# Self-Cleaning Fluidized Bed Slurry Heat Exchangers: Processing of Laterite Ore Slurries for the Extraction of Nickel and Cobalt In High-Pressure-Acid-Leach (HPAL) Plants

D.G. Klaren and E.F. de Boer
KLAREN BV, Hillegom, the Netherlands

Brett Crossley
Met Chem Consultants, Mahogany Creek, Western Australia

Presented at
34th Annual Hydrometallurgical Meeting
October 23-27, 2004,
Banff, Alberta, Canada
Rimrock Resort Hotel

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

# Self-cleaning fluidized bed slurry heat exchangers: Processing of laterite ore slurries for the extraction of nickel and cobalt in high-pressure-acid-leach (HPAL) plants.

D.G. Klaren and E.F. de Boer
KLAREN BV
Vincent van Goghsingel 40
2182 LP Hillegom, the Netherlands
info@klarenbv.com

B. Crossley
Met Chem Consultants
345 Thornbill Place
Mahogany Creek, Western Australia 6072

## ABSTRACT

Self-cleaning fluidized bed heat exchangers have demonstrated unparalleled performance internationally for the implementation of indirect heat transfer in severely fouling fluid environments. The ingenious configuration of recirculated cleaning particles through the tubes of vertical shell and tube heat exchangers provides the ability to solve any problems that arise as a consequence of tube-side fouling during indirect heat transfer to process fluids or slurries. In most cases, the cleaning particles consist of chopped metal wire, however other process-specific materials have been used. In addition to the mitigation of fouling effects, a number of other significant benefits for slurry heating are afforded by the mode of operation of the self-cleaning fluidized bed heat exchangers. Increased turbulence at the slurry/tube interface is imparted by the action of the fluidised particles, resulting in very high heat transfers at relatively low liquid velocities. Furthermore, given the thixotropic nature of most process slurries, the action of the fluidised particles imparts additional shear to the process slurry, resulting in shear thinning effects with a consequent reduction in pressure drop and enhancement of heat transfer across the heat exchanger. The benefits provided by the self-cleaning fluidized bed heat exchanger make it the ideal option for the indirect heating of laterite nickel slurry for High-Pressure-Acid-Leach (HPAL) plants. This article explains the principle and application of the self-cleaning fluidized bed heat exchanger technology for the processing of laterite nickel and cobalt slurries in HPAL plants. It also presents an elegant method to revamp existing direct heated laterite nickel and cobalt processing plants into an indirect heated configuration employing self-cleaning fluidized bed heat exchangers.

## INTRODUCTION

Self-cleaning heat exchange technology applying a fluidized bed of particles inside the tubes of vertical shell and tube heat exchangers 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. For more information about the principle and the applications of the self-cleaning fluidized bed heat exchangers, the reader is referred to the pertinent literature (1-4).

In the late 90s, a chemical plant in the United States compared for their severely fouling application the installation of conventional shell and tube heat exchangers versus self-cleaning heat exchangers. The result of this comparison is shown in table I. As could be expected, but also convinced by a test, plant management decided in favour of the self-cleaning configuration. During operation, the conditions for the self-cleaning heat exchangers were fully met and the results were better than expected: After 26 months of continuous operation, the self-cleaning heat exchangers still have not been cleaned. A more detailed description of this case exists elsewhere (5).

Table I – Comparison of Self-Cleaning Heat Exchangers Versus Conventional Heat Exchangers.

| | Self-cleaning heat exchanger | Conventional heat exchanger |
|---|---|---|
| Heat transfer surface ($m^2$) | 4,600 | 24,000 |
| Pumping power (kW) | 840 | 2,100 |
| Number of cleanings per year | 0 | 12 |

This striking example of the self-cleaning heat exchange technology and later improvements as a result of new developments have very much increased the interest for this technology and the number of potential applications, which can benefit from this unique heat exchange technology. One of these applications refers to the indirect heating of laterite nickel and cobalt slurries for High-Pressure-Acid-Leach (HPAL) plants and will be presented and discussed in this article.

