Case Study Involving Severely Fouling Heat Transfer: Design and Operating Experience of a Self-Cleaning Fluidized Bed Heat Exchanger and its Comparison with the Newly Developed Compact Self-Cleaning Fluidized Bed Heat Exchanger with EM Baffles

Dr.Ir. Ing. Dick G. Klaren and Ing. Eric F. de Boer
KLAREN BV, Hillegom, the Netherlands

Presented at the Fachveranstaltung:
Verminderung der Ablagerungsbildung an Wärmeübertragerflächen
4.-5. Oktober, 2004,
Gartenhotel Heusser, Bad Dürkheim

Unpublished

KLAREN BV, HILLEGOM, THE NETHERLANDS
Tel.: (31) 252 530606; Fax.: (31) 252 530605; E-mail: info@klarenbv.com
Internet: www.klarenbv.com

Case Study Involving Severely Fouling Heat Transfer: Design and Operating Experience of a Self-Cleaning Fluidized Bed Heat Exchanger and its Comparison with the Newly Developed Compact Self-Cleaning Fluidized Bed Heat Exchanger with EM baffles

Dr.Ir. Dick G. Klaren and Ing. Eric F. de Boer
KLAREN BV, Hillegom, the Netherlands

Introduction.

The self-cleaning heat exchange technology applying a fluidized bed of particles through the tubes of a vertical shell and tube exchanger was developed in the early 70s for seawater desalination service. Since that time, several generations of technological advancements have made the modern self-cleaning heat exchanger the best solution for most severely fouling liquids. The reference listed at the end of this article gives an excellent review what happened in fluidized bed heat transfer over the past 30 years.

In 1998 four large self-cleaning fluidized bed shell and tube heat exchangers were put into operation at a chemical plant in the USA in a severely fouling service. Their excellent performance in comparison with what could be achieved with severely fouling conventional shell and tube heat exchangers surprised the heat exchange community. However, we expect even more surprise if we explain the design and advantages of the newly developed and highly innovative compact self-cleaning fluidized bed heat exchangers for the same severely fouling service equipped with EM baffles in the shell.

Principle of Self-Cleaning Heat Exchanger.

In the following text of this presentation, we prefer to shorten expressions and leave out the term ‘fluidized bed’ if we refer to self-cleaning heat exchangers and compact self-cleaning heat exchangers employing a fluidized bed.

The principle of operation is shown in figure 1. The fouling liquid is fed upward through a vertical shell and tube exchanger which has specially designed inlet and outlet channels. Solid particles are also fed at the inlet where an internal flow distribution system provides a uniform distribution of the liquid and suspended particles throughout the internal surface of the bundle. The particles are carried through the tubes by the upward flow of liquid where they impart a mild scraping effect on the heat exchange tubes, thereby removing any deposit at an early stage of formation. These particles can be cut metal wire, glass or ceramic balls with diameters varying from 1 to 4 mm. At the top, within the separator connected to the outlet channel, the particles disengage from the liquid and are returned to the inlet channel through a downcomer and the cycle is repeated. Figure 2 shows an improved configuration where a new type of separator is used which does not apply centrifugal separation and, therefore, requires less pressure drop and does not experience any wear.

