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Self-Cleaning Fluidised Bed Heat Exchangers for Severely Fouling Liquids and Their Impact on Process Design

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1. Introduction

The invention of the self-cleaning fluidised bed heat exchangers dates back to 1971 when the principal author of this chapter was involved in the discovery and development of a very unique Multi-Stage Flash (MSF) evaporator for the desalination of seawater. The condensers used in this thermal desalination plant used stationary fluidised beds in multi-parallel condenser tubes. The particles fluidised in these tubes consisted of glass beads of 2 mm diameter. These small glass beads knocked of scale crystals from the tube wall at their very early stage of formation and, moreover, the turbulence created by the stirring action of the glass beads in the liquid caused thinning of the laminar boundary layer. This dramatically improved the heat transfer film coefficient in spite of very low liquid velocities in the tubes and reduced pumping power requirements.

Since the early 80s, the chemical processing industries showed a lot of interest for this unique heat exchanger, which seemed to be able to solve any fouling problem, even those problems, which required cleaning of conventional heat exchanger every few days or even hours.

In the next paragraphs we will pay attention to the consequences of heat exchanger fouling and in particular its cost. We explain the self-cleaning fluidised bed technology and also present a couple of installations. We also show some examples where the benefits of the self-cleaning fluidised bed heat exchange technology are responsible for a much wider range of advantages with respect to process design than non-fouling heat exchange only.

2. Fouling of heat exchangers

2.1 Consequences of heat exchanger fouling

It can be stated that a general solution to heat exchanger fouling still does not exist. This is not surprising, as knowledge of underlying mechanisms of the fouling process remains limited. Moreover, fouling in heat exchangers often concerns different types of heat exchangers, each with its own unique characteristics. Also, there are large differences in physical properties of the fluids to be applied in the exchangers. The consequences of heat exchanger fouling are:

- Loss of energy,
- loss of production or reduced capacity operation,
- over sizing and / or redundancy of equipment,
- excessive maintenance cost,
- hazardous cleaning solution handling and disposal.

Over sizing of heat transfer equipment has become an accepted approach to increase the period of time necessary to reach the fouled state. The equipment is then cleaned (chemically or mechanically) to return the heat transfer surface to a near clean condition with recurring maintenance cost and the possibility of cleaning solution disposal problems. Later in this chapter, it will be shown that there are existing cases where over sizing of heat transfer surface can involve the installation of two to five times the surface required for the clean condition. Also, in these severe cases it may be necessary to carry out the cleaning procedure every two or three days, resulting in excessive downtime, maintenance costs and solution disposal problems. Sometimes the fouling problems are so severe that heat transfer performance reduces to almost zero in a matter of hours.

Experience has shown that the alternatives to recurring fouling problems associated with the cooling or heating of a severe fouling liquid are certainly limited. In the case of cooling applications unsuccessful attempts to recover energy from hot waste streams may lead to the total abandonment of an otherwise promising energy management program.

Frequently the only acceptable approach to heating severe fouling liquids will involve direct steam injection. This results in a loss of condensate and the dilution of the process stream, which often requires costly reconcentration later in the process. However, heating by direct steam injection does offer a unique opportunity to define the actual cost of fouling in terms of lost condensate and the subsequent cost of water removal. In the next paragraph we will pay attention to the very high cost of heat exchanger fouling on a global scale, and for one process in particular.

2.2 Cost associated with heat exchanger fouling

The heat exchangers in a crude oil train of a refinery for the distillation of crude oil in lighter fractions are often subject to severe fouling, and do represent globally a very high level of cost. In this sub-paragraph we like to explain this particular example in a nutshell. For a much more detailed explanation one is referred to Ref. [5].

Fig. 1 gives an schematic impression of the heating of crude oil in a crude oil train downstream the desalter and in the furnace, where after the oil is cracked in much lighter fractions in the distillation column. Fig. 2 gives an impression of the temperatures in this very much simplified example.

Fouling of the crude oil heat exchangers downstream the desalter, Ex4 up to and inclusive Ex8, is shown at first instance by a drop of the inlet temperature 271 °C of the crude oil in the furnace, which means that more heat has to be supplied into the furnace to meet the required outlet temperature 380 °C of the crude oil entering the distillation column. This, of course, a phenomenon caused by fouling of the heat exchangers, does requires extra fuel (i.e. extra energy) to be burned in the furnace to keep the distillation facility in operation. At a certain moment, the inlet temperature of the crude oil in the furnace has dropped to such an

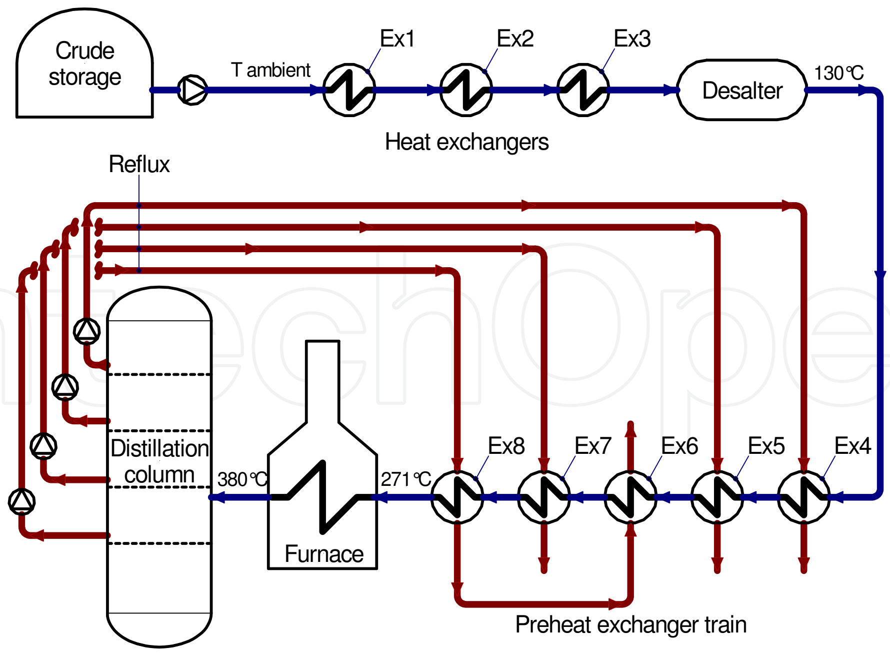

Fig. 1. Simplified flow diagram of a crude oil preheat train.

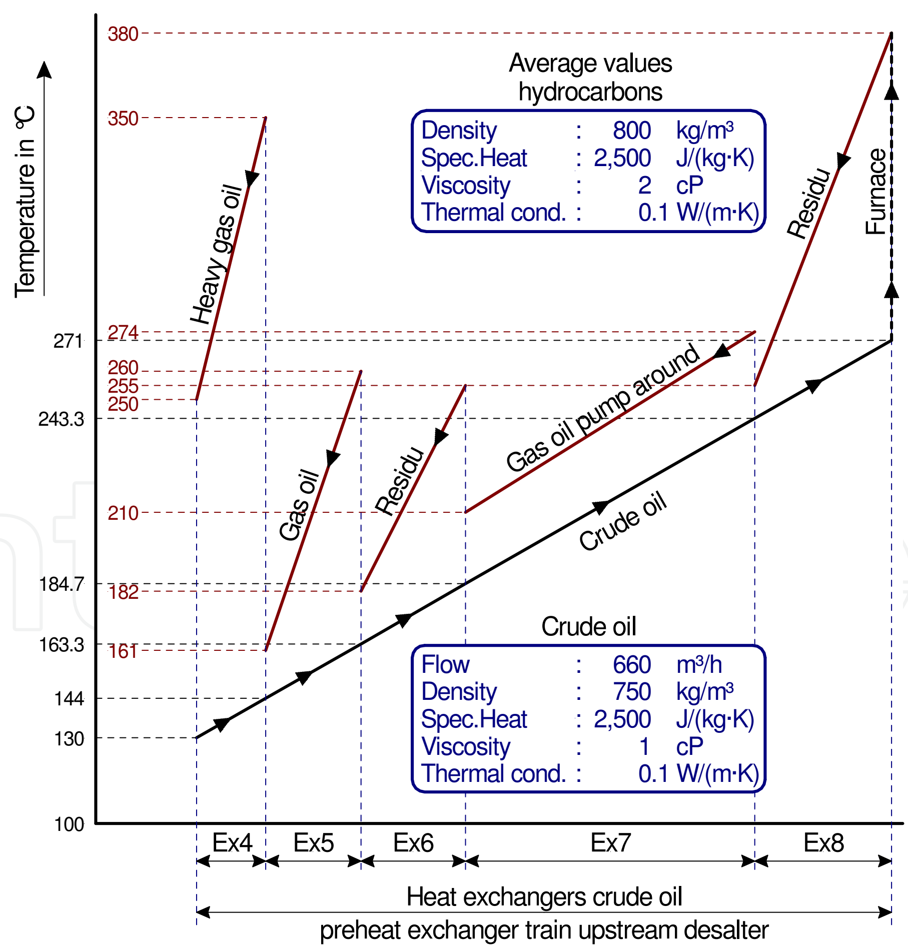

Fig. 2. Temperature diagram crude oil preheaters in simplified flow diagram shown in Fig. 1.

extent that the heating capacity of the furnace is insufficient to meet the required outlet temperature of the crude oil. This temperature can only be maintained by reducing the throughput of crude oil through the heat exchanger train, which, however, also reduces the production capacity of the refinery. This example shows very clearly that fouling of heat exchangers does cost extra energy and may also reduce the production capacity of an installation. For our crude oil preheat train, both facts, including the maintenance cost, increases the refining cost for each barrel of crude oil. What are these costs on a global scale?

At this moment (2011), the global production of crude oil amounts to approx. 85 million barrels per day (bpd). Table 1 has been derived from information given in Ref. [5], and gives an impression about the annual fouling cost for the crude oil being processed in the crude oil preheater trains of all refineries in the world as a function of the price per barrel crude oil.

	Crude oil price in US$ per barrel			
	$ 45	$ 60	$ 75	$ 90
Fouling costs in billion US dollars	10.9	12.5	14.1	15.7

Table 1. Fouling costs crude oil trains as a function of crude oil price.

It is assumed that for a crude oil price of US$ 60 / barrel, the total fouling cost in crude oil preheat trains processing the global crude oil production of 85 million bpd represents approx. 10 % of the worldwide fouling costs in heat exchangers, which costs include all kind of heat exchangers for both liquids and gases. From this statement and the numbers presented in Table 1, it can be concluded that the total cost the world has to pay annually for fouling of heat exchangers amounts to approx. US$ 125 billion. In Ref. [1], Garrett-Price used a different approach and concluded that the fouling of heat exchangers do cost an industrialised nation approx. 0.3 % of its Gross National Product (GNP). If we apply this rule to the GNP of the whole world (2007) of US$ 55 000 billion, then we find for the global fouling cost US$ 165 billion. This is higher than US$ 125 billion, but, very likely, because not all countries can be considered as sufficiently industrialised.

It is evident that the often excessive costs of heat exchanger fouling have led to a number of initiatives to develop some additional alternative solutions, often derived from research into the various fouling mechanisms. Over a period of forty years, the principal author Dr. Ir. Dick G. Klaren has participated in the development of one of the more promising alternatives: The self-cleaning or non-fouling fluidised bed heat exchanger. During this period the concept was taken from a laboratory tool to a fully developed heat transfer tool, which is now used to resolve severe fouling problems in a range of applications throughout the process industries.

3. Principle of the self-cleaning fluidised bed heat exchanger

Over the past 40 years, the principle of the fluidised bed heat exchange technology evolved from a type that applied a stationary fluidised bed into a more widely applicable concept that uses a circulating fluidised bed. This section pays attention to both principles of which the circulating concept is more widely applicable in comparison with the stationary type.

In principle such a stationary fluidised bed heat exchanger consists of a large number of parallel vertical tubes, in which small solid particles are kept in a stationary fluidised condition by the liquid passing up the tubes. The solid particles regularly break through the boundary layer of the liquid in the tubes, so that good heat transfer is achieved in spite of comparatively low liquid velocities in the tubes. Further, the solid particles have a slightly abrasive effect on the tube wall of the exchanger tubes, removing any deposit at an early stage.

Fig. 3 shows a heat exchanger with a stationary fluidised bed, which means there is no change in position of the particles as a function of time. The inlet channel contains a fluidised bed and a flow distribution system which is of utmost importance to achieve stable operation of all parallel exchanger tubes, or said otherwise: Equal distribution of liquid and solid particles over all the tubes. This exchanger is characterised by the use of glass beads with diameters of 2 to 3 mm and very low liquid velocities in the tubes. The glass beads are fluidised along the tubes and form a shallow fluidised bed layer in the outlet channel. This exchanger is only suitable for operation on constant flow.

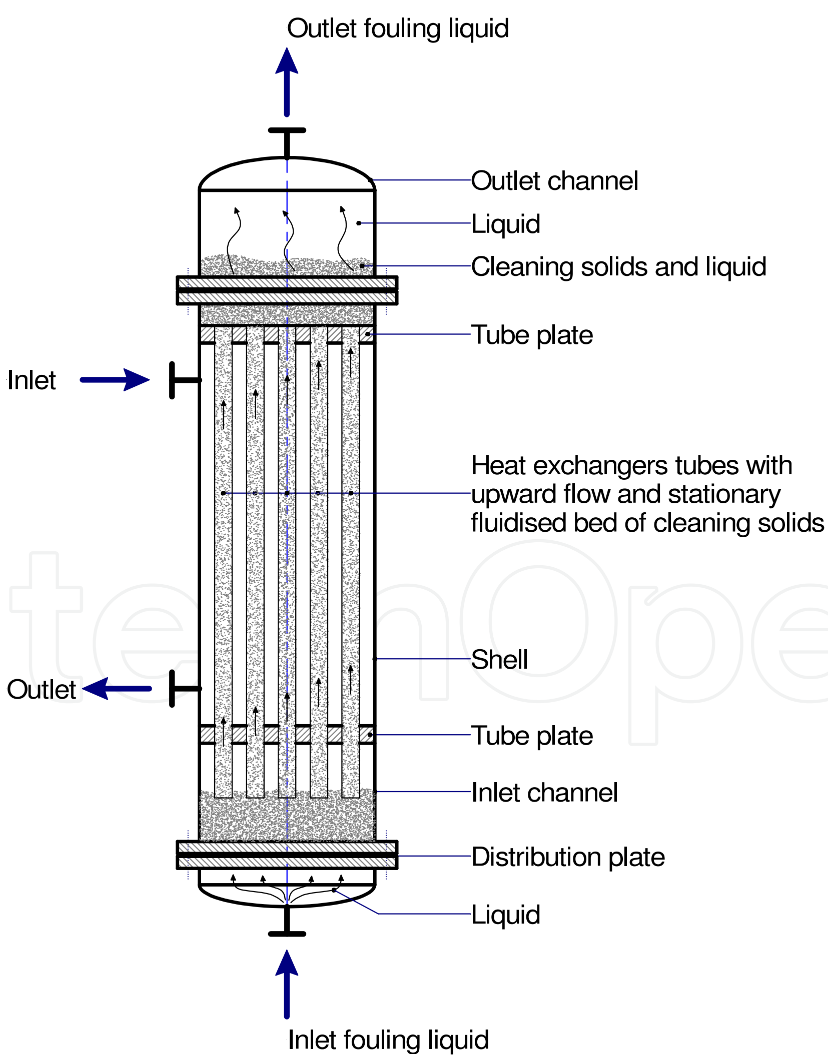

Fig. 3. Self-cleaning heat exchanger with stationary fluidised bed of cleaning solids.