## PRINCIPLE OF SELF-CLEANING HEAT EXCHANGER FOR SLURRIES AND ITS OPERATING RELIABILITY

The operating principle of self-cleaning heat exchanger for liquids in general and slurries in particular, according to the latest state of development, is shown in Figure 1. The fouling liquid or slurry 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 or slurry and the suspended particles throughout the internal surface of the

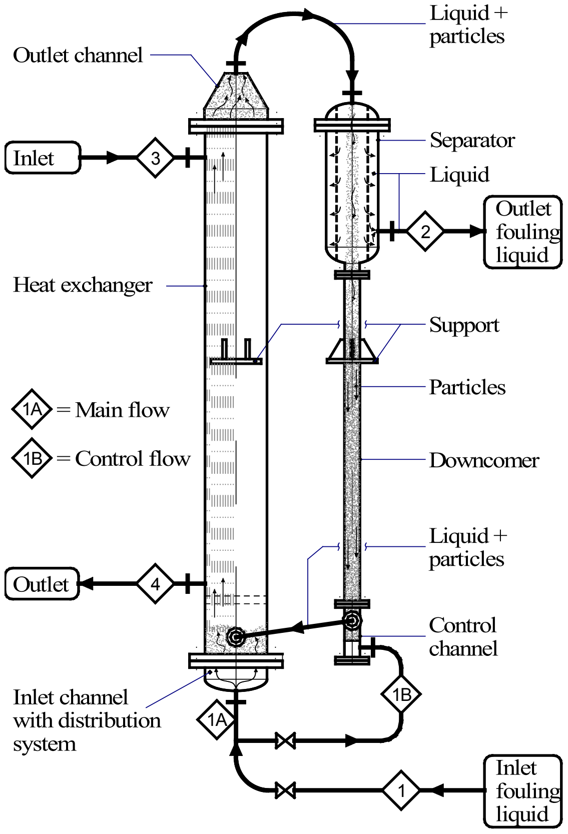

Figure 1 - Principle of Self-Cleaning Heat Exchanger.

bundle. The particles are carried through the tubes by the upward flow of slurry, 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. These particles can be cut metal wire, glass or ceramic balls with diameters varying from 1 to 5 mm. After passing through the outlet channel, the slurry and particles enter a separator where the particles disengage from the slurry and are returned to the inlet channel through an external downcomer and recirculated continuously.

The slurry flow 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 control of aggressiveness of the cleaning mechanism. It allows the particles to be either continuous or intermittent.

Many years of continued developments have made this self-cleaning heat exchanger for slurries so reliable that it should be able to handle all kinds of mishaps, if any, during normal operation of an HPAL plant, either caused by the environment or by mistakes made by the operators, such as:

- Power failures.
- Loss of cleaning particles which then could move downstream the process.
- Large pieces of scale breaking loose from the walls of the piping upstream the self-cleaning heat exchanger and supplied by the pump.
- Pulsation type of flow supplied by the positive displacement pump used at the high-temperature end of the HPAL plant.
- Varying properties of the slurry supplied to the heat exchanger.

### Power Failures

The result of a possible power failure is a complete stagnation of the slurry flow. Normally, this causes the cleaning particles to settle in the tubes as a packed bed over a certain height. New insights and ideas have solved this problem. Now, in case of a power failure, it is possible to restart the slurry flow through the exchanger without the risk of plugging any of the tubes.

### Loss of Cleaning Particles

This problem, which may have serious consequences for the operation of the plant and may cause severe damage to components of the plant downstream the exchanger, must be avoided under all operating circumstances. For this purpose, a new type of separator has been developed which is placed on top of the downcomer as is also shown in the Figure 1. This separator contains a vertical cylinder made of thin-walled perforated plate with holes of a size slightly smaller than the cleaning particles, e.g. 4 mm holes for 5 mm particles. The cleaning particles carried by the slurry enter into the separator at the top and will be sucked towards the screen, which can be passed by the slurry but not by the particles. As a consequence, these particles remain in contact with the surface of the screen and impose a scouring effect, which prevents any fouling of the screen by scale deposits. Plugging of the holes in the screen is not very likely, if the wall thickness of the corrosion resistant perforated plate is thin enough (0.5 mm to 1.0 mm) and the velocity of the slurry through the holes is sufficiently high (0.1 m/s to 0.25 m/s) so that these holes will be cleaned by the scouring effect of the solids in the slurry. It is important that the slurry does not contain solids, like gravel, with dimensions exceeding the holes in the screen. If there is a chance that some oversized gravel tends to accumulate in the exchanger, there are methods to remove the gravel.