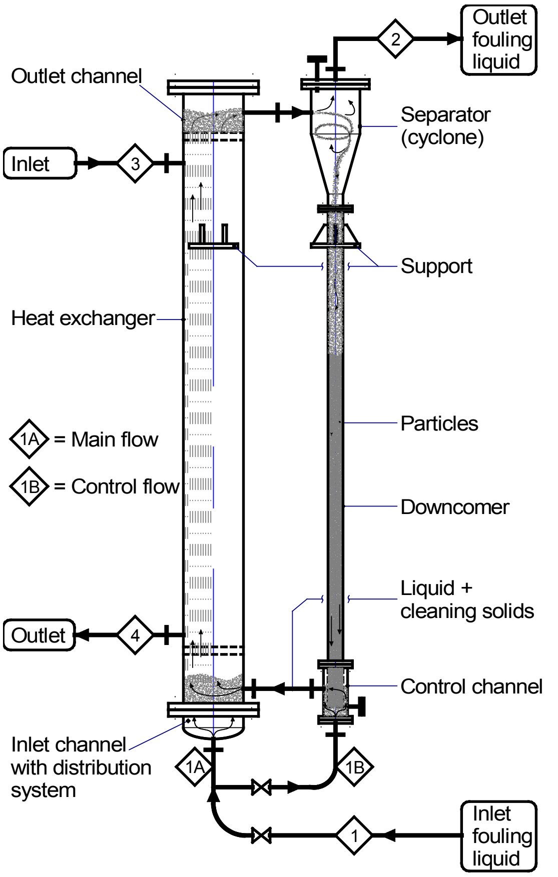

Figure 1: **Principle of self-cleaning heat exchanger with cyclone.**

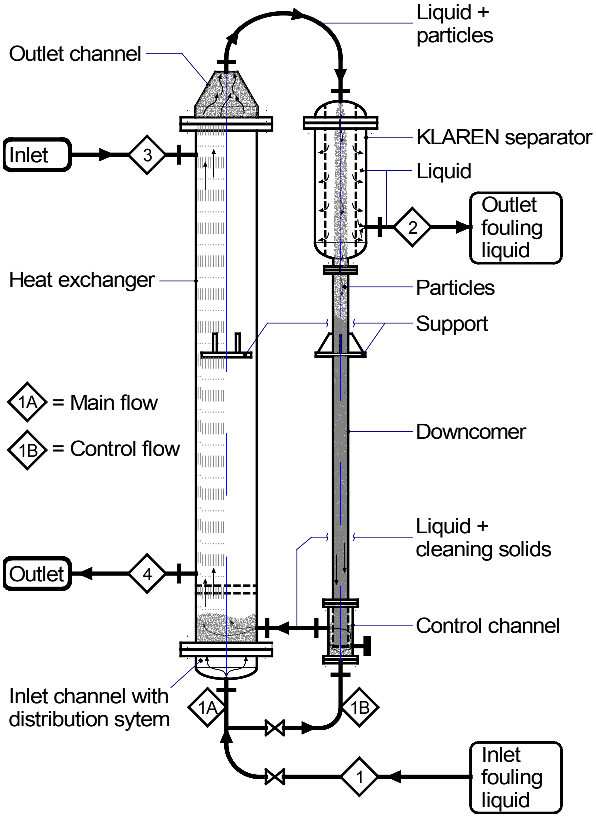

Figure 2: **Principle of self-cleaning heat exchanger with KLAREN separator.**

For both configurations, the process liquid fed to the exchanger is divided into a main flow and a control flow that sweeps the particles into the exchanger. By varying the control flow, it is now possible to control the amount of particles in the tubes. This provides control of aggressiveness of the cleaning mechanism. It allows the particle circulation to be either continuous or intermittent.

Example of Severely Fouling Service and Solution of the Problem.

A chemical plant in the United States cooled large quench water flows from a proprietary process in open cooling towers. This quench water released volatile organic compounds (VOCs) into the atmosphere. As a consequence of environmental regulations the quench water cycle had to be closed by installing heat exchangers between the quench water and the cooling water from the cooling towers. Figure 3 gives a simplified flow diagram of the proposed installation consisting of two process lines and equipped with shell and tube heat exchangers.

An experiment with a small conventional shell and tube test exchanger indicated that the proprietary process liquid would cause very severe fouling in the tubes. The results of this test are shown in figure 4. In anticipation of this expected fouling, a well-known engineering company designed the system as shown in figure 5. Each process line was designed for a capacity of 3 x 50% = 150% with 2 x 50% in operation and the remaining 50% as spare for cleaning. This design would require 24 heat exchangers with 1,000 m² surface for each heat exchanger.

As an alternative for this very expensive design, plant management decided to look into the possibility of using self-cleaning shell and tube heat exchangers. However, this required a test with a small self-cleaning heat exchanger. The results of this test in comparison with the results of the earlier test for the conventional configuration are also shown in figure 4 and justified the decision by plant management in favor of the self-cleaning design.

Figure 6 shows the self-cleaning design. Each process line was now designed for a capacity of 2 x 50% = 100%. Spare capacity was not considered necessary by plant management, which reflects their confi-dence in the self-cleaning design after they had seen the results of the test with the small self-cleaning exchanger. Figure 7 gives an impression of the dimensions of a self-cleaning heat exchanger and figure 8 shows the real installation with the four parallel self-cleaning heat exchangers at the plant site.

