Refereed Proceedings

Heat Exchanger Fouling and Cleaning: Fundamentals and Applications

Engineering Conferences International *Year* 2003

Improvements and New Developments in Self-Cleaning Heat Transfer Leading to New Applications

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IMPROVEMENTS AND NEW DEVELOPMENTS IN SELF-CLEANING HEAT TRANSFER LEADING TO NEW APPLICATIONS

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ABSTRACT

Improvements in the design have made the fluidized bed heat exchanger better suitable for the revamp of existing vertical severely fouling heat exchangers in evaporators, crystallizers and reboilers into a self-cleaning configuration. Highly viscous non-Newtonian slurries used in mineral processing can benefit from the fluidized bed heat exchanger not only due to its self-cleaning performance, but also as a result of the shear-thinning action of the fluidized particles which dramatically lowers the viscosity of the slurry. New developments have created the possibility to design compact self-cleaning fluidized bed heat exchangers which can compete with plate and frame exchangers.

INTRODUCTION

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 1970s for sea-water 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.

In the 90s, a chemical plant in the United States compared for their severely fouling application a conventional solution versus the installation of self-cleaning heat exchangers. The result of this comparison is also shown in table 1. As could be expected, but also convinced by a test, plant management decided in favor of the self-cleaning configuration. During operation, the expectations for the self-cleaning heat exchangers were fully met and even better than that: After 26 months of continuous operation, the self-cleaning heat exchangers still have not been cleaned. For a more detailed description of this particular case, see also Klaren (2000).

Table 1. Comparison of self-cleaning heat exchanger versus conventional heat exchanger.

	Self-cleaning heat exchanger	Conventional heat exchanger
Heat transfer surface	4,600 m²	24,000 m²
Pumping power	840 kW	2,100 kW
Number of cleanings per year	0	12

This striking example of the self-cleaning heat exchange technology and a large number of improvements and new developments have substantially increased the potential applications which can benefit from this unique self-cleaning heat exchange technology. These improvements and developments leading to new and very interesting applications will be discussed in the next paragraphs.

PRINCIPLES OF OPERATION

The principle of operation with respect to the original configuration of the self-cleaning heat exchanger employing an external downcomer is shown in figure 1.

The fouling liquid is fed upward through a vertical shell and tube exchanger that 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 wall of the heat exchange tubes, thereby removing any deposit at an early stage of formation.

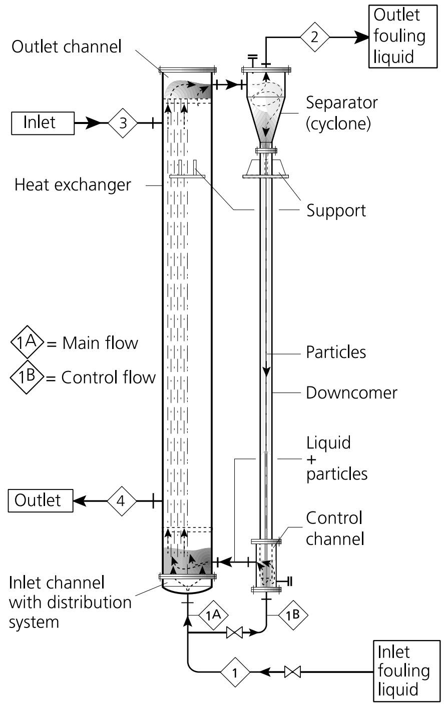

Fig. 1 Principle of self-cleaning heat exchangers with cyclone.

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. Now, the particles disengage from the liquid in a widened outlet channel and, then, are again returned to the inlet channel through an external downcomer and are recirculated continuously.