Fig. 4 shows a heat exchanger with an 'internally circulating' fluidised bed. In this heat exchanger the liquid and particles flow through the tubes from the inlet channel into the widened outlet channel, where the particles disengage from the liquid and are returned to the inlet channel through multiple downcomer tubes, which are uniformly distributed over the actual heat exchanger or riser tubes. Now, the particles in the tubes experience a change of position with time. This heat exchanger can also use higher density materials like chopped metal wire as particles with dimensions up to 4 mm, and normally operates on higher liquid velocities in the tubes than the exchanger with the stationary fluidised bed. Depending on the design, this exchanger can also operate on a varying flow and in case of chopped metal wire particles; this exchanger represents the ultimate tool for handling the most severe fouling problems in liquid heat transfer.

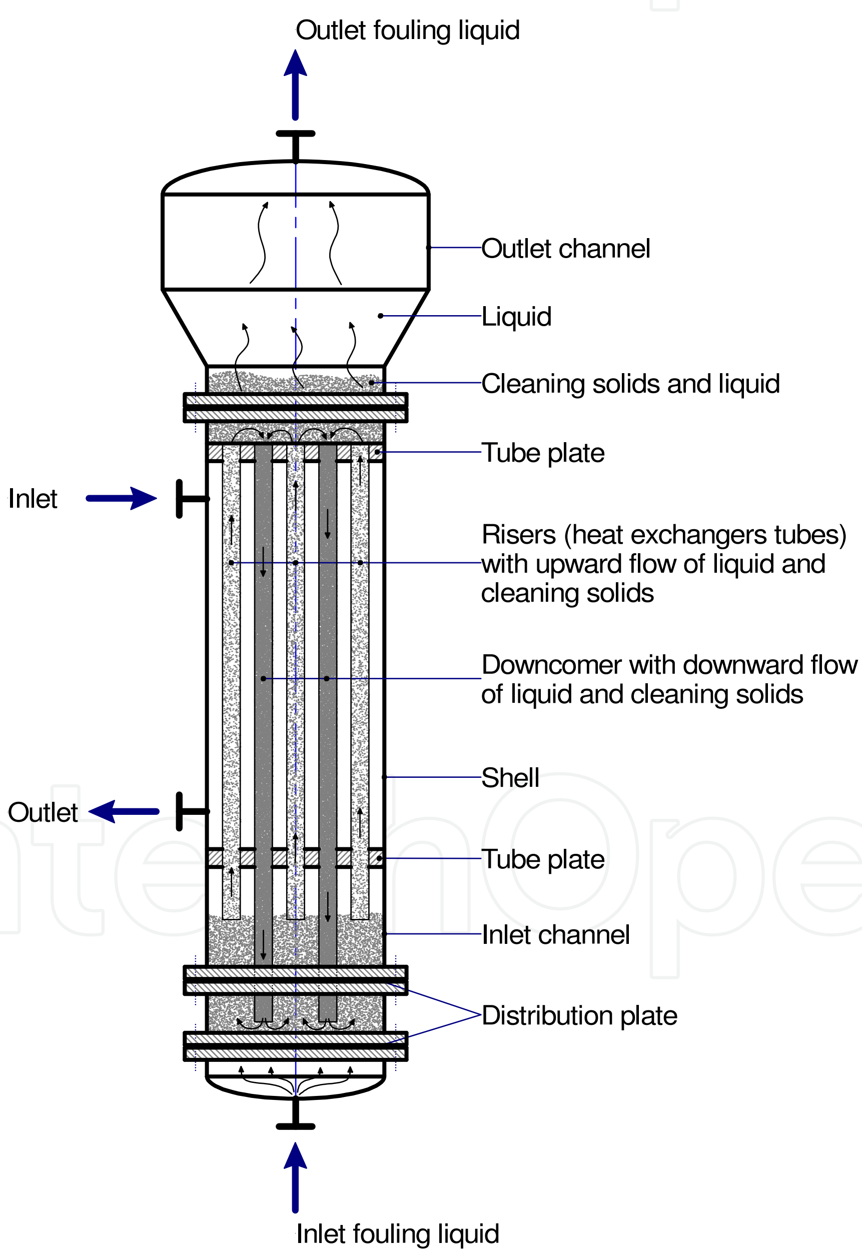

Fig. 4. Self-cleaning heat exchanger with internal circulation of cleaning solids.

The heat exchanger shown in Fig. 5 applies an 'externally circulating' fluidised bed. In this heat exchanger the liquid en particles flow from the outlet channel into an external separator where the particles are separated from the liquid, where after the particles flow from the separator into the inlet channel through only one downcomer and control channel For hydraulic stability reasons, this heat exchanger has the advantage that it only uses one downcomer, and the flow through this external and accessible downcomer can be monitored, influenced and varied by the control flow through line 1B. This flow only represents approximately 5 % of the feed flow through line 1 and shutting off this flow makes it possible to use the particles intermittently. This configuration also makes it possible to revamp existing severely fouling vertical conventional heat exchangers into a self-cleaning configuration as will be presented later in this chapter; this is a major advantage in comparison with the configuration shown in Fig. 4.

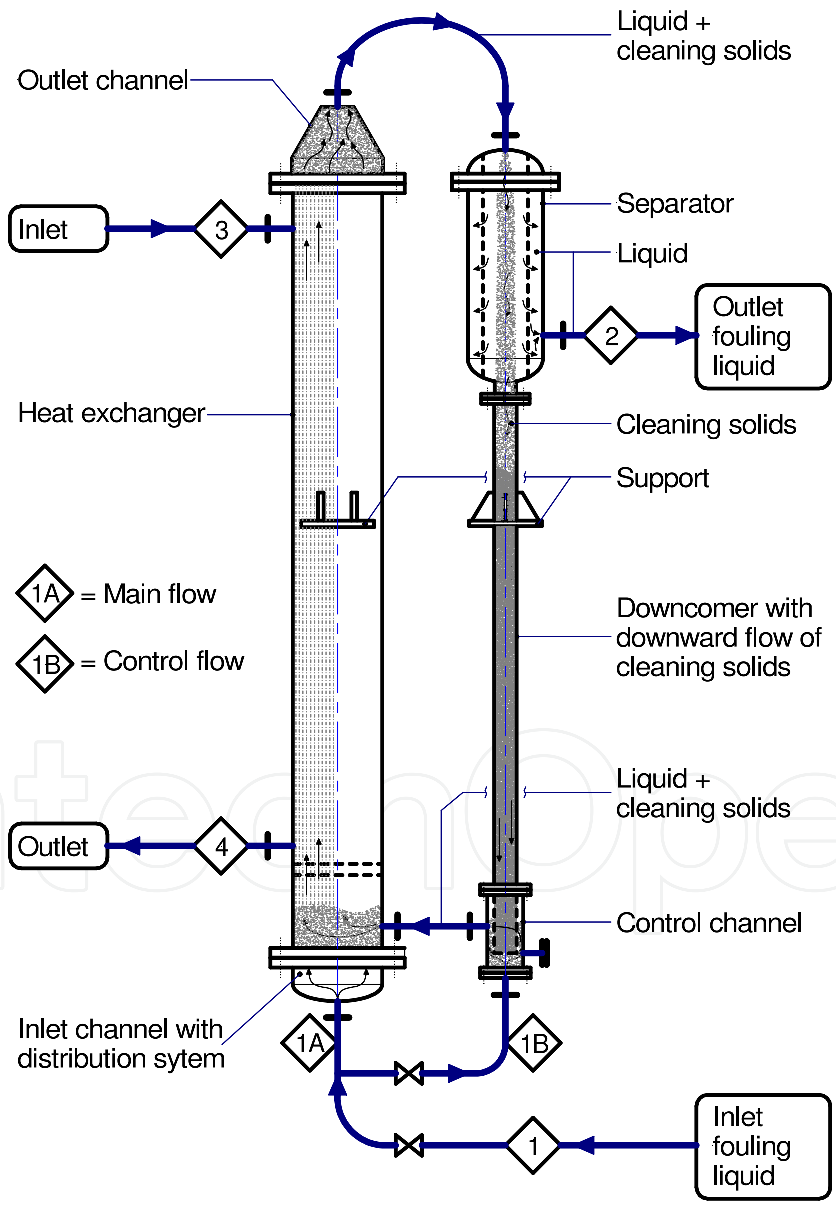

Fig. 5. Self-cleaning heat exchanger with external circulation of cleaning solids.

4. Performance of the self-cleaning fluidised bed heat exchanger

The performance of a self-cleaning fluidised bed heat exchanger and its design consequences have to be divided in the following subjects:

- Heat transfer correlation.
- Design consequences.
- Pumping power requirements.
- Fouling removal.
- Wear.

4.1 Heat transfer correlation

We briefly explain the composition of the tube-side heat transfer correlation for a heat exchanger which also applies recirculation of the particles and the liquid.

Fig. 6 shows the significant liquid velocities influencing the wall-to-liquid heat transfer coefficient for an exchanger with a circulating fluidised bed, such as:

U_s = superficial liquid velocity in the tubes relative to the tube wall,
$U_{b,w}$ = velocity of (moving) swarm of fluidised particles relative to the tube wall,
$U_{l,s}$ = superficial liquid velocity relative to the boundary limits of the (moving) swarm.

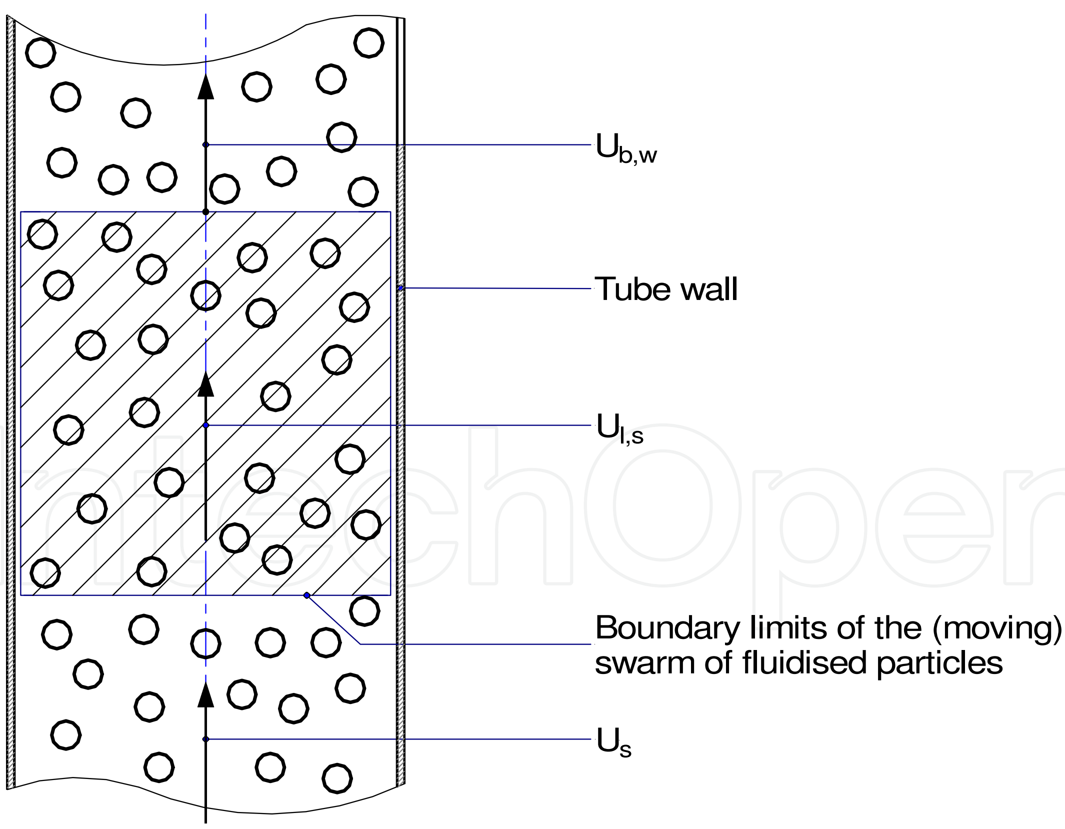

Fig. 6. Significant liquid velocities in tube of exchanger with circulating fluidised bed.

Where the superficial liquid velocity refers to the tube liquid velocity in the empty tube. From the explanation above, it follows:

$$U_s = U_{b,w} + U_{l,s} \tag{1}$$

For $U_{b,w} = 0$, the circulating fluidised bed satisfies the conditions of a stationary fluidised bed, which then yields:

$$U_s = U_{l,s} \tag{2}$$

where $U_{l,s}$ follows from the theory presented by Richardson and Zaki, Ref. [10].