The advantages of the self-cleaning heat exchanger in comparison with the conventional shell and tube exchanger for this severely fouling service go even much further than zero-fouling and the much smaller heat transfer surface to be installed.

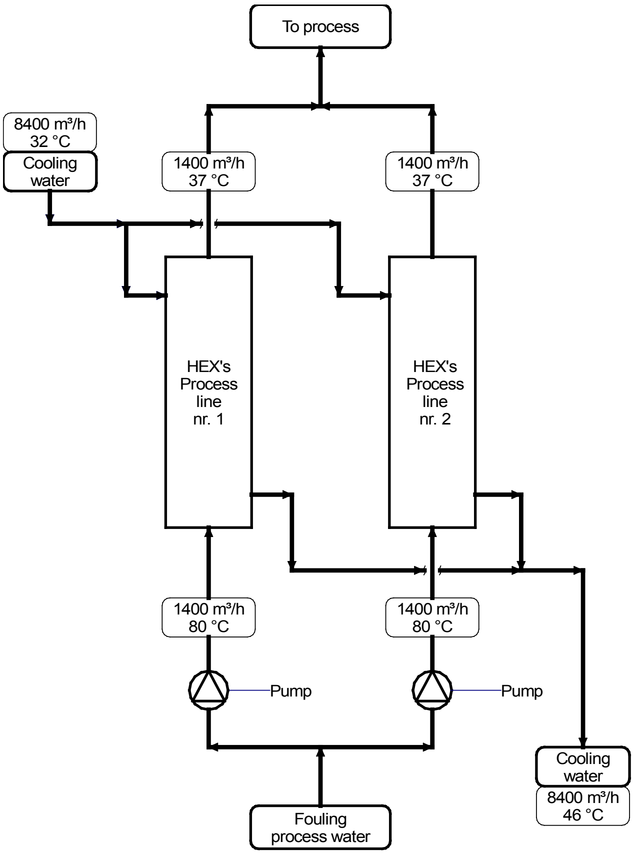

Figure 3: Simplified flow diagram of installation.

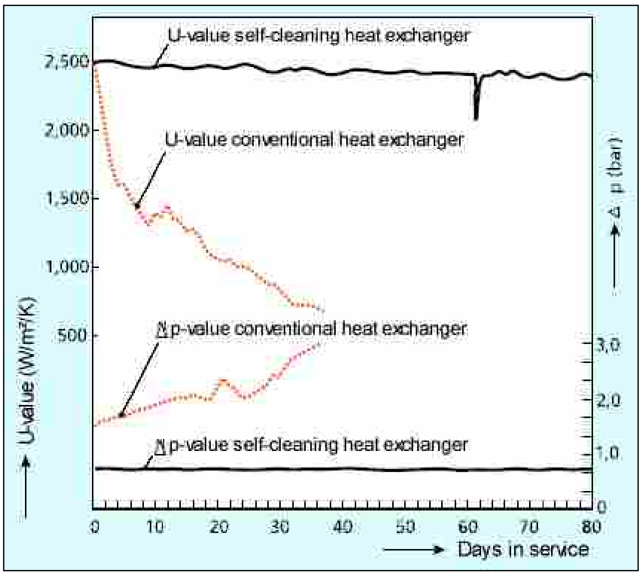

Figure 4: Test results conventional and self-cleaning heat exchanger.