### Large Pieces of Scale in the Slurry

It should be avoided that large pieces of scale will enter into the inlet channel of the exchanger as this might cause plugging of the distribution system. Such pieces of scale may be formed on the walls of storage tanks and / or connecting piping upstream the exchanger and break loose from these walls, whereupon these pieces will be transported with the slurry into the inlet channel. The best way to prevent this problem is the installation of a newly developed filter in the inlet channel with the possibility that this filter can also be back-flushed. Scale pieces formed downstream of the screen in the separator might also break loose, but then should be removed by the filter in the inlet channel of the next exchanger.

Pulsation Type of Slurry Flow

The exchanger operating at the highest temperatures and pressures of the HPAL plant will be supplied with slurry by a positive displacement pump. Flow pulsation’s caused by this pump do not effect the fluidization and / or transportation of the cleaning particles in the heat exchange tubes because of the inertia of these particles.

Varying Properties of the Slurry

This important subject will be discussed later in this article.

## HEAT EXCHANGE PRINCIPLES IN HIGH-PRESSURE-ACID-LEACHING

For the processing of laterite nickel and cobalt in HPAL plants, it is necessary to heat a large slurry flow from approximately 65°C to a temperature of 230°C, 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 of the slurry even further to 260°C. 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.

Figure 2 shows a flow diagram of a state-of-the-art HPAL plant heating cold incoming slurry and recovering heat from the hot discharged slurry, while applying direct contact heat transfer by heating the cold slurry with the flash vapour produced from the hot slurry in spray-towers/mixing condenser and using high pressure steam in a spray-tower/mixing condenser as the final heating step.

Figure 3 shows a flow diagram for an HPAL plant using a large number of conventional shell and tube heat exchangers in series for indirect heating of the slurry in two preheaters as well as in the final heater. It should be recognized that each preheater consists of 'n' heat exchanger shells in series, while the final heater employs 'm' shells in series. Later the value for the total number of heat exchanger shells in series, i.e. (2n + m) will be explained for a particular design and plant capacity.

Figure 4 shows a flow diagram for an HPAL plant utilizing self-cleaning fluidized bed heat exchangers. This figure shows only two heat exchanger shells in series. One shell contains both preheaters, while a second shell contains the final heater. Later in this article, it will be explained why the self-cleaning fluidized bed configuration requires so much fewer heat exchangers in series in comparison with conventional shell and tube exchangers.

The advantage of using indirect heat transfer by employing heat exchangers is that the fresh slurry feed is not diluted with the condensates in the various mixing condensers. This then results in a higher utilization of high-pressure autoclaves allowing an increased nickel and cobalt throughput per cubic metre of autoclave volume. In addition, the use of heat exchangers will result in reduced water and acid consumption along with increased water recoveries.