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

TREATABLE FOULING SERVICES, TYPE OF DEPOSITS, SELF-CLEANING PERFORMANCE

Fouling services which can be treated with the self-cleaning exchanger with external circulation of the cleaning particles are:

1. Forced circulation evaporators and reboilers.
2. Chemical processes where heating or cooling causes polymerization fouling or resinous deposits.
3. Heat recovery from hard scaling and/or biologically fouled (waste) waters.
4. Concentration of waste-waters by evaporation.
5. Cooling and evaporative cooling crystallization.
6. White-water and black-liquor heating in pulp and paper industries.
7. Raw juice heating in food processing.
8. District heating and/or power generation with geothermal brines.
9. Brackish water and sea-water desalination.
10. Production of medium and high pressure steam from severely fouling chemically untreated waters.
11. Self-cleaning lube oil chillers to replace conventional scraped surfaces.
12. Heating of slurries with a very high concentration of solids and a high viscosity.

Commercial operating experience gained with a substantial number of heat exchangers has shown that the self-cleaning heat exchanger, which can remain clean for long operating periods or even indefinitely, is a cost effective alternative to the conventional heat exchanger which suffers from severe fouling in a couple of hours, days, weeks or months. Any type of fouling deposit, whether hard or soft, biological or chemical, fibrous or protein, or other organic types, or a combination of the above can be effectively handled by the self-cleaning heat exchanger

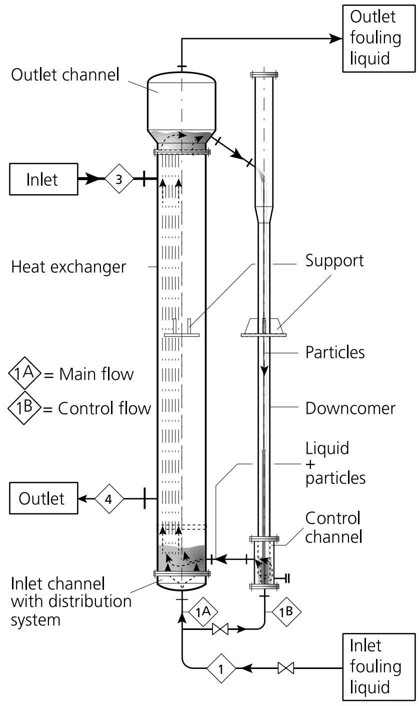

Fig. 2 Principle of self-cleaning heat exchanger with widened outlet channel.

ADVANTAGES WIDENED OUTLET CHANNEL FOR REVAMP PURPOSES

The self-cleaning heat exchange technology employing an external downcomer does offer the possibility of revamping existing conventional vertical fouling exchangers into a self-cleaning configuration. Much interest has been received for the revamp of severely fouling reboilers, evaporators and crystallizers. A typical example of a conventional reboiler installation that is suitable for revamping is shown in figure 3.

Generally speaking, the requirements specified by plant management for the majority of revamps can be summarized as follows:

1. The same process conditions should be maintained as in the original installation, i.e. flow, liquid velocity in the tubes, evaporation in the tubes or suppressed evaporation in the tubes with flash evaporation in column.
2. The connections to the column should be maintained.
3. The installed pumps should be used.
4. It must be possible to remove the cleaning particles during operation in case the revamp does not sufficiently reduce the fouling problem. In this case the reboiler can continue to operate in the same way as before the retrofit.
5. The revamp must be carried out within the available space

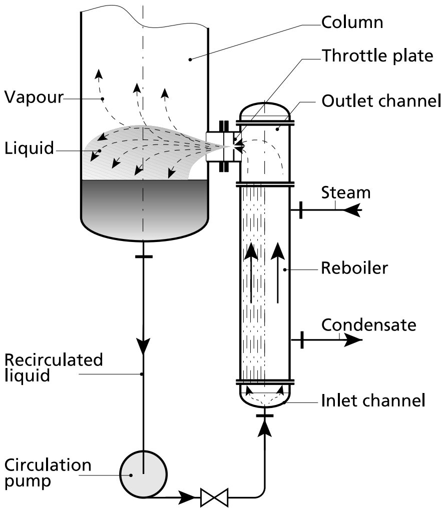

Fig. 3 Existing conventional reboiler.