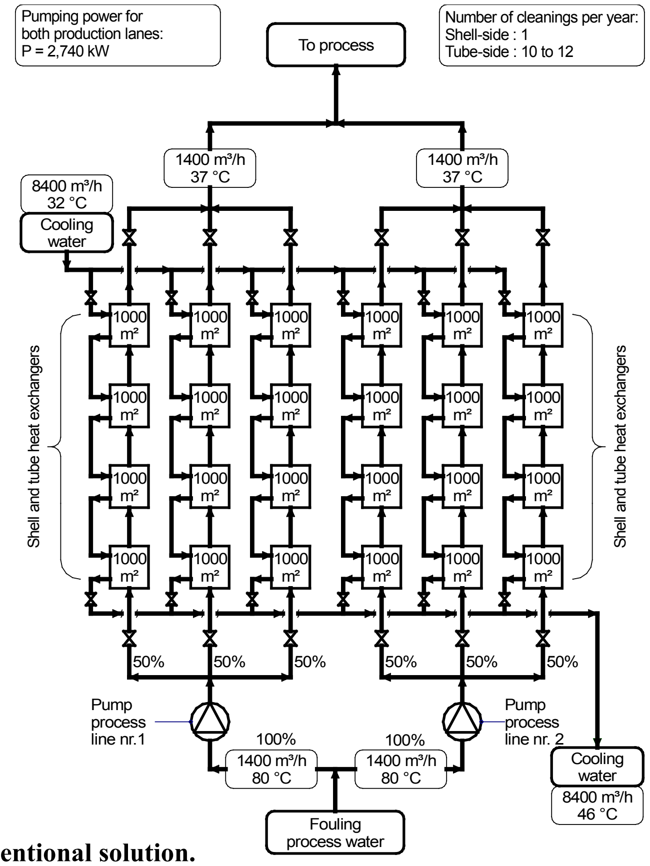

Figure 5: Conventional solution.

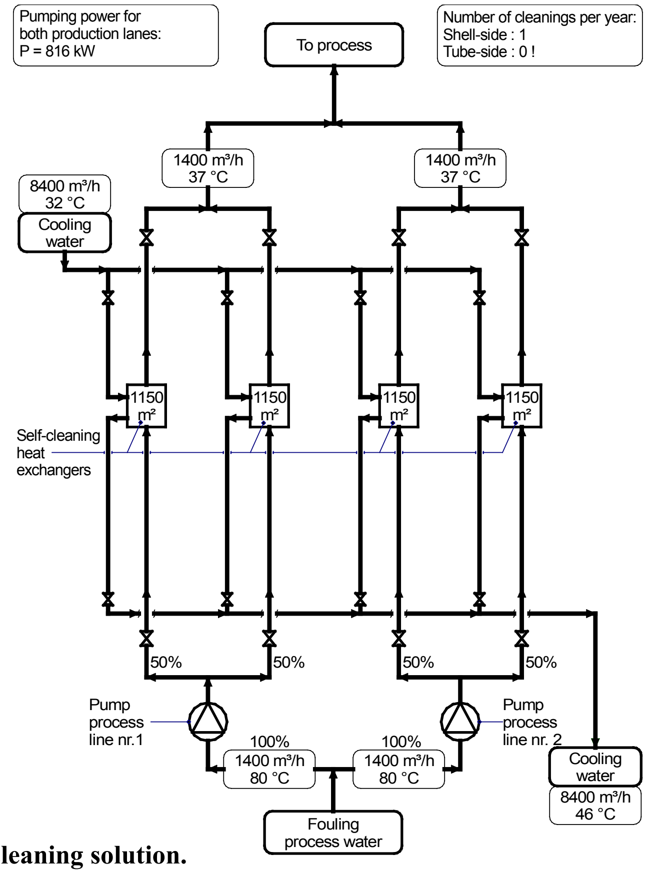

Figure 6: Self-cleaning solution.

Table 1 presents a more detailed comparison between both types of heat exchangers each handling 50% of the flow of one of the process lines.

	Conventional	**Self-cleaning**
Flow tube-side (m^3/h)	700	700
Flow shell-side (m^3/h)	2,100	2,100
Total number of heat exchangers in series	4	1
	Specifications per heat exchanger	
Total number of tubes	1,663	704
Tube diameter (mm)	19.05 x 1.65	31.75 x 1.65
Tube pitch (mm)	24.0	40.0
Tube length (mm)	12,000	16,000
Number of passes tube-side	3	1
Number of passes shell-side	1	1
Baffle type	segmented cross	segmented cross
Baffle pitch (mm)	550	550
Diameter shell (mm)	1,300	1,350
Installed heat exchange surface (m^2)	1,000	1,122
Liquid velocity in tubes (m/s)	1.8	0.45
Particle size (mm)	not applicable	1.6
Bed porosity in tube (%)	not applicable	91
Total weight of particles (kg)	not applicable	9,000
Clean k-value ($W/m^2/K$)	2,400 1)	2,500 2)
Design k-value ($W/m^2/K$)	500 1)	1,800 2)
Pressure drop clean tube-side (bar)	0.84 1)	2.2
Pressure drop clean shell-side (bar)	1.8 1)	2.4
Operating times between tube-side cleanings in weeks	4 to 5	larger than 120
1) *Drop in k-value and increase in pressure drop due to fouling tubes takes place in 4 to 5 weeks*		
2) *Differences between k-value determined by preferred overdesign not due to fouling*		

Table 1: Comparison significant parameters conventional vs. self-cleaning heat exchangers.