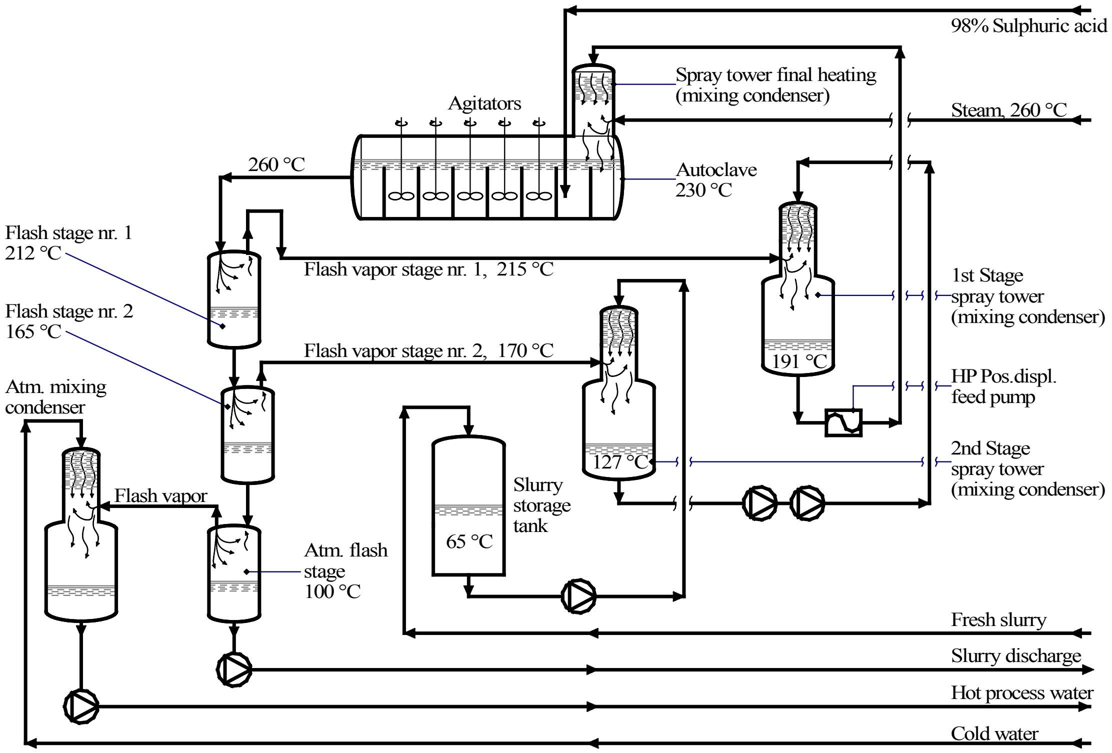

Figure 2 - HPAL for Laterite Nickel Employing Direct Heat Transfer.

In the text below, it will be shown that in case of indirect heating by employing heat exchangers, the price and performance of self-cleaning heat exchangers cannot be matched by conventional heat exchangers.

## HEAT TRANSFER EQUATION AND ADVANTAGES OF SELF-CLEANING HEAT EXCHANGERS

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 heat exchange tube as a function of its performance. This equation reads:

$$L_t / D_o = (D_i / D_o)^2 \times ( \rho_l \times c_l \times V_l ) / (4 \times U ) \times (\Delta T / \Delta T_{log}) \qquad (1)$$

where

$L_t$ = Tube length
$D_o$ = Outer diameter of the tube.
$D_i$ = Inner diameter of the tube.
$\rho_l$ = Density of the liquid.
$c_l$ = Specific heat of the liquid.
$V_l$ = Velocity of the liquid in the tube.
$U$ = Overall heat transfer coefficient.
$\Delta T$ = Temperature difference of the liquid between tube inlet and tube outlet.
$\Delta T_{log}$ = Logarithmic mean temperature difference across tube.

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

$$L_t = C_0 \times D_o \times V_l / U \qquad (2)$$

Where $C_0$ is a constant for a particular installation / application. In other words, the length of the tubes $L_t$ is directly proportional to the outer diameter of the tubes $D_o$ and to the liquid velocity in the tubes $V_l$, but inversely proportional to the heat transfer coefficient U.