The heat transfer coefficient $\alpha_{w,l}$ between the wall and the liquid of a circulating fluidised bed exchanger, is composed as follows:

$$\alpha_{w,l} = \alpha_l + \alpha_c \tag{3}$$

where:

α_l = wall-to-liquid heat transfer coefficient of a stationary fluidised bed with a superficial velocity $U_{l,s}$ related to the porosity ε of the bed
α_c = wall-to-liquid heat transfer coefficient for forced convection in a tube, taking into account a liquid velocity $U_{b,w}$, which actually corresponds with the velocity of the (stationary) fluidised bed moving along the tube wall

For the heat transfer coefficient α_l one is referred to Ruckenstein, Ref. [11], as long as superficial liquid velocities are calculated from porosities (ε) lower than 0.9. For porosities in the range $0.9 < \varepsilon \leq 1.0$, the following equation is suggested:

$$\alpha_l = \alpha_l\big|_{\varepsilon = 1.0} + \frac{(1 - \varepsilon)}{(1 - 0.9)} \times \left\{ \alpha_l\big|_{\varepsilon = 0.9} - \alpha_l\big|_{\varepsilon = 1.0} \right\} \tag{4}$$

The heat transfer coefficient $\alpha_l|_{\varepsilon = 1.0}$ is calculated using the equation of Dittus and Boelter taking into account the liquid velocity in the tube which corresponds with the terminal falling velocity on one single particle in the tube, i.e. ε = 1.0, as the liquid velocity used in the Reynolds number.

The heat transfer coefficient α_c is also obtained using the equation of Dittus and Boelter with $U_{b,w}$ as the liquid velocity used in the Reynolds number.

Fig. 7 shows the wall-to-liquid heat transfer coefficients in an exchanger with a circulating fluidised bed as a function of the various process parameters using 2.0 mm glass particles. It should be noticed that in Fig. 7 the curve $U_s = U_{l,s}$ shows the relation between heat transfer coefficient and relevant parameters for the stationary fluidised bed bed.

It should be emphasised that this heat transfer correlation is only an attempt to produce some approximate numbers for the overall heat transfer coefficients for any preliminary design. The real numbers which should be used in the performance guarantee of the heat exchanger follow from experimental operation of a representative pilot plant. Such a pilot plant is anyhow necessary to demonstrate the non-fouling operation.

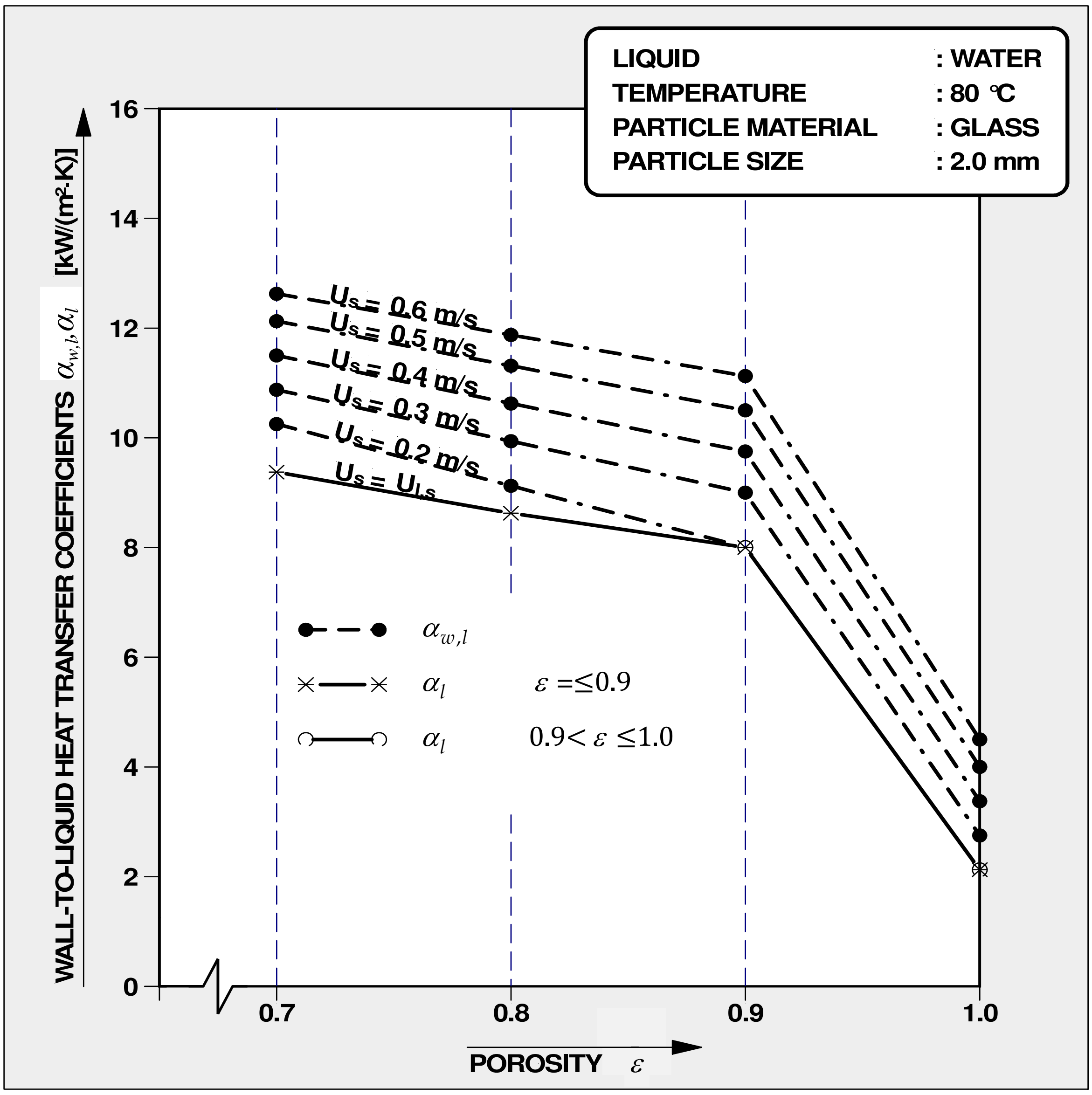

Fig. 7. Heat transfer coefficients in exchanger with circulating fluidised bed.

4.2 Design consequences

A fluidised bed exchanger offers the possibility to obtain heat transfer film coefficients at the tube-side of the same order of magnitude as normally achieved in conventional tubular exchangers, although at much lower liquid velocities. For example, a stationary fluidised bed heat exchanger using glass beads of only 2 mm with a porosity of the fluidised bed in the tubes of 75 % (i.e. the liquid volume fraction in the tube) can achieve heat transfer film coefficients of approx. 10 kW/(m² ·K) at a superficial velocity of approx. 0.12 m/s, which can only be realised in a conventional tubular heat exchanger with a liquid velocity of approx. 1.8 m/s.

The design consequences of this unique behaviour for a fluidised bed heat exchanger can be best explained with the help of the equation below for a heat exchange tube, which has been derived from the conservation equations for mass and energy:

$$L_t = D_o \times \left(\frac{D_i}{D_o}\right)^2 \times \frac{\rho_l \times c_l \times V_l}{4 \times k} \times \frac{\Delta T}{\Delta T_{\log}} \tag{5}$$

Where:

L_t	=	Tube length [m]
D_o	=	Outer diameter of the tube[m]
D_i	=	Inner diameter of the tube [m]
ρ_l	=	Density of the liquid [kg/m³]
c_l	=	Specific heat of the liquid [J/(kg·K)]
V_l	=	Superficial liquid velocity in the tube [m/s]
k	=	Overall heat transfer coefficient [W/(m²·K)]
ΔT	=	Temperature difference of the liquid between tube inlet and tube outlet [°C]
ΔT_{log}	=	Logarithmic mean temperature difference across tube [°C]

For a comparison of the tube length between different types of exchangers for the same duty and temperatures, Equation (5) can be simplified:

$$L_t = C_1 \times \frac{D_o \times V_l}{k} \tag{6}$$

Where C_1 is a constant for a particular installation / application.

Or in words: The length of the tubes L_t is directly proportional to the diameter of the tube D_o, the liquid velocity in the tubes V_l, but inversely proportional to the heat transfer coefficient k. It can be stated that the clean k-values for self-cleaning fluidised bed heat exchangers are always somewhat higher than for the conventional heat exchangers at their normally much higher liquid velocities, with the remark that the clean k-values for the self-cleaning fluidised bed heat exchangers correspond with the design values used for the full-size self-cleaning fluidised bed heat exchanger with no need for cleaning, while for the conventional heat exchangers due to fouling the design k-value may be 2, 3, 4 or even 5 times lower than the clean k-value and frequent cleanings may be still necessary.

What the design consequences of excellent heat transfer at very low liquid velocities do mean for a self-cleaning fluidised bed heat exchanger in comparison with a conventional heat exchanger for the same application can be best explained with the following striking example:

A conventional Multi-Stage Flash (MSF) evaporator for seawater desalination with a seawater velocity of 1.8 m/s in the condenser tubes of 19.05 × 1.21 mm and an average heat transfer coefficient of 2500 W/(m²·K) required a total length of the condenser tubes of 173 m. Depending on the design of this seawater evaporator, this tube length requires the installation of 8 evaporator vessels in series, each vessel with a length of 20 m or even more.

The same MSF desalination plant equipped with stationary fluidised bed heat exchangers required a seawater velocity in the tubes of only 0.125 m/s to maintain a fluidised bed in all parallel operating tubes with a porosity of 75 % using glass particles with a density of

2 750 kg/m³ and a diameter of 2 mm. In spite of this low seawater velocity, an overall heat transfer coefficient of 2 500 W/(m²·K) was achieved. From the equations above, it can be concluded that this desalination plant required only $0.125 / 1.8 \times 173 = 12$ m condenser tube length in series, which can be installed in only one vessel with an overall height of less than 15 m.

4.3 Pumping power requirements

Pumping power is influenced by the pressure drop across the heat exchanger and the pressure drop to support a stationary fluidised bed, which is determined by the following equation:

$$\Delta P_t = L_t \times (\rho_s - \rho_l) \times (1 - \varepsilon_t) \times g \tag{7}$$

Where:

ΔP_t	=	pressure drop across the tube due to bed weight	[N/m²]
L_t	=	tube height	[m]
ρ_s	=	density of the material of the solid particles	[kg/m³]
ρ_l	=	density of the liquid	[kg/m³]
ε_t	=	liquid volume fraction in tube or porosity	[-]
g	=	earth gravity	[m/s²]

For the MSF desalination plant with stationary fluidised bed condensers specified above, the pressure drop to support the bed weight amounts to 47 000 N/m². On top of this pressure drop we have to add a pressure drop caused by the flow distribution system of 4 000 N/m² for stabilisation of the flow through all tubes. Pressure drop due to wall friction has not to be taken into account because of the very low liquid velocities in the tubes of only 0.125 m/s. However, for this particular application, we have to add the lifting height for the liquid which requires an additional pressure drop of 120 000 N/m² resulting in a total pressure drop of 47 000 + 4 000 + 120 000 = 171 000 N/m².

For the conventional MSF desalination plant we calculate a pressure drop of approx. 400 000 N/m² required by the wall friction in these very long condenser tubes with much higher liquid velocities, and when we take into account the losses in water boxes we end up with a total pressure drop of approx. 450 000 N/m².

It should be emphasised that for this particular application the pressure drop influencing the heat transfer coefficient and required by the condenser bundle installed in the conventional MSF is a factor 400 000 / 51 000 = 7.9 (!!) higher than this pressure drop for the MSF equipped with stationary fluidised bed condensers. These differences in pressure drop directly influence the pumping power requirements for both installations. In general, when also considering ‘circulating’ fluidised bed heat exchangers operating at somewhat higher liquid velocities and using higher density solid particles, the differences in pumping power requirements will not be that much as presented above, although, for all applications, the differences in pumping power remain easily a factor 2 to 3 times lower for the fluidised bed heat exchanger compared to the conventional shell and tube heat exchanger.

4.4 Fouling removal

Fouling of heat exchangers is experienced by a gradual and steady reduction in the value of the overall heat transfer coefficient. A closer look into this phenomenon shows that there are always two causes:

1. Fouling of the actual heat transfer surface by the forming of an insulating layer of deposits, which reduces the heat transfer through the tube wall.
2. Clogging of flow distribution system in the inlet channel and / or the inlets of the heat exchanger tubes by large pieces of dirt or deposits broken loose from the wall of vessel and piping upstream the exchanger and present in the feed flow of the exchanger. Clogging of tubes removes heat exchanger tubes from participation in the actual process of heat transfer.

The first cause can be solved by the mild scouring action of the fluidised solid particles in the tubes. The second cause, at least of the same importance as the first cause but often neglected, can only be solved by the installation of a strainer upstream the self-cleaning fluidised bed heat exchanger. To minimise the cost for such a strainer and the ground area for the heat exchanger and its accessories, we have developed a proprietary self-cleaning strainer which forms an integral part with the inlet channel of the exchanger.

Now, let us pay attention to some of our fouling removal experiences in a fluidised bed heat exchanger and, therefore, we once more should pay attention to our MSF seawater evaporators:

It is known that natural seawater cannot be heated to temperatures above 40 to 50 °C because of the formation of calcium carbonate scale. Conventional MSF evaporators often operate at maximum seawater temperatures of 100 °C, but only after chemical treatment of the seawater feed which removes the bicarbonates from the seawater and prevents the forming of scale. Of course, this is a complication in the process and does cost money. The MSF evaporator equipped with the stationary fluidised bed condensers, using 2 mm glass beads, has convincingly demonstrated that it can operate at even much higher temperatures than 100 °C without scale forming on the tube walls. Although, the scale crystals are precipitating from the seawater on the tube walls these crystals are knocked off by the glass beads at an early stage, so that it never comes to the formation of an insulating scale layer and the tube walls remain clean and shiny. Here we have clearly demonstrated the fouling removal, self-cleaning or non-fouling behaviour of a fluidised bed heat exchanger operating under harsh conditions as the result of the scouring action of the fluidised particles. No doubt that this feature is of extreme importance for heat exchangers operating on severely fouling liquids.

Meanwhile, with many self-cleaning fluidised bed heat exchangers already installed in different industries, commercial operating experiences have shown that the self-cleaning fluidised bed heat exchanger, which can remain clean indefinitely, is a cost-effective alternative to the conventional heat exchanger which suffers from severe fouling in a couple of hours, days or weeks and even months. Any type of fouling deposit, whether hard or soft; biological or chemical; fibrous, protein, or other organic types; or a combination of the above can be handled by the self-cleaning fluidised bed heat exchanger. Moreover, later in this chapter it will be shown that the unique characteristics of this heat exchange technology allow for the introduction of major design changes of installations in traditional processes and, therefore, the advantages of this heat exchange technology does reach much further than solving heat exchanger fouling problems only.