A typical and unique characteristic of the self-cleaning heat exchanger is the low liquid velocity in the tubes in comparison with the conventional exchanger. Even in spite of this low velocity the self-cleaning heat exchanger has an excellent clean k-value, which remains high in spite of the very severe fouling behavior of the liquid. As we ran into a couple of uncertainties with the self-cleaning heat exchanger and preferred an excellent reference installation, we installed some more surface than strictly required, which explains the lower design k-value in comparison with the clean k-value. This overdesign had nothing to do with fouling and even after very long operating periods the self-cleaning heat exchangers performed close to their clean k-value and the first inspection after 30 months of continuous operation showed shiny tubes. At the shell-side, we experienced very little fouling, which, because of the biological nature, could easily be controlled on line by an intermittent chemical treatment of the cooling water.

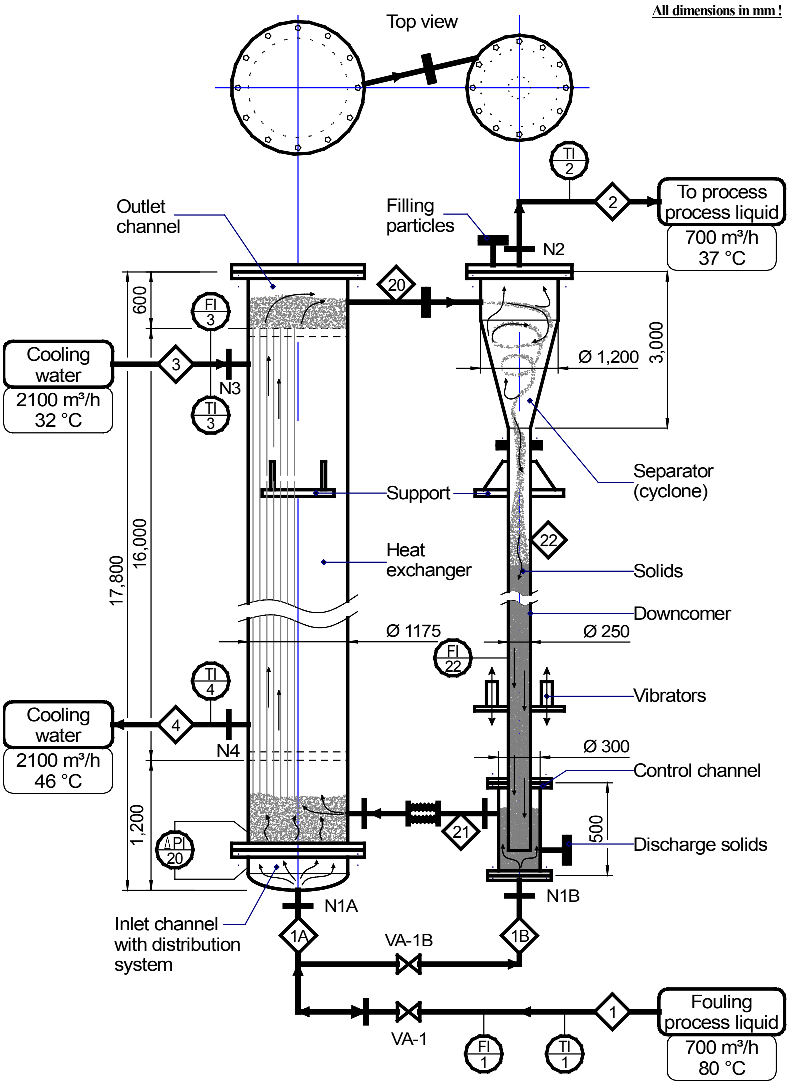

Figure 7: Design self-cleaning heat exchanger.

Figure 8: 4,600 m² self-cleaning heat exchanger surface replacing 24,000 m² conventional surface.