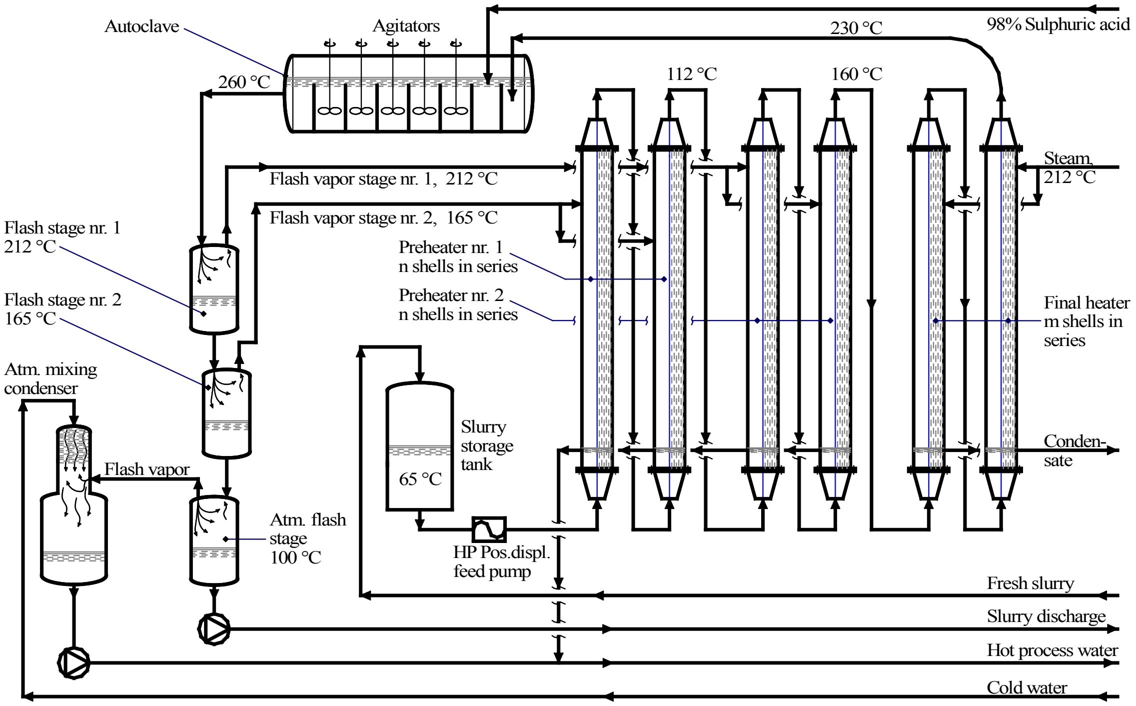

Figure 3 – HPAL for Laterite Nickel with Indirect Heat Transfer (conventional hex's).

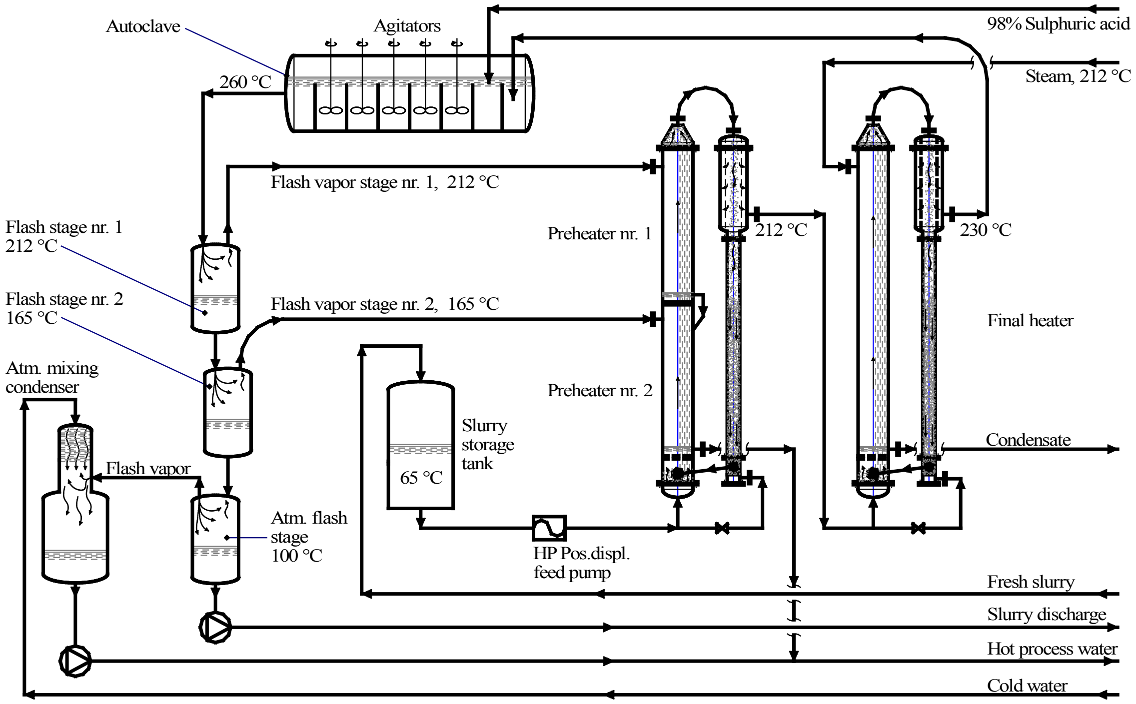

Figure 4 – HPAL for Laterite Nickel With Indirect Heat Transfer (self-cleaning hex's).

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:

- Self-cleaning behaviour as a result of the presence of fluidized particles (cut metal wire with a diameter of 4 mm to 5 mm) in the liquid or slurry.
- Low liquid or slurry velocities in combination with excellent overall heat transfer coefficients.
- Dramatic shear thinning effects on liquids and/or slurries, which behave strongly non-Newtonian and again influence the heat transfer performance in a positive manner.

## EXPERIMENTAL RESULTS

Experiments with dry laterites in West Australia showed the following striking results:

Conventional Shell and Tube Heat Transfer

For slurries with a solid percentage of approx. 32% and a velocity in the tubes of 1.40 m/s and again condensing steam in the shell, a heat transfer coefficient of 700 $W/(m^2 \cdot K)$ to 800 $W/(m^2 \cdot K)$ could be realized. Although long term operating experiments with a conventional heat exchanger showed a drop in this heat transfer coefficient, due to fouling to a value less than half the clean heat transfer coefficient, i.e. 350 W/($m^2$·K) in only four weeks of operation. As a consequence, a typical design value for a conventional heat exchanger operating on this particular type of slurry should be 350 W/($m^2$·K), in combination with the requirement of monthly cleanings! In the conventional heat exchanger, the slurry behaved as a liquid with a viscosity somewhere between 50 cP and 75 cP.

Self-Cleaning Fluidized Bed Heat Transfer

For slurries with a solids percentage of 35% and a slurry velocity in the tubes of only 35 cm/s and condensing steam in the shell of the exchanger, it was possible to realize an overall heat transfer coefficient of 1800 W/($m^2$·K) to 2000 W/($m^2$·K) for heating from 50°C to 85°C. In the self-cleaning heat exchanger, the slurry behaved as a liquid with a viscosity of only 15 cP. It is very likely that over the total temperature range in HPAL for laterite nickel, the average overall heat transfer coefficient would be higher than 2,000 W/($m^2$·K) and remain at that value due to the self-cleaning action of the fluidized particles. As a consequence, a heat transfer coefficient of 2,000 W/($m^2$·K) can be used as a design value, which, however, can be maintained indefinitely!

## CONSEQUENCES AND COMPARISON

From equation (2), and assuming an outer diameter of the tubes for the self-cleaning heat exchanger of 60 mm and 38 mm for the conventional exchanger, substitution of the values for the relevant parameters in table II gives the numbers that are directly proportional to the tube length for both types of exchanger:

Conventional: $0.038\ [\mathrm{m}] \times 1.40\ [\mathrm{m/s}] / 350\ [\mathrm{W/m^2/K}] = 15.2 \times 10^{-5}\ [\mathrm{m^4 \cdot K/J}]$

Self-cleaning: $0.060\ [\mathrm{m}] \times 0.35\ [\mathrm{m/s}] / 2000\ [\mathrm{W/m^2/K}] = 1.05 \times 10^{-5}\ [\mathrm{m^4 \cdot K/J}]$

This implies that the required tube length to be installed for the conventional heat exchanger is 15.2 / 1.05 = 14 times longer than that for the self-cleaning heat exchanger. This means that if the calculations for the self-cleaning configuration result in 24 m of tube length in series (which can be accommodated in only 2 vertical single-pass bundles of 12 m length each), the conventional heat exchanger would require 14 × 24 = 336 m of installed tube length in series.

If these conventional heat exchangers are designed as vertical single-pass shell and tube exchangers (which, for this type of slurry, is undoubtedly the preferred design), it requires (2n + m) = 28 (!!) bundles in series, each bundle with a tube length of 12 m. What this means for interconnecting piping between the bundles, steam and/or vapour distribution lines and condensate collection from all the shells does not need any further explanation. The cost for the conventional design will be staggering.

Table II compares both designs for a plant with a production of 45,000 ton nickel/year and 4,500 ton cobalt/year and undoubtedly proves the enormous advantages of the self-cleaning heat exchangers. From the operational point of view, one might even wonder, if the conventional design with so many heat exchangers in series can be considered a reliable option.

Table II – 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 | 440,000 kg/h | |
| Slurry density in $kg/m^3$ | 1,320 | 1,350 |
| Slurry velocity in tubes in m/s | 1.4 | 0.35 |
| Slurry viscosity in tubes in cP | 50 ÷ 70 | ~ 15 |
| Outside diameter of tubes in mm | 38 | 60 |
| Diameter cleaning particles in mm | Not applicable | 5 |
| Tube length 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 $W/(m^2 \cdot K)$ | 700 ÷ 1,000 | 2,000 |
| Design U- value in $W/(m^2 \cdot K)$ | 350 | 2,000 |
| Total number of shells in series | 28 | 2 |
| Total installed heat transfer surface in $m^2$ | 3,200 | 550 |
| Total number of cleaning required per year | 12 | 1 |
| Materials in contact with slurry and/or flash vapour at temperature lower then 170°C | Duplex | Duplex |
| Materials in contact with slurry and/or flash vapour