4.5 Wear

Now we have been informed about the remarkable effects of scouring particles on the heat transfer film coefficients at very low liquid velocities, low pumping power requirements and their potential to remove fouling, one might wonder what the consequences are of the scouring action of the particles with respect to wear and / or material loss of the heat exchanger tubes and the particles. After many years operating experiences we have come to the conclusion that only in case of the formation of a weak corrosion layer on tube and / or particle material, the scouring action of the particles may cause material loss due to the removal of this corrosion layer. For applications where corrosion of metal surfaces does not play a role, we present the following examples:

In a US plant, after one year of operation, the cleaning particles made of chopped stainless steel wire lost 2.5 % of weight. This is caused by the rounding-off effects of the sharp edged cylindrical particles. In the second year, being substantially rounded-off already during the first year of operation, the weight loss of the particles dropped to less than 0.5 %. Because the smooth stainless steel tube wall is not subjected to metal loss as a result of rounding-off effects, the material loss of the tubes should be much less than 0.5 % per year.

Similar experiences have been obtained in Japan with stainless steel tubes and particles. Again, after one year of operation a weight loss of approx. 2 % was measured. In the second year, this weight loss was negligible. Fig. 8 shows the rounding-off effects of chopped stainless steel wire as a function of operating time. The loss of approx. 2 % in the first year of operation as mentioned above can also be avoided by using particles which have already been rounded-off mechanically directly after their fabrication (chopping) process.

5. New installations equipped with self-cleaning fluidised bed heat exchangers

5.1 Multi-Stage Flash / Fluidised Bed Evaporator (MSF / FBE); most promising tool for thermal seawater desalination

As the development of this heat exchanger began in the early 70s with the application of stationary fluidised bed condensers in MSF evaporators, we like to begin this paragraph with what we may consider 'the origin of the fluidised bed heat exchange technology' as developed for seawater desalination, and referred to as Multi-Stage Flash / Fluidised Bed Evaporator or MSF / FBE. In the example below, we compare this evaporator with a conventional MSF. This comparison shows that the advantages of the self-cleaning fluidised bed heat exchange technology for the MSF are responsible for a much wider range of improvements than non-fouling heat exchange only.

A picture of the conventional MSF and its corresponding temperature diagram is shown in Fig. 9. The principle of this MSF can be best described as a large counter-current heat exchanger, where the cold feed is heated by the condensing vapour in the heat recovery section and the external heat supply takes place in the final heater. After leaving the final heat exchanger at its highest temperature, the liquid flashes through all stages, by way of

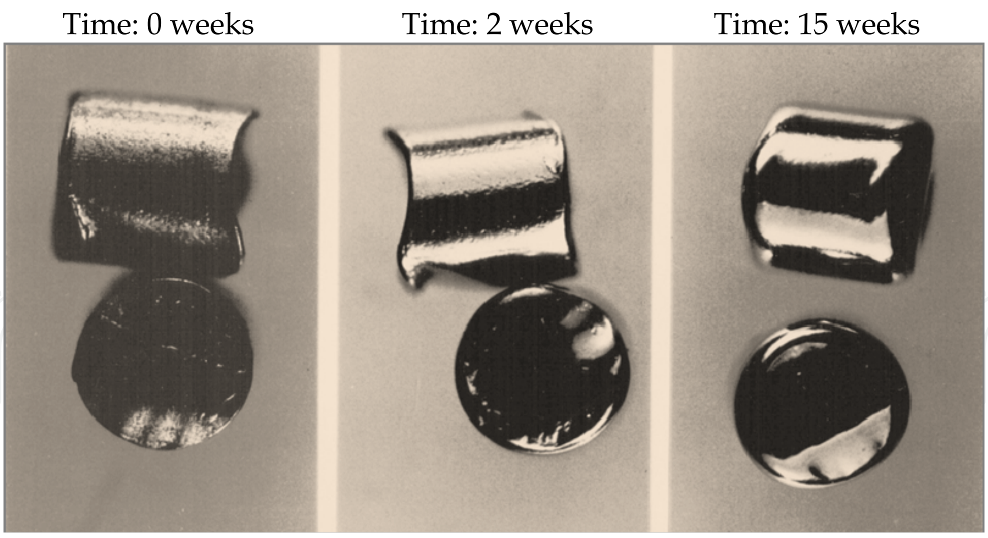

Fig. 8. Rounding-off effects of 2 mm stainless steel particles as a function of operating period.

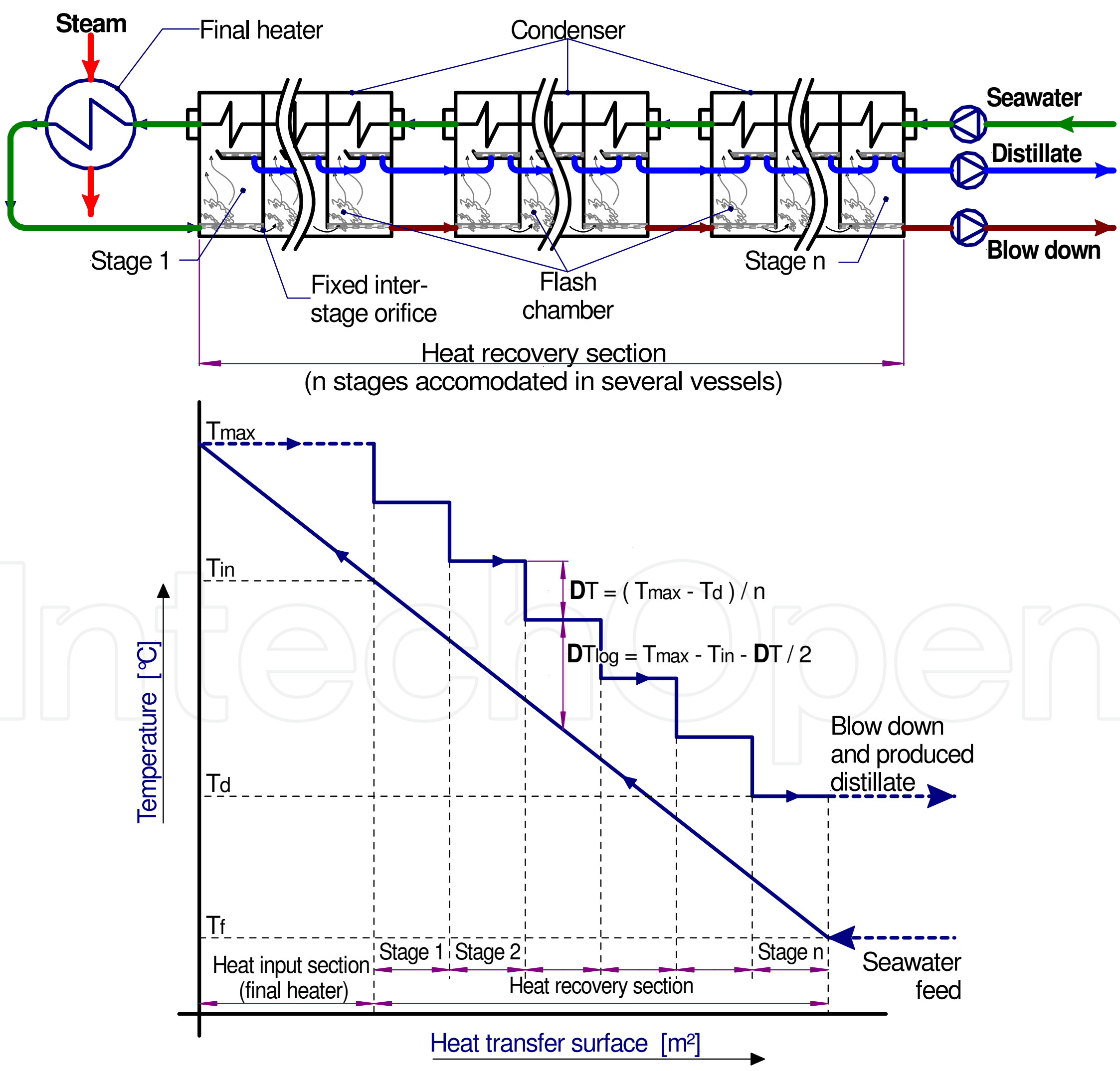

Fig. 9. Principle of conventional MSF and its temperature diagram.

openings in the bottom or intersection walls of the stages, and a gradual drop in saturation temperature takes place resulting in a partial evaporation of the liquid in each flash chamber. The flash vapour flows through the water-steam separators and finally condenses on the condenser surfaces, which are cooled by the colder incoming feed. The distillate is collected at the bottom of each stage and cascades down in the same way as the liquid in the flash chambers to the next stage. The plant has to be completed with pumps for the removal of the concentrated liquid or brine and distillate out of the coldest stage and for the feed supply. Dissolved gases and in-leaking non-condensables are removed from the feed by a vacuum line connected to a vacuum pump. The installation of the great length of horizontal condenser tubes in a conventional MSF requires the installation of several vessels in series.

The principle of the MSF / FBE is not much different from a conventional MSF, although, we have already shown that the total length of the vertical condenser tubes passing through all stages can be much shorter for an MSF / FBE than for a conventional MSF. This makes it possible to install all condenser tubes and flash chambers in only one vessel of limited height as is shown in Fig. 10.

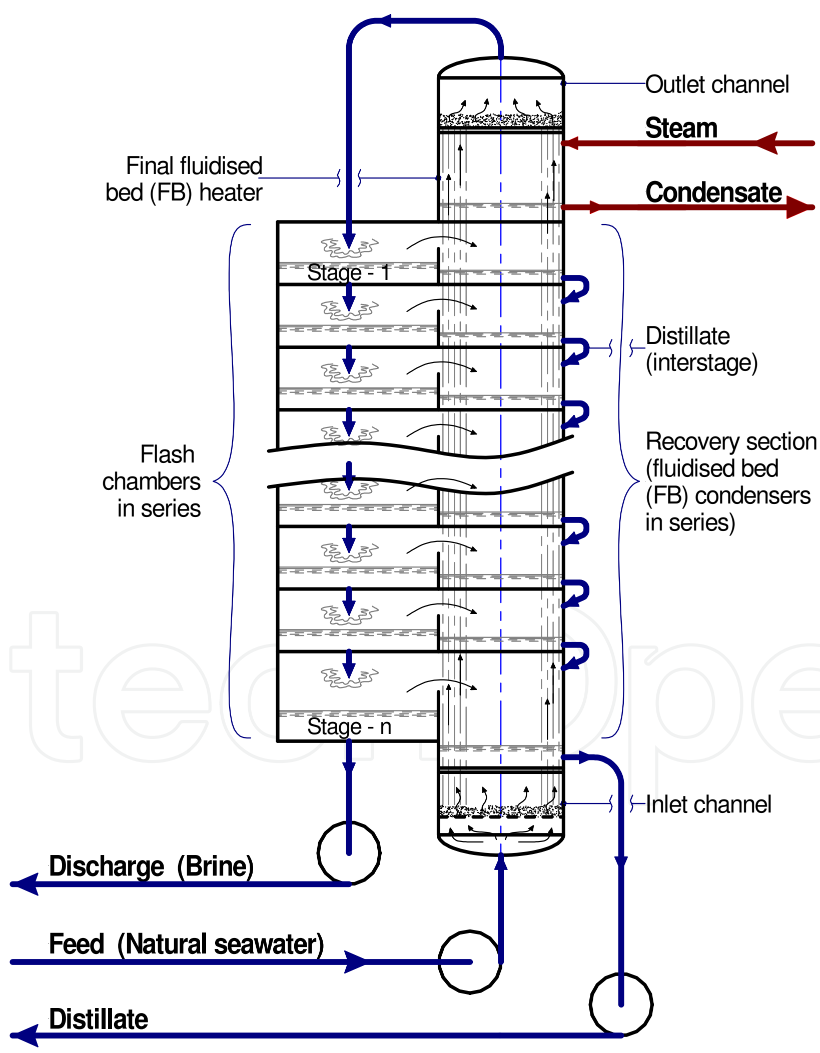

Fig. 10. Principle MSF / FBE.

As the result of the vertical layout of the MSF / FBE and the flashing down flow in the flash chambers with a height for each chamber of approx. 0.4 m, we are able to add a number of interesting improvements to the MSF / FBE in comparison with the conventional MSF, such as:

- It has already been mentioned that not only excellent heat transfer can be achieved at very low liquid velocities and very low pressure drop, but that the scouring action of the glass beads also remove scale deposits at an early stage. This makes it possible to operate the MSF / FBE at much higher maximum temperatures of the heated seawater than the conventional MSF without the need of chemicals to prevent scale. A higher maximum temperature increases the recovery of distillate from a particular seawater feed and makes it possible to design evaporators for a higher gain-ratio or lower specific heat consumption.
- *The vertical layout of the MSF/FBE* makes it possible to achieve a complete flash-off of the spraying brine flow in the flash chambers, which means that the evaporating liquid and produced vapours are in equilibrium with each other. Further, we do not need wire mesh demister for the separation of droplets from the vapour flowing into the condenser which reduces the pressure drop of the vapour flow on its way to the condenser. These advantages reduce the irreversible temperature losses in the heat transfer process, which makes it possible to save on heat transfer surface and / or reduce the specific heat consumption of the evaporator.
- *The vertical layout of the MSF/FBE* with a relatively short stage height, its high vapour space loadings, low brine levels in the flash chambers and no need for the installation of voluminous wire mesh demisters makes the flash chambers very compact, which reduces the plot area and the overall dimensions of the evaporator, and, consequently, its steel weight.
- *The vertical layout of the MSF/FBE* assures sufficient driving force for the interstage brine flow caused by the height of the brine level in the flash chambers only. Consequently, not much vapour pressure difference between stages is required to assure the interstage brine flow, which means that a large number of stages can be installed in a given flash range $\Delta T = T_{max} - T_d$ shown in Fig. 9, which again makes it possible to reduce the specific heat consumption of the evaporator.
- *The vertical layout of the MSF/FBE* makes it possible to install interstage valves between all stages using only one activator. This valve system guarantees low brine levels in all stages at varying maximum temperatures or flash range of the evaporator. A varying maximum temperature or flash range makes it possible to vary the distillate production between 0 and 100 %, while still maintaining an excellent distillate quality.