The design of the conventional and self-cleaning exchangers was very much influenced by the potential vibration problem of the tubes in the shell. At the time of the design of this installation, we decided to control the tube vibration problem by installing segmented cross baffles in the shell.

Table 2 compares both complete installations consisting of two parallel process lines and the advantages of the self-cleaning heat exchange configuration do not need any further explanation. However, we would like to draw attention to the large pumping power required for the conventional exchangers. This is caused by the pressure drop and the four shells in series, which (4 x 12 m = 48 m) are 3 times longer than the single shell of the self-cleaning exchanger (1 x 16 m = 16 m). Evidently, this factor 3 also applies for the design value of the shell-side pressure drop.

	Conventional	**Self-cleaning**
Total number of heat exchangers	24	4
Total installed heat transfer surface (m²)	24 x 1,000 = 24,000	4 x 1,150 = 4,600
Total required pumping power for tube-side based on design conditions (kW)	868	192
Total required pumping power for shell-side based on design conditions (kW)	1,872	624
Total required pumping power (kW)	2,740	816
Time between tube-side cleanings in weeks	5	larger than 120

Table 2: Comparison significant parameters conventional vs. self-cleaning installation.

What we actually have accomplished with the self-cleaning heat exchanger is a rather unique achievement in heat transfer:

Excellent heat transfer without fouling, in spite of low velocities of the fouling liquid in the tubes, and requiring very little pressure drop and pumping power.

As far as we know, there is no other heat exchange mechanism which combines these unique and, to a certain extent, contradictory characteristics.

The Compact Self-Cleaning Heat Exchanger with EM baffles

Although, we have shown that the self-cleaning heat exchanger performs excellently in a severely fouling service in comparison with conventional shell and tube exchangers, we can do even better. Therefore, we have to introduce the compact self-cleaning heat exchange technology in combination with the so-called EM baffles in the shell.

The compact self-cleaning heat exchanger

For 30 years, it was considered impossible to apply the self-cleaning fluidized bed heat exchange principle in tubes with an inner diameter D_i smaller than 30 mm and in combination with chopped metal wire cleaning particles with a diameter d_p of 2 mm. Or said otherwise:

For a satisfactory operation of a self-cleaning heat exchanger employing chopped metal wire particles of 2 mm, it was generally recommended to use tubes with an inner diameter of at least 30 mm and maintain a ratio Di / dp larger than 15. Until foreign researchers made a revolutionary discovery and demonstrated the feasibility of the self-cleaning principle in a single tube with an inner diameter of only 9.7 mm using chopped metal wire particles with a diameter of 2 mm, i.e. D_i / d_p < 5. We (KLAREN engineers) have found the design rules to make this unique discovery also workable in bundles with many parallel tubes. The consequences of this new development are that self-cleaning heat exchangers can now be designed with the following characteristics:

- Small hydraulic diameter,
- thin tube wall,
- high degree of turbulence,
- low liquid velocities,
- excellent film coefficients for heat transfer.

These characteristics result in very compact self-cleaning heat exchangers and, particularly, a drastic reduction of the height of the self-cleaning heat exchanger.

The EM baffle

Shell Global Solutions International BV developed a new type of baffle for shell and tube heat exchangers. This new and really innovative tube support technology is based on ‘Expanded Metal’ (EM) and an example is shown in figure 9. Expanded metal is a rigid piece of cold rolled metal that has been slit and expanded. In the expansion process, the metal length can be expanded up to ten times its original size. The exchanger can be designed as a longitudinal or crossflow exchanger on the shell side with one or more passes for the tube side. The EM baffle combines the advantages of other non-segmental (rod-baffle) heat exchanger types, such as less pressure drop, excellent heat transfer, reduction of fouling and no vibrations. These baffles can be fabricated at low cost. Many EM baffles in series create a static mixing effect of the liquid in the shell between the tubes which explains its excellent performance in heat transfer.