A suggestion for a retrofitted reboiler, employing a cyclone for the separation of the cleaning particles, is shown in figure 4. However, this configuration has the disadvantage that it may not always meet the requirements 3 and 5 mentioned above.

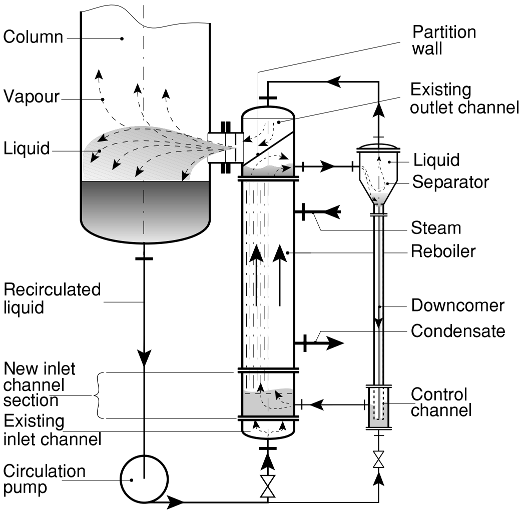

Fig. 4 Existing conventional reboiler retrofitted into self-cleaning configuration.

The cyclone does require a substantial pressure drop which could make it impossible to use the existing pumps and in many of the existing installations, space for the cyclone including its support next to the outlet channel is not easily available.

From figure 5, it follows that the improved configuration of the self-cleaning heat exchanger as shown in figure 2 is much better suited for the revamp of a conventional reboiler into a self-cleaning configuration. This configuration easily meets the requirements 3 and 5. Disengagement of the cleaning particles from the liquid using a widened outlet channel does not require a pressure

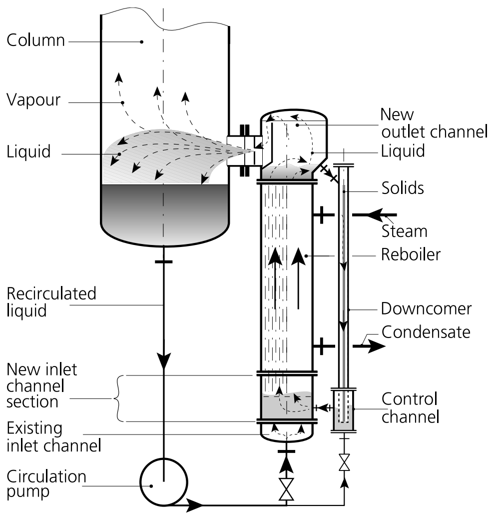

Fig. 5 Existing conventional reboiler retrofitted into self-cleaning configuration.

using a widened outlet channel does not require a pressure drop, while replacing the old outlet channel by the new widened outlet channel on top of the bundle is seldom hampered by lack of space.

A first successful revamp applying a widened outlet channel has already been carried out in a paper mill in the Netherlands. At this moment, a revamp of 6 heat exchangers in a chemical plant in Mexico which suffer from severe fouling due to the precipitation of Glauber's salt is under consideration. Another revamp in the United States regards the heat exchangers of 10 phosphoric acid evaporators, which suffer from severe fouling and have to be cleaned every 7 to 9 days.

For the Mexican plant as well as the plant in the United States, the increased production easily justifies the revamps. See also Klaren (2003).

HEATING OF VISCOUS NON-NEWTONIAN SLURRIES

The typical characteristics of self-cleaning heat exchangers can indeed have an enormous positive influence on the design and cost of a heat exchange train in comparison with conventional heat exchangers. This will be shown in the example below, which received an overwhelming interest from mineral processing and mining companies around the world.

For the processing of laterite nickel and cobalt in so-called High-Pressure-Acid-Leach (HPAL) plants, it is necessary to heat a slurry flow from approximately 65^0C to a temperature of 230^0C, while maintaining the slurry in an autoclave for a considerable period of time.

In this autoclave, large quantities of strong acid are added, which increase the temperature even further to 260^0C. Finally, the slurry is discharged from the autoclave and the heat in the slurry is recovered as much as possible by the cold incoming slurry flow. As a consequece, this process requires the installation of preferably vertical single-pass shell and tube heat exchangers in series consisting of recovery heaters and so-called final heaters

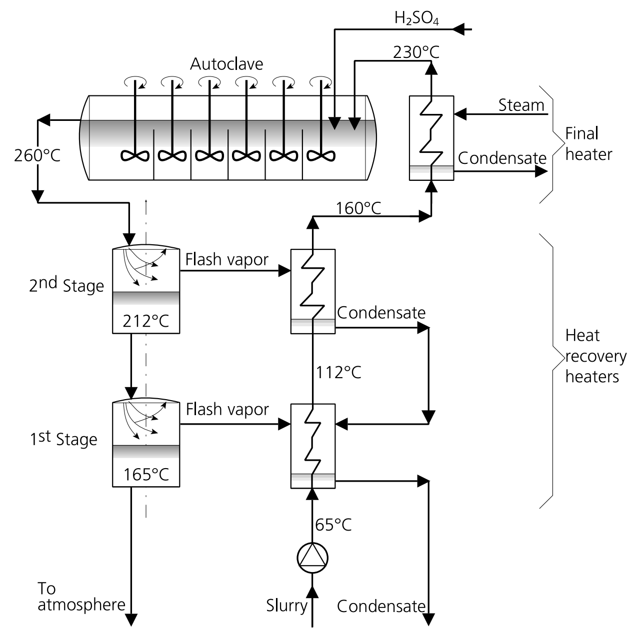

Fig. 6 Principle HPAL for laterite slurry

where live steam is added. The principle is shown in figure 6.

The advantages of self-cleaning heat exchangers over conventional heat exchangers can best be explained with the help of the equation which determines the dimensions of a single heat exchange tube as a function of its design parameters. This equation reads:

$$L_t / D_o = (D_i / D_o)^2 . (\rho_l . c_l . V_l) / (4.U).(\Delta T_l / \Delta T_{log}) \quad (1)$$

For a real comparison between self-cleaning and conventional exchangers, only the following simplified equation is important:

$$L_t \ (:)\ D_o . V_l / U \quad (2)$$

Or said otherwise:
The length of the tubes L_t is directly proportional to the outer diameter of the tubes D_o and to the slurry velocity in the tubes V_l, but inversely proportional to the heat transfer coefficient U.

For a more detailed evaluation of the consequences of equation [2] in the comparison of both types of heat exchanger, the typical characteristics of self-cleaning fluidized bed heat exchangers must be taken into account, such as:

1. Self-cleaning behaviour as a result of the presence of fluidized particles (cut metal wire with a diameter of 4mm or 5mm) in the slurry.
2. Low slurry velocities in combination with excellent heat transfer.
3. Dramatic shear-thinning effects on very viscous slurries which behave strongly non-Newtonian and this again influences the heat transfer performance in a positive manner

Experiments with a laterite slurry in West Australia for the production of nickel and cobalt provided enough information about velocities, heat transfer coefficients, viscosity and shear-thinning behavior of a fluidized bed on the slurry that a comparative design could be made for a heat exchanger train of conventional shell and tube and

Table 2. Comparison HPAL plants equipped with conventional shell and tube heat exchangers and self-cleaning fluidized bed heat exchangers

	Conventional hex's	Self-cleaning hex's
Total production	45,000 ton Ni/y + 4,500 ton Co/y	
Numbers parallel processing lines	3	
Slurry feed flow / processing line in kg/h	450,000	440,000
Slurry density in kg/m³	1,320	1,350
Slurry velocity in tubes in m/s	**1.4**	**0.35**
Slurry viscosity in tubes in cP	**50 ÷ 70**	**~ 15**
Outer diameter of tubes in mm	38	60
Diameter cleaning particles in mm	Not applicable	5
Tube lenght per shell in mm	12,000	12,000
Number of passes per shell	Single-pass	Single-pass
Shell inner diameter in mm	520	960
Average "clean" U-value in W/m² K	**700 ÷ 1,000**	**2,000**
Design U-value in W/m² K	**350**	**2,000**
Total number of shells in series	**28**	**2**
Total installed heat transfer surface in m²	**3,200**	**550**
Total number of cleaning required per year	**12**	**1**
Materials in contact with slurry and/or flash vapor at temperature lower than 170°C	Duplex	Duplex
Materials in contact with slurry and/or flash vapor at temperatures higher than 170°C	Titanium and/or carbon steel clad with titanium	Titanium and/or carbon steel clad with titanium
Materials in contact with steam in final heater	Carbon steel	Carbon steel
Pressure drop across all heaters in series in bar	**~ 10**	**~ 3**
Cost of all hex's for all three production lines, including steel construction, inter connecting piping, steam-flash vapor- condensate manifold and relevant instrumentation	**~ US $ 30,000,000.-**	**~ US $ 9,000,000.-**

self-cleaning fluidized bed heat exchangers for a certain plant capacity.

Table 2 compares the heat exchanger train for both type of exchangers. Attention is asked for the bold printed numbers which reflect the large differences in the design parameters, such as: velocities, viscosities, installed tube length in series for the conventional design (28 shells x 12 m length per shell = 336 m) versus the self-cleaning configuration (2 shells x 12 m length per shell = 24 m), design U-values, installed heat transfer surface, total number of cleanings per year, pressure drop and costs.

From the results presented above, it is understandable that in the future self-cleaning fluidized bed heat exchangers will play an important role in mineral processing. For more information about this subject, one is referred to Klaren (2002).

COMPACT SELF-CLEANING HEAT EXCHANGERS

From equation (2), it follows that the tube length of a self-cleaning heat exchanger depends very much on the diameter of the tubes. Because of experiences in the past, it was always believed, that a tube diameter of approx. 30 mm is the minimum diameter possible in combination with 2 mm steel particles and a bed porosity of 85%. In case of smaller tube diameters, there appeared to be a serious risk for packed bed conditions in the tubes which finally led to plugging of the tubes.

However, recent innovations and developments have made it possible to achieve the above conditions for particle size and bed porosity in tubes of even less than 10 mm internal diameter, with corresponding thin tube walls. Such a heat exchanger has the same features as the plate and frame heat exchanger:

1. Small hydraulic diameter.
2. Low liquid velocity.
3. High turbulence level.
4. High heat transfer coefficient.

Above features lead to a very compact (!) self-cleaning shell and tube heat exchanger with no fouling in the tubes (!), no gaskets (!)and suitable for high temperatures (!) and high pressures (!). We believe that this Small-Internal-Diameter (SID) self-cleaning heat exchanger can become a serious competitor for many applications that are now very much reserved for the traditional plate and frame exchanger. Interest is already shown for cooling purposes using sea-water and ultra-high-temperature heating of milk.

CONCLUSIONS

The many improvements which have been made during the past years regarding the self-cleaning heat exchange technology with external circulation of the cleaning particles, broaden the range of potential applications, while the successful operation of an ever increasing number of installations continue to generate an overwhelming interest for this technology.

NOMENCLATURE

D	diameter, m
L	length, m
U	overall heat transfer coefficient, W/m^2 K
V	velocity, m/s
C	specific heat, J/kg K
P	density, kg/m^3
ΔT	temperature difference between tube inlet and outlet, ^0C
ΔT_{log}	logarithmic mean temperature difference across tube, ^0C

Subscript

i	inner
l	slurry
o	outer
t	tube

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