Above, we have clearly shown that *the vertical layout of the MSF/FBE*, as the result of the integration of the vertical stationary fluidised bed condenser with the flash chambers, increases the advantages of this evaporator too such an extent, that this evaporator may be considered as the most promising tool for thermal seawater desalination in the future. Fig. 11 shows an MSF / FBE demonstration plant operating on natural seawater for a distillate production of 500 m^3/d.

For more information about this fascinating evaporator, one is referred to the Ref. [8] and [9].

Fig. 11. MSF / FBE evaporator, Isle of Texel.

5.2 Reboiler at chemical plant; annual turnaround replaces cleaning every 4 to 5 days

A steam-heated evaporation system at a chemical plant in the Unites States recovers a volatile organic from a heavy organic solution laden with foulants. A hard black scale, that was forming in the upper 25 % of the tubes, was forcing the plant to switch two parallel once through rising film evaporators with a clean pair every four to five days.

When asked to increase throughput and simplify operations engineers considered installing a 190 m² falling film evaporator to operate in series with the existing rising film evaporators. Although the combination system was expected to run approximately 10 weeks between cleanings, a better solution was needed and found when engineers heard of an innovative self-cleaning fluidised bed heat exchanger technology being used at another chemical plant in the United States. The final decision in favour of the self-cleaning fluidised bed heat exchanger was made after the engineers viewed a 1 m tall, transparent desktop demonstration unit with six 12 mm up flow tubes and one 12 mm down flow (downcomer) tube.

The full-size exchanger with widened outlet channel shown in Fig. 12 at the right of the distillation column contains 73 m² of heat transfer surface. It applies internal circulation of 2.0 mm chopped stainless steel wire particles and uses 51 up flow and four down flow (downcomer) tubes according to the design shown in Fig. 4. The process liquid circulated at a constant flow of 160 m^3/h, is raised from about 120 to 150 °C with condensing steam at the shell-side. Back pressure is maintained on the process side of the exchanger to prevent vaporisation which would interfere with the fluidisation of the particles. Upon discharge from the exchanger, the heated liquid flashes across a control valve into the base of the recovery column.

Comments by the operators in September 1992 after the heat exchanger had been in service for over a year without any operating problems:

There have been no shutdowns for cleaning tubes and no process upsets, and maintenance has been nil. This is a significant cost cutting result from the higher recovery of acetic acid and the more concentrated residue in the bottoms. The self-cleaning fluidised bed heat exchanger appears capable for at least a full year between turnarounds. A sample of chopped metal wire particles taken from the unit after several months of operation indicated only normal rounding off of the edges. Under the new system, the reboiler circulation rate has been constant, thus providing uniform tower operation and more total throughput. If the alternative falling film evaporator had been installed, a shutdown would have been required every 10 weeks for a costly cleaning operation.

Today, July 2011, twenty years after the heat exchanger has been put in service and after 150 000 operating hours, the heat exchanger is still in operation using the same shiny tubes and to entire satisfaction of the operators. For more information, see Ref. [2].

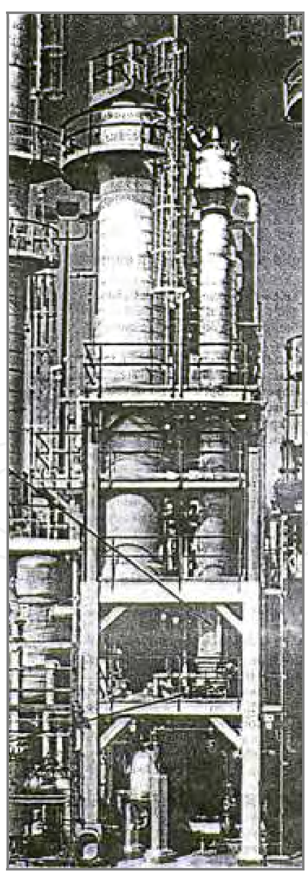

Fig. 12. Self-cleaning fluidised bed heat exchanger at chemical plant eliminates reboiler fouling.

5.3 Quench coolers at chemical plant; the real breakthrough of the self-cleaning fluidised bed heat exchange technology

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 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.

In August 1997, after considering other solutions using conventional shell and tube heat exchangers, plant management decided to carry out a test with a small self-cleaning fluidised bed heat exchanger and compared its performance with that of a conventional shell and tube heat exchanger, which suffered from a severe fouling deposit consisting of a tarry substance. Fig. 13 shows the results of this test, while Table 2 compares the design consequences for the self-cleaning heat exchangers and the conventional shell and tube exchangers. Plant management decided in favour of the self-cleaning fluidised bed heat exchange technology because of the above results and the dramatic savings on investment and operating cost.

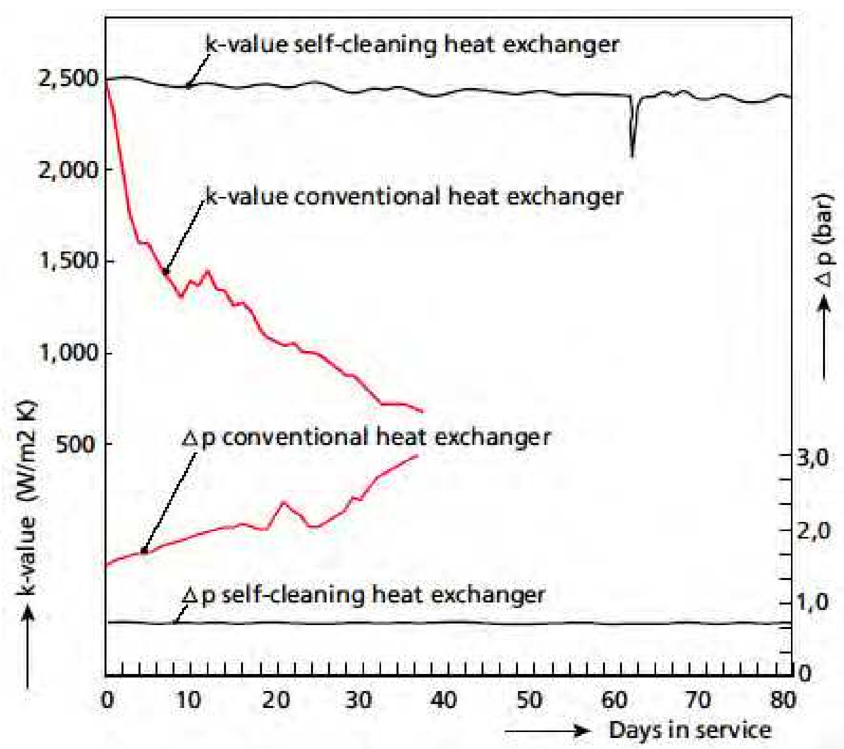

Fig. 13. Overall heat transfer coefficient (k-value) and pressure drop (Δp) as function of operating time.

	Unit	Conventional heat exchanger	Self-cleaning heat exchanger
Heat transfer surface	m^2	24 000	4 600
Total number of heat exchangers	-	24 × 1 000 m^2	4 × 1 150 m^2
Configuration	-	3 × 50 %	2 × 50 %
Pumping power	kW	2 100	840
Number of cleanings per year	-	12	0

Table 2. Comparison conventional heat exchanger versus self-cleaning fluidised bed heat exchanger.

Fig. 14. Installation of 4 600 m^2 self-cleaning surface replacing 24 000 m^2 conventional surface.

Fig. 14 shows the installation which serves two parallel production lines. In each production line two identical self-cleaning fluidised bed heat exchangers were installed handling 2 × 700 m^3/h process liquid at the tube-side and 2 × 2 100 m^3/h cooling water at the shell-side. Each exchanger applies external circulation of the particles as shown in Fig. 5, has a shell diameter of 1 200 mm, a total height of 20 m and a heat transfer surface of 1 150 m^2, which surface consists of 700 parallel tubes with an outer diameter of 31.75 mm. Each exchanger uses 9 000 kg cut metal wire particles with a diameter of 1.6 mm.

The exchangers serving the first production line were put into operation in October 1998. Fig. 15 presents the trend of the overall heat transfer coefficient (k-value) after start-up till the end of April 1999. In spite of some fluctuations at the beginning, this figure shows a constant k-value of approximately 2 000 W/(m^2·K). During a period of more than six months both exchangers operated continuously, with exception of a few short sops caused by interruptions in the power supply. The dotted line in Fig. 15 shows the trend of the k-

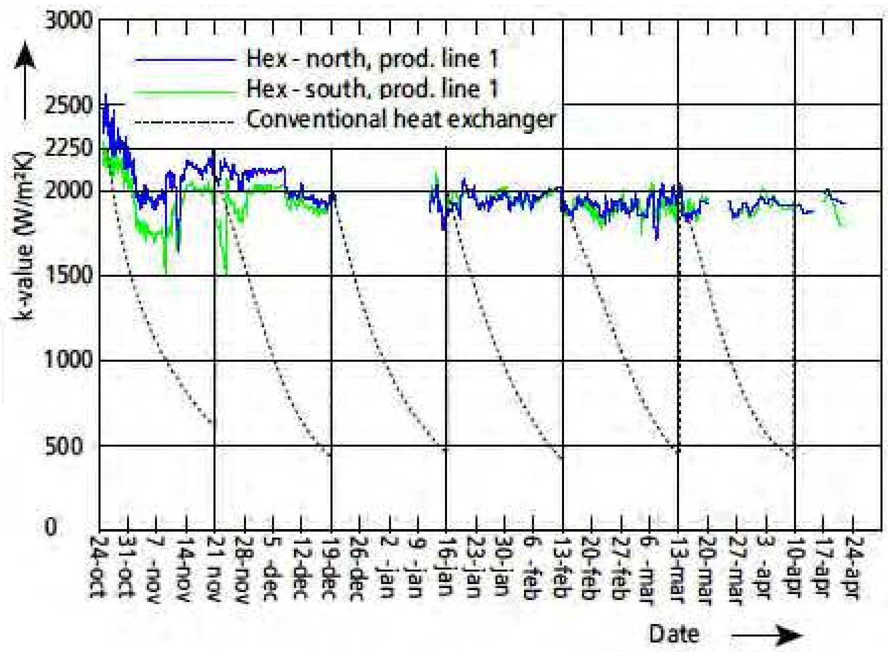

Fig. 15. k-values for self-cleaning heat exchangers of first production line, as a function of operating time and compared with the performance of conventional heat exchanger.

value for conventional shell and tube exchangers as derived from the test results shown in Fig. 13. The two exchangers of the second production line were put in operation in May 1999 and showed the same trend in k-value as the exchangers of the first production line. In December 2000, this chemical plant stopped production and the exchangers, after a final inspection, were mothballed and have never been put into operation again. This final inspection did not reveal any measurable wear of the tubes. All tubes were shiny and

	Unit	Conventional heat exchanger	Self-cleaning heat exchanger (1998)	Self-cleaning heat exchanger (2005)
Total heat transfer surface	m^2	24 000	4 600	3 332
Total number of heat exchangers	-	24 × 1 000 m^2	4 × 1 150 m^2	4 × 833 m^2
Configuration	-	3 × 50 %	2 × 50 %	2 × 50 %
Tube diameter / tube length	mm	25.4×1.65 / 12 000	31.75×1.65 / 16 000	15.88×1.21 / 8 700
Shell-side baffle type	-	segmented cross	segmented cross	EM
Total weight particles	kg	n.a.	36 000	20 000
Pumping power	kW	2 100	840	416
Number of cleanings per year	-	12	0	0

Table 3. Comparison conventional heat exchanger versus self-cleaning fluidised bed heat exchangers, state-of-the-art 1998 and 2005.

open. The cut metal wire particles showed a slight weight loss caused by rounding-off effects as discussed earlier. For more information about these fascinating heat exchange application, one is referred to Ref. [3].

In the first years of the new millennium, research and development concentrated on reducing the tube diameter of the self-cleaning fluidised bed heat exchangers in combination with rather large particles. A smaller tube diameter reduces the length of the heat exchanger tubes which creates a more compact heat exchanger with less height and, consequently, reduces the pumping power required for the process liquid. Then, we also paid attention to the installation of a novel type of baffle in the shell of the exchanger. This very innovative baffle is called the EM baffle and has been developed by Shell Global Solutions. The results of this redesign of the self-cleaning fluidised bed heat exchangers shown in Fig. 14 as far as heat transfer surface and pumping power are considered are presented in Table 3. For more information about this improved design, one is referred to Ref. [4].

6. Existing conventional severely fouling heat exchangers revamped into a self-cleaning fluidised bed configuration

The idea of changing internal circulation of particles as shown in Fig. 4 into the configuration where this circulation takes place through only one external downcomer shown in Fig. 5 was proposed by engineers of Shell in the early 90s. According to these engineers, this modification would make it possible to revamp existing vertical severely fouling conventionally designed reboilers into a self-cleaning configuration. Moreover, it would be an elegant and rather low cost but also a low risk approach to introduce a new technology due to the possibility of an immediate fallback from new technology to old proven technology. This idea is not only applicable for reboilers but also for evaporators and crystallisers and the constant circulating flow required by these unit operations corresponds with the preferred type of flow for the self-cleaning fluidised bed heat exchanger.

Moreover, also in this paragraph, it will be shown that this approach of introducing the self-cleaning heat exchange technology in existing plants could not only be an attractive solution for straight forward rather simple heat exchange applications suffering from severe fouling, but also for very complex industrial processes.

6.1 Reboiler

A typical example of a conventional reboiler that is suitable for revamping is shown in Fig. 16 with the revamped configuration shown in Fig. 17. Generally speaking, the requirements specified by plant management for the majority of revamps can be summarised as follows:

1. The same process conditions should be maintained as in the original installation, i.e. flow, temperatures and liquid velocity in the tubes.
2. The connections to the column should be maintained.
3. The installed pumps should be used and can be used because pumping power requirements are generally lower for the self-cleaning fluidised bed heat exchangers than for the conventional severe fouling shell and tube exchanger.