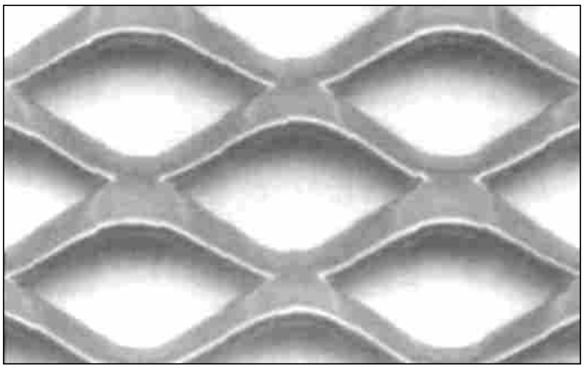

Figure 9: Expanded metal in EM baffle.

The combination of compact self-cleaning cleaning heat exchanger and EM baffles

Figure 10 shows the self-cleaning heat exchanger with a longitudinal flow and EM baffles in the shell. Table 3 compares the four self-cleaning designs three of which are compact and provided with EM baffles. For comparison, all exchangers are overdesigned by the same factor 1.38, but again, it should be emphasized that this difference between clean k-value and design k-value was not inspired by fouling. As we did not experience serious fouling at the shell-side, and in case of fouling could solve the problem with chemicals, the bundle was not removable from the shell and the minimum distance between the tubes could be made very small, determined by the minimum allowable tube pitch. This, of course, also contributes to the compact design.

	Self-cleaning	**Self-cleaning compact #1**	**Self-cleaning compact #2**	**Self-cleaning compact #3**
Total number of tubes	704	1639	1981	4057
Tube diameter (mm)	31.75 x 1.65	19.05 x 1.65	15.88 x 1.21	12.70 x 0.90
Tube pitch (mm)	40	24	20	16
Minimum distance between tubes (mm)	8,25	4,95	4,12	3.30
Tube length (mm)	16,000	9,700	8,700	5,100
Number of passes tube-side / shell-side	1	1	1	1
Baffle type	segmented cross	EM	EM	EM
Baffle pitch (mm)	550	unknown	unknown	unknown
Diameter shell (mm)	1,350	1,065	970	1,110
Installed heat exchange surface (m^2)	1,150	951	833	824
Liquid velocity in the tubes (m/s)	0.45	0.6	0.7	0.5
Particle size (mm)	1.6	2.5	2.5	1.6
Bed porosity (%)	91	91	91	91
Total weight of particles (kg)	9,000	5,700	5,000	3,900
Clean k-value (W/m^2/K)	2,500 1)	3,300 1)	3,900 1)	3,900 1)
Design k-value (W/m^2/K)	1,800 1)	2,391 1)	2,826 1)	2,826 1)
Overdimensioning factor	1,38	1.38	1.38	1.38
Pressure drop tube-side (bar)	2.2	1.3	1.2	1.0
Pressure drop shell-side (bar)	2.4	1.2	1.2	0.6
Total required pumping power tube-side (kW)	48	29	26	22
Total required pumping power shell-side (kW)	156	78	78	39
Total required pumping power tube + shell-side (kW)	204	107	107	61

1) *Differences k-value by overdesign not due to fouling*

Table 3: Comparison significant parameters self-cleaning vs. compact self-cleaning heat exchanger.

Overall comparison

Table 4 highlights and summarizes the important differences between the various designs for the complete installation handling 4 x 700 m³/h process flow. In our earlier comparisons, we have seen that the conventional and self-cleaning heat exchangers are equipped with segmented cross baffles and not with EM baffles. For a fair comparison, this table also shows what differences in shell-side pressure drop and pumping power could be expected, if these exchangers would have been provided with EM baffles. However, there still remains some imbalance in this comparison:

For the self-cleaning design, it is an advantage to create a film coefficient as high as possible at the shell-side, even at the expense of some more shell-side pressure drop by installing more EM baffles. For the conventional design, the very severe tube-side fouling limits the gain in overall heat transfer which can be achieved by installing many EM baffles and improving the shell-side film coefficient. How far we can go in limiting the number of EM baffles and shell-side pressure drop without increasing the negative effects of shell-side fouling can only be determined by experiments.

