for the self-cleaning configuration is less than for the conventional crude preheater. More details about the advantages of ‘zero fouling’ self-cleaning crude preheater in comparison with the conventional crude preheater are given in (Klaren and de Boer, July 2005).

CONCLUSIONS

It is now possible to design ‘zero fouling’ shell and tube heat exchangers handling two severely fouling process streams, i.e. one in the tubes and one in the shell, by employing the self-cleaning heat exchange technology, which makes use of the circulation of cleaning particles and a sophisticated shell side design.

This new 'zero fouling' self-cleaning design has been compared with a conventional severely fouling crude oil preheater and it has been shown that a reduction in required heat transfer surface from 700 m² for the conventional exchanger to 229 m² for the newly designed heat exchanger can be achieved.

This self-cleaning heat exchange technology has already realized very large savings in other industrial applications that suffer from severely fouling heat exchangers as explained in (Klaren and Sullivan, 2001; Klaren, 2002; Klaren and de Boer, March 2004; Klaren and de Boer, October 2004). Since the fouling rate of crude oil preheaters is relatively low in comparison with earlier experiences where the self-cleaning technology has been applied with great success, 'zero fouling' of the self-cleaning crude oil preheater would be easily achieved.

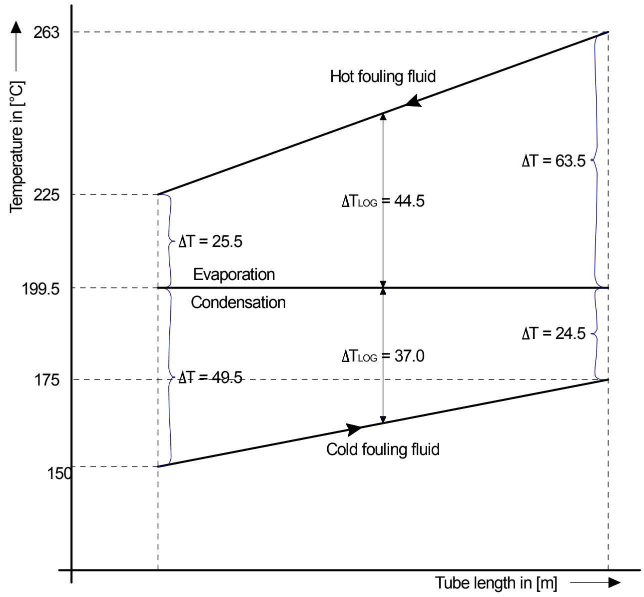

Figure 7: Temperatures referring to the design , specified in Table 2.

Table 2: Process and design data for both parallel operating self-cleaning heat exchangers.

	Unit	Evaporator (cooling hydrocarbon)	Condenser (heating crude oil)
Duty	kW	6,510	6,510
Flow	m³/h	308	500
Inlet temperature	°C	263	150
Outlet temperature	°C	225	175
For physical properties	-	See Table 1.	
Total number of tubes	-	494	515
Diameter of tubes	mm	19.05 x 2.11	19.05 x 2.11
Effective tube length	mm	3,800	3,800
Fluid velocity in tubes	m/s	1.0	1.56
Particle size (l/d = 1.0)	mm	3.0 (cut metal wire)	3.0 (cut metal wire)
Bed porosity	%	92	97
Tube-side fouling factor	m²·K/W	0.0	0.0
Shell-side fouling factor	m²·K/W	0.0	0.0
Heat transfer coefficient	W/(m²·K)	1,306	1,504
Condensation / evaporation temperature	°C	199.5	199.5
Log. temperature difference	°C	44.5	37.0
Heat transfer surface	m²	112	117
Total required heat transfer surface	m²	112 + 117 = 229	

Table 3: Comparison conventional design versus 'zero fouling' self-cleaning design.

	Unit	**Conventional**	**'Zero Fouling' Self-Cleaning**	
			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	$W/(m^2 \cdot K)$	125	1,306	1,504
Removable tube bundle	-	Yes	No	No
Positioning heat exchanger	-	Horizontal	Vertical	Vertical

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