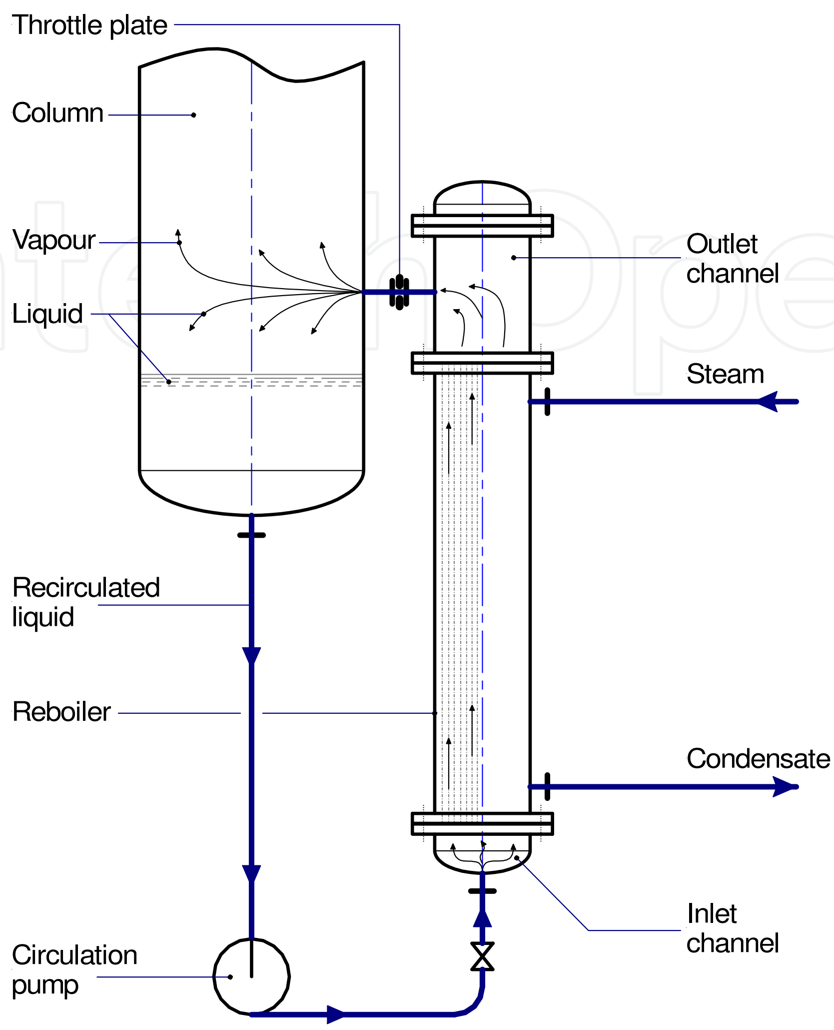

Fig. 16. Evaporator equipped with conventional heat exchanger.

4. As many components of the existing installation should be used in the revamped configuration like bundle, channels or maybe even modified channels.
5. The revamp must be carried out within the available space. This often means that a revamp can only be carried out when the existing installation has already a vertical position.

The advantages of most revamps are much lower maintenance cost, an increased production and 'smoother' operation.

6.2 Cooling crystallisation plant

A 2-stage cooling crystallisation plant in Egypt produces Sodium Sulphate. The chillers of both stages suffer from severe fouling caused by heavy deposits of crystals. Shutdown of the installation every 24 hours for melting out these deposits is common. The conventional cooling crystalliser is shown in Fig. 18, while Fig. 19 depicts this installation after its revamp into a self-cleaning configuration.

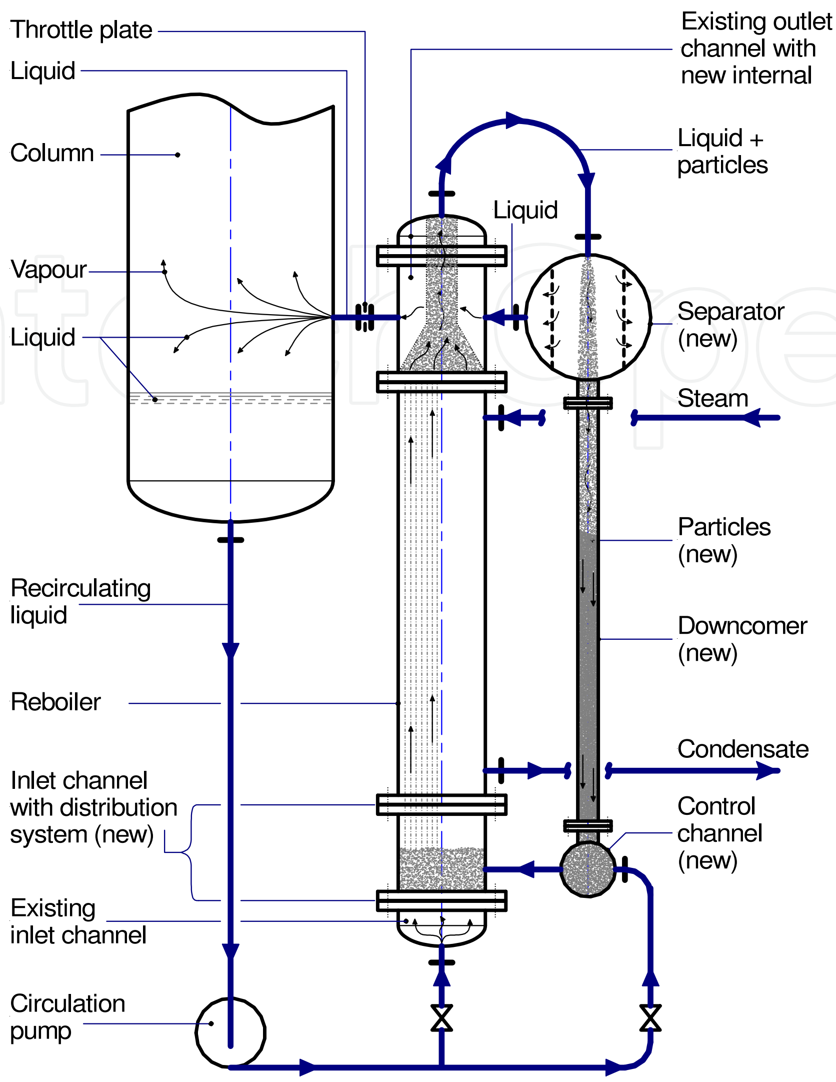

Fig. 17. Conventional evaporator revamped into a self-cleaning configuration.

Calculations have shown that the investments necessary for the modification of the existing installation into a self-cleaning configuration will be paid back by a substantially increased production in approximately six months.

Information about the reboiler, the cooling crystallisation plant and other applications discussed in this paragraph can be found in Ref. [7]

6.3 Evaporator for concentration of very viscous severely fouling slurry

In one of the Scandinavian countries, a production plant of a proprietary product operates a very large MVR evaporator for the concentration of a slurry up to approx. 70 % solids. Even at a temperature of 100 °C this slurry, which behaves non-Newtonian, has a very high viscosity varying between 50 and more than 200 cP. This very large shell and tube heat exchanger suffers from severe fouling which sometimes requires one month (!!) of mechanical cleaning after only three months (!!) of operation. In Fig. 20, the test plant in parallel with the existing evaporator is shown and the dimensions of the existing installation

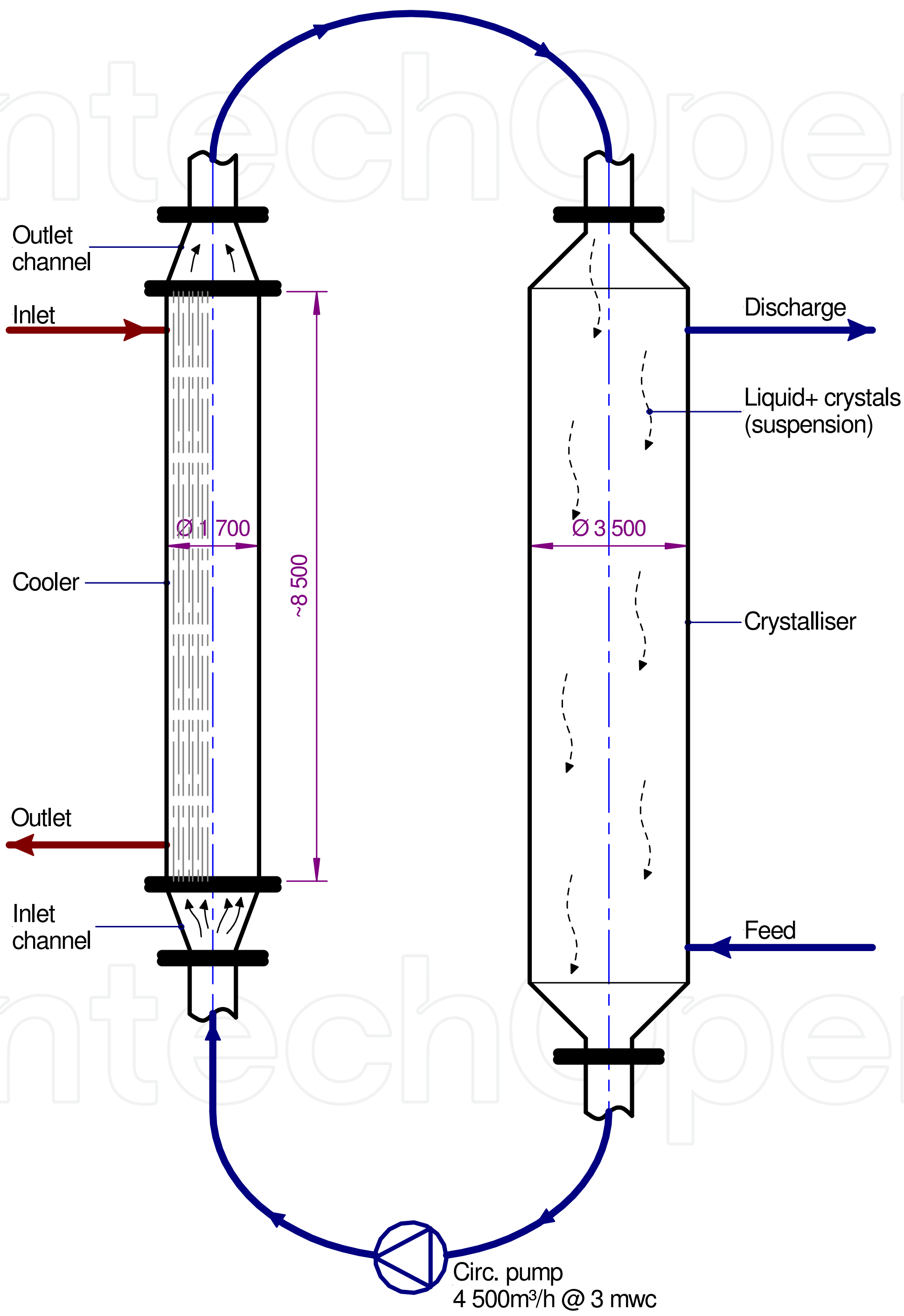

Fig. 18. Conventional cooling crystalliser.

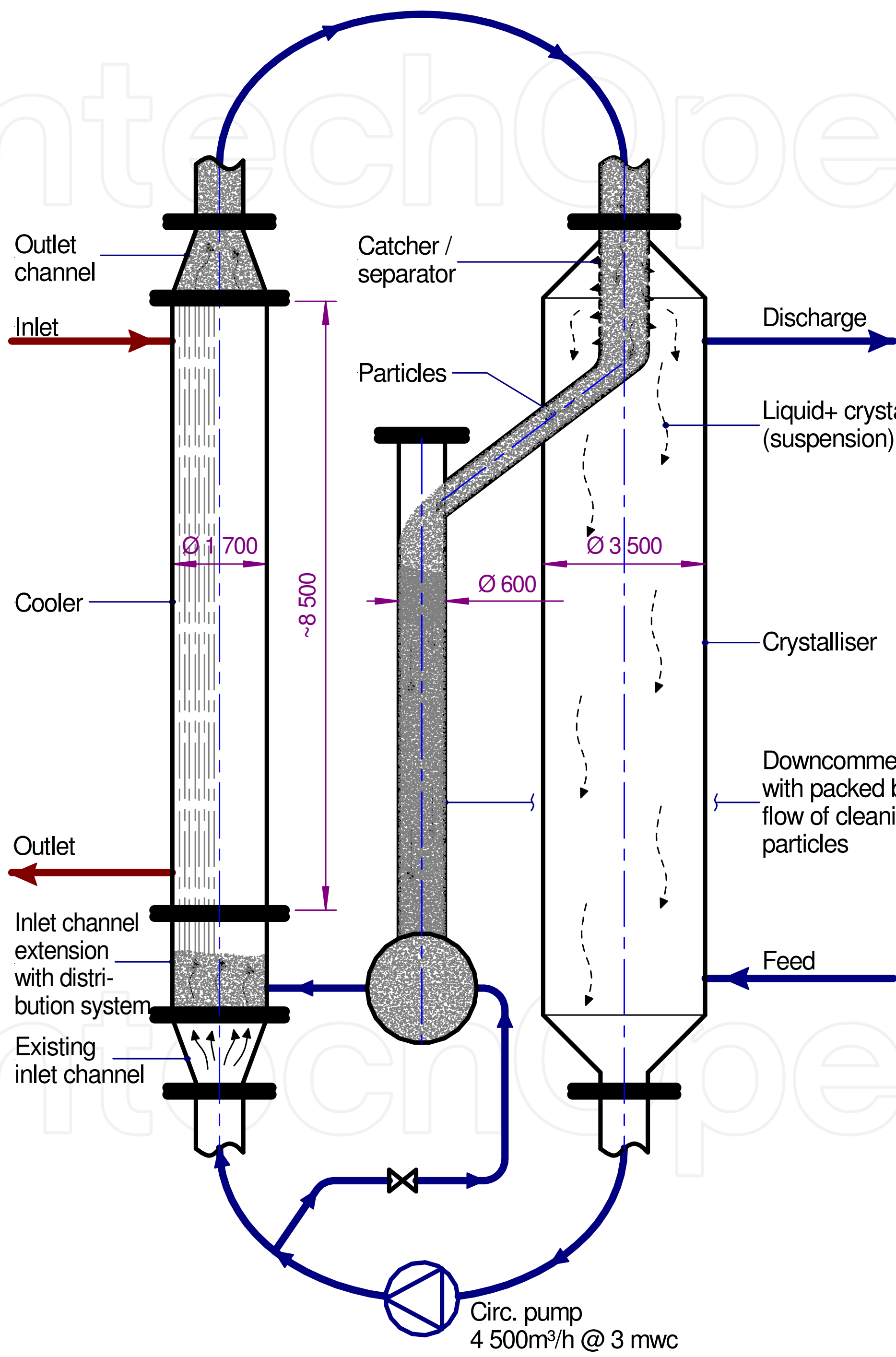

Fig. 19. Revamped into self-cleaning configuration of Fig. 18.

give a good impression about its size, although provided with relatively small diameter tubes with an ID of only 20 mm.

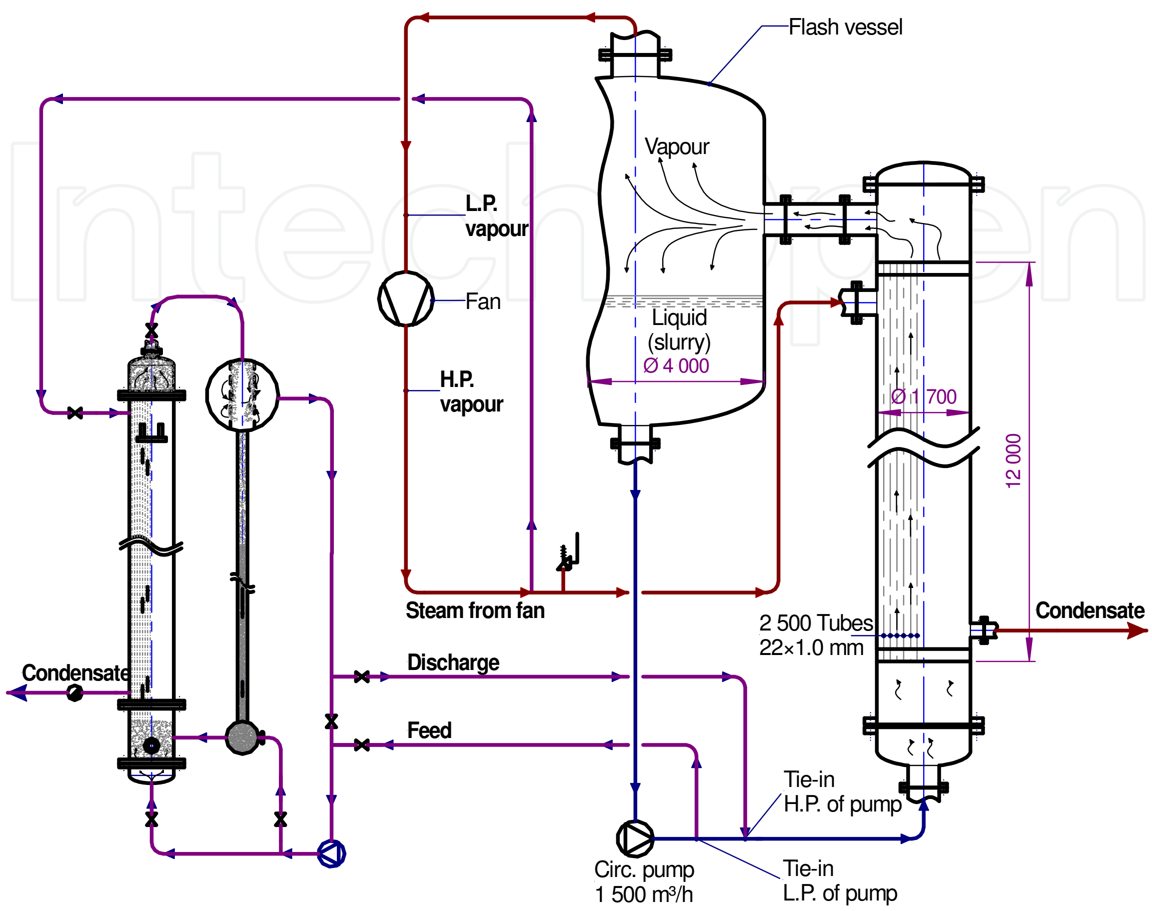

Fig. 20. Existing evaporator and test installation.

The proposal for the revamp of this installation is shown in Fig. 21 and uses a maximum of the very large existing components, including the circulation pump. The first series of experiments with the test installation are promising and shear-thinning effects caused by the increased turbulence of the slurry induced by the action of the fluidised particles are reducing the viscosity of the slurry substantially and have produced heat transfer coefficients or k-values between 1 000 and 2 000 W/(m^2·K) depending on the concentration of the slurry without fouling. These coefficients should be compared with the clean heat transfer coefficients of approximately 600 W/(m^2·K) for the conventional heat exchanger which, in a couple of months, reduces to only a fraction of its clean value due to by fouling.

This potential revamp reflects the benefits of recent developments which make it possible to operate a self-cleaning fluidised bed heat exchanger on a very viscous slurry and use rather large stainless steel particles (2.5 mm) in small tube diameter with an ID of only 20 mm.

6.4 Combination of preheater and thermal siphon reboiler

A chemical plant in the United States operates the preheater in series with the thermal syphon reboiler shown in Fig. 22. The 8-pass preheater with tubes with an O.D. of 25 mm, a very high liquid velocity in the tubes of 4.5 m/s and heated by L.P. steam experiences severe fouling still requiring cleanings every two months, while the thermal syphon reboiler heated by M.P. steam requires cleanings every four months.

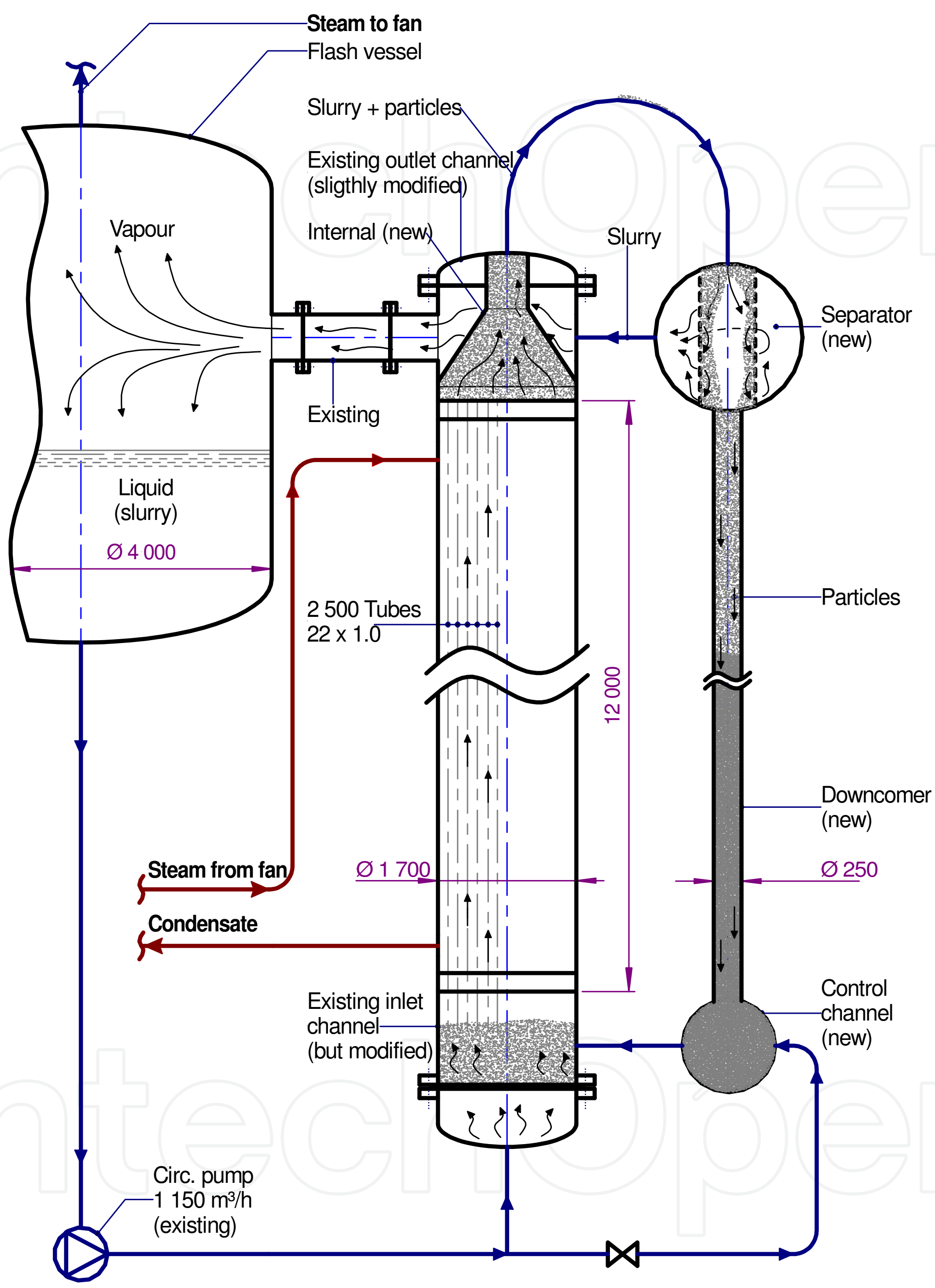

Fig. 21. Existing evaporator revamped into self-cleaning configuration.

The solution we are proposing to solve this problem is quite unique and explained in Fig. 23. As a matter of fact, we have increased the tendency of fouling in the preheater due to the precipitation of solids by increasing the outlet temperature of the preheater. This can be realised by adding M.P. steam to the shell of the preheater instead of L.P. steam. As a result of this temperature increase, the preheater will also partly contribute to the degassing

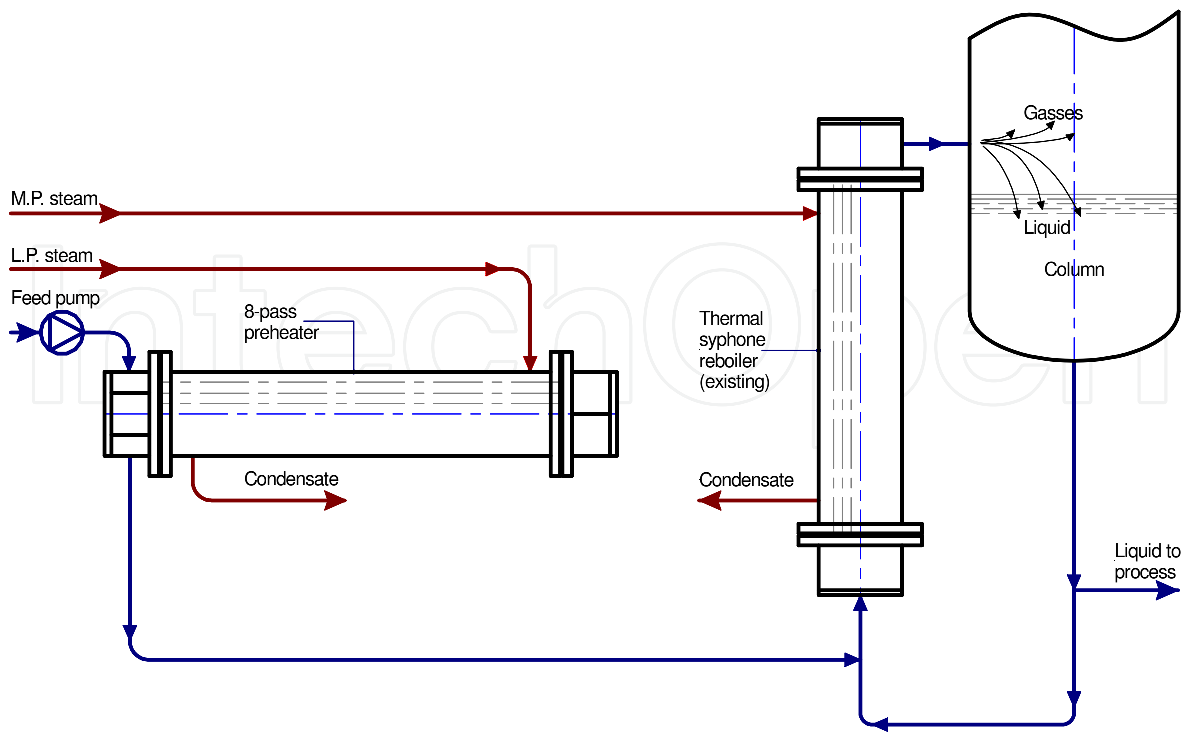

Fig. 22. Conventional preheater in series with thermal syphon reboiler.

of the liquid which is normally done in the reboiler. Above goals have been realised by revamping the existing 8-pass horizontal conventional heat exchanger into a vertical single-pass self-cleaning fluidised bed configuration using stainless steel cleaning particles with a diameter of 2.5 mm and also installing an extra circulation pump to maintain sufficient velocity in the tubes of our single-pass configuration for circulation of the cleaning particles. Although, we have indeed increased the tendency for fouling, we expect that the introduction of our self-cleaning technology will keep the preheater clean.

The separation of the gasses from the mixture of liquid and particles takes place in the widened outlet channel of the preheater, these gasses are fed into the reboiler and evenly distributed over all the tubes of the reboiler where they contribute to the (natural) circulation effect of this thermal syphon reboiler.

Considering the fact that a substantial fraction of the totally required degassing is not done anymore in the reboiler, the heat load of the reboiler can be reduced, which reduces the condensing steam temperature, the tube wall temperature and, consequently, the fouling of the reboiler.

The advantage of this approach is the revamp of the conventional preheater into a self-cleaning configuration at an increased heat load. An experiment with a single-tube self-cleaning pilot plant in parallel with the existing severely fouling preheater should demonstrate the non-fouling performance of the self-cleaning heat exchange technology. If this is indeed the case, then, we have not only solved the fouling problem of the preheater at an even higher heat load, but also reduced the fouling of the conventional thermal syphon reboiler.

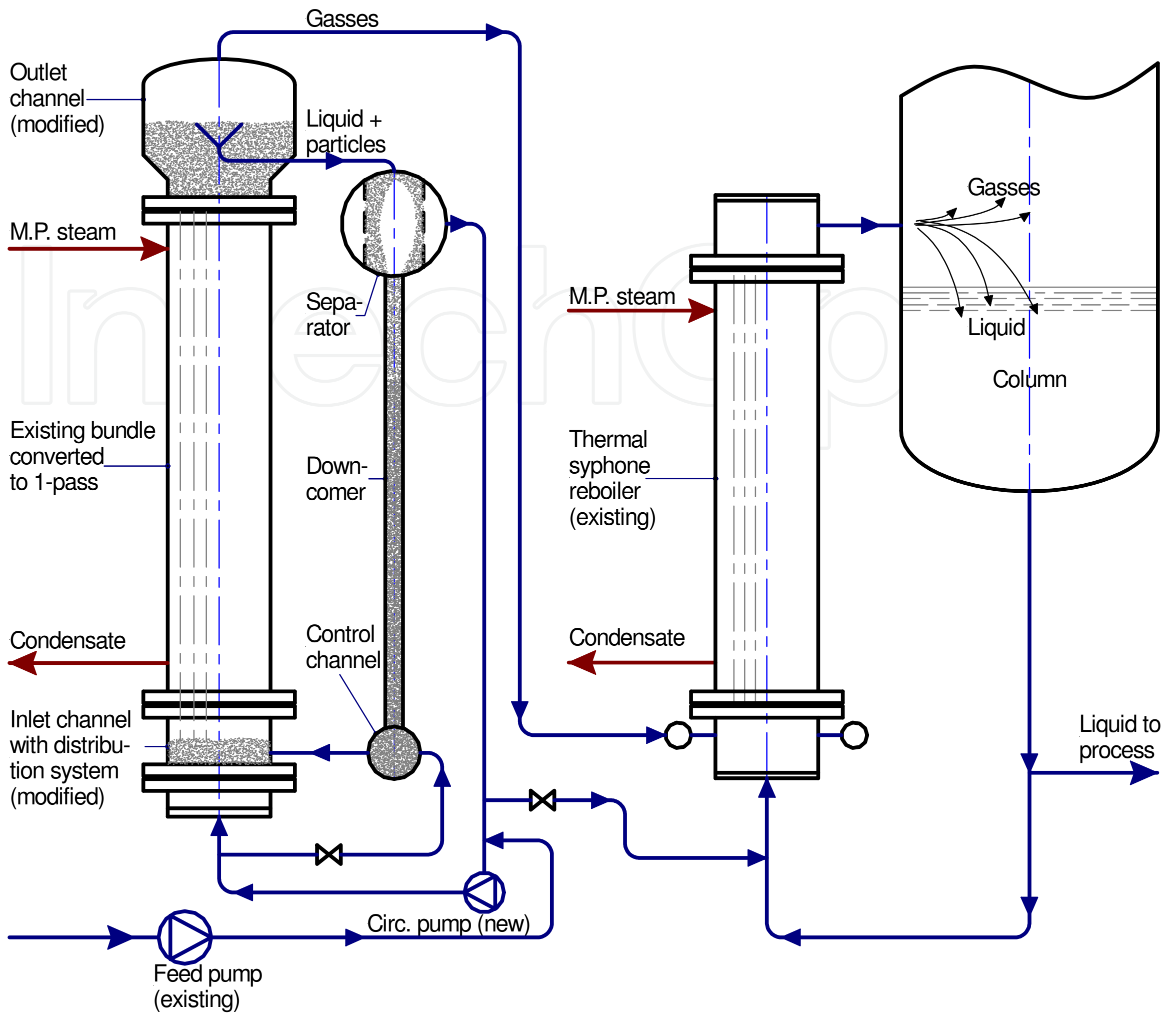

Fig. 23. Conventional preheater revamped into self-cleaning configuration and operating in series with thermal syphon reboiler.

For the proposed solution of this problem, we have introduced the concept of evaporation of a fraction of the liquid creating a mixture of liquid, vapour and particles in the tubes. We know that this is possible if certain design criteria are taken into account. Consequently, with this example, we have presented the possibility that our self-cleaning heat exchange technology can also be applied for applications where we even experience boiling or evaporation in the tubes.

6.5 Self-cleaning fluidised bed heat exchangers in existing 'directly heated' HPAL plants

There exist a strong drive to apply indirect heating (i.e. using heat exchangers) in High Pressure Acid Leach (HPAL) plants for the extraction of nickel and cobalt from laterite ore slurry, because of the benefits of indirect heating in comparison with direct heating (i.e. using steam injection or slurry / vapour mixing condensation), which benefits we summarise below:

- Increased autoclave production capacity.
- Reduced acid consumption.

- Reduced neutralizing agent consumption.
- Recovery of demineralised condensate and process condensate.

Poor heat transfer and hydraulic performance of conventional shell and tube heat exchangers have worked against the introduction of indirect heating in HPAL plants. We believe that self-cleaning fluidised bed heat exchangers offer a much better option, and in the example below, we introduce a 'directly heated' HPAL plant which is retrofitted into an 'indirectly heated' configuration using two different kinds of heat exchangers.

Fig. 24 shows the flow diagram, including relevant temperatures, of a 'directly heated' HPAL plant. Fig. 25 shows the above flow diagram, but, now extended in such a way that direct heating can be fully replaced by indirect heating. Now, for the high temperature end of the installation shown in Fig. 25, we have engineered these two different kinds of indirect heating solutions. One of the indirect heating solutions uses conventional shell and tube heat exchangers and the other self-cleaning fluidised bed heat exchangers. Table 4 compares both indirect heating solutions. The advantages in favour of the self-cleaning fluidised bed configuration are very convincing and we like to emphasise these advantages:

- Shear-thinning of the non-Newtonian highly viscous slurry due to the increased turbulence of the slurry induced by the fluidised particles, which reduces the viscosity of the slurry experienced by the fluidised bed by a factor 4 to 5 or even more.
- High heat transfer coefficients,
- low slurry velocities,
- low pressure drops in the tubes, and
- non-fouling due to the scouring action of the fluidised particles on the tube wall.

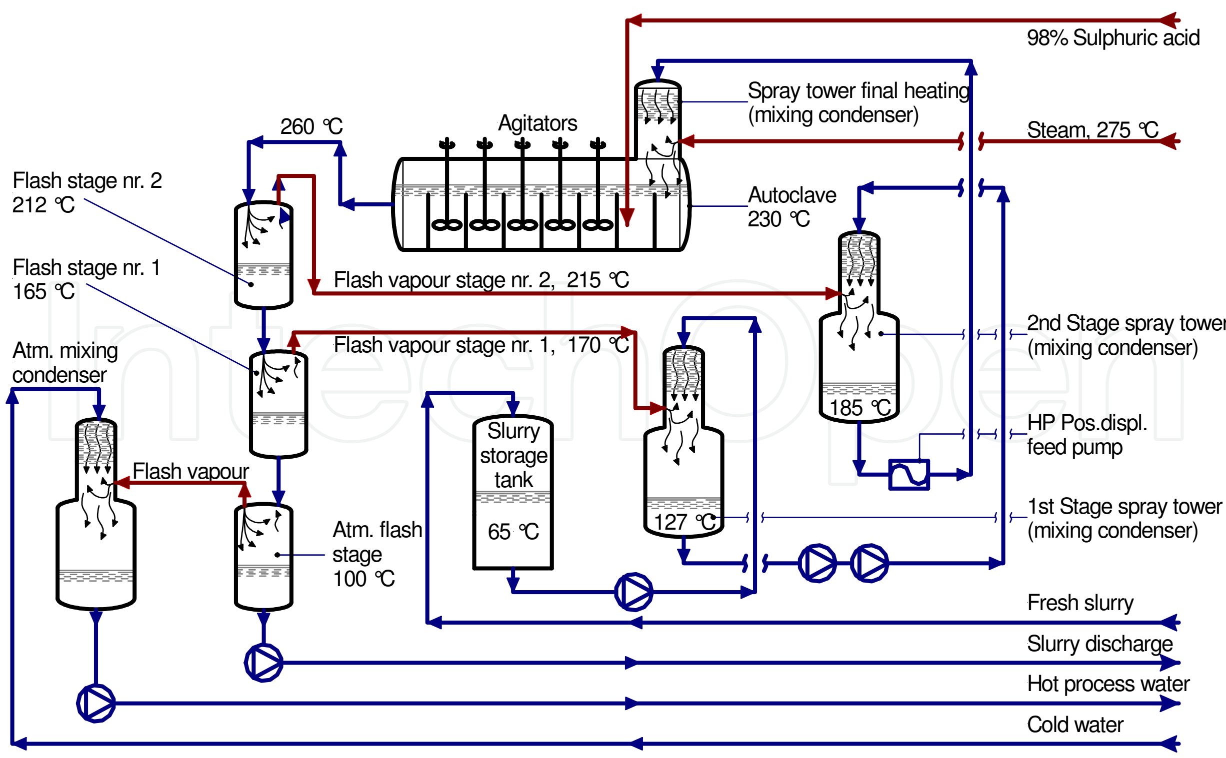

Fig. 24. HPAL plant for laterite nickel employing direct heat transfer.

Particularly, the high heat transfer coefficient and low slurry velocity do affect the total length of the installed heat exchange tubes. This follows from the Equation (5) for the tube length presented in paragraph 0 of his chapter, after substitution of the design and process parameters. As a consequence, the number of shells in series for the self-cleaning fluidised bed heat exchanger is a fraction (just one) in comparison with the large number of shells in series for the conventional shell and tube heat exchanger.

For this HPAL application, the scope of the benefits already mentioned at the beginning of this sub-paragraph increases when indirect heating is not only applied to the highest temperature stage of the installation but to all stages. It is not surprising that all major mining companies show much interest in the self-cleaning fluidised bed heat exchange technology for an even greater variety of applications than only HPAL for the extraction of metals from laterites.

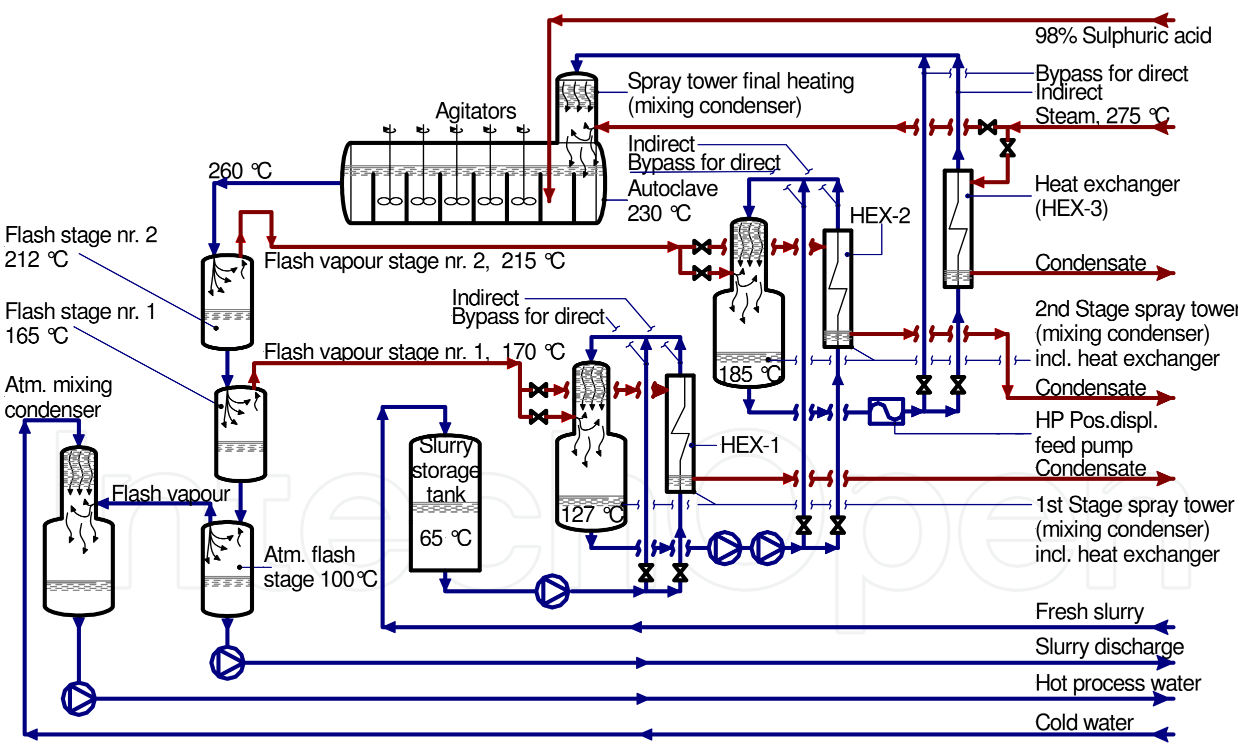

Fig. 25. HPAL plant for laterite nickel employing direct heat transfer revamped into indirect heated configuration.

For more information about the performance and the potential of HPAL plants equipped with self-cleaning fluidised bed heat exchangers, one is referred to Ref. [6].

	Unit	Conventional shell and tube	Self-cleaning fluidised bed
Inlet- / Outlet- / Steam temperature	°C	185 / 235 / 275	185 / 235 275
Density slurry	kg/m³	1 340	1 340
Specific heat slurry [kJ/(kg K)]	kJ/(kg K)	3.6	3.6
Dynamic viscosity	cP	50 - 70	10 - 15
Tube velocity slurry	m/s	2.0	0.35
Diameter tube	mm	38 × 3.0	38 × 3.0
Diameter- / Material particles	mm	n.a.	4.0 / Titanium
Clean- / Design k-value	W/(m²·K)	~ 600 / 300	1 500 / 1 500
Tube length based on design k-values and Eq. (5)	m	166.8	5.84
Total number of shells in series for 1-pass tube-side and tube length per shell equal to 8 m	-	21	1
Total number of shells in series for 2-pass tube-side and tube length per shell equal to 8 m	-	11	n.a.
Pressure drop	bar	~ 6 - 10	< 1.0

Table 4. Comparison significant parameters for indirect heating of high temperature stage of HPAL plant of Fig. 25.

7. Final remarks

We have given an indication about the cost of fouling of heat exchangers on a global scale and we have shown that the self-cleaning fluidised bed heat exchange technology can play a significant role in battling these fouling cost, and does have even more potential that solving fouling problems only.

Particularly, the latter aspect has caught the attention of an increasing number of very large companies which are very much interested to implement the self-cleaning fluidised heat exchange technology for the upgrading of their existing proprietary processes, or even for the development of completely new processes.

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