	Conven-tional	**Self-cleaning**	**Self-cleaning compact #1**	**Self-cleaning compact #2**	**Self-cleaning compact #3**
Total number of heat exchangers	24	4	4	4	4
Total installed heat transfer surface (m²)	24 x 1,000 = 24,000	4 x 1,150 = 4,600	4 x 951 = 3,804	4x 833 = 3,332	4 x 824 = 3,296
Total required pumping power for tube-side based on design conditions (kW)	868	192	116	104	88
Total required pumping power for shell-side based on design conditions and segmented cross baffles (kW)	1,872	624	-	-	-
Total required pumping power for shell-side based on design conditions and EM baffles (kW)	1,248	416	312	312	156
Total required pumping power with EM baffles in shell-side (kW)	868 + 1,248 = 2,116	192 + 416 = 608	428	416	244
Volumetric power factor (MW/m³)	0.37	1.52	4.22	5.45	7.10
Time between tube-side cleanings in weeks	5	>120	>120	>120	>120

Table 4: Important differences between the various designs.

A newly introduced but also interesting parameter for comparison of the various designs for a particular application is the total heat transferred (i.e. also power) in MW divided by the volume of all heat exchanger shells, including the spares, in m³ and referred to in this publication as the 'Volumetric power factor'. This factor is an indication for the 'compactness' of the total installed heat transfer surface in the total number of shells of the installation. Table 4 presents this factor for the various designs and the compact self-cleaning heat exchanger is an excellent tool to transfer many megawatts in a small shell volume. It would be worthwhile to compare the achievements of the compact self-cleaning shell and tube heat exchanger with plate heat exchangers.

Conclusions

We believe that in a very convincing manner we have shown how the already superior self-cleaning heat exchange design of 1998 can be further improved by a compact self-cleaning design in combination with EM baffles at the shell-side. The results presented in Table 4 are a revelation in shell and tube heat transfer and have never been achieved before. We expect that these excellent results will accelerate the acceptance and penetration of self-cleaning heat exchangers in the market.

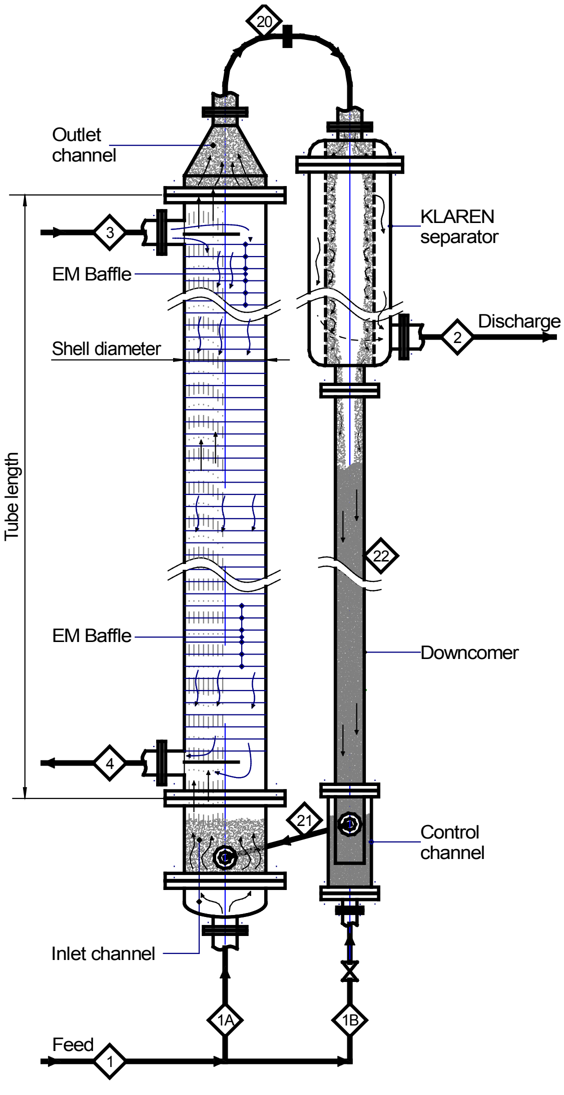

Figure 10: Self-cleaning fluidized bed heat exchanger with EM baffles.

Aknowledgements

Dr. Klaren expresses his appreciation for his discussions with the inventor of the EM baffle Technology, Ir. D.F. Mulder MSc. of Shell Global Solutions International in Amsterdam, the Netherlands.

REFERENCE

Klaren, D.G. and E.F. de Boer (2004); Synoptic of the History of Thirty Years of Developments and Achievements in Self-Cleaning Fluidized Bed Exchangers. Internal Report KBV Nr. 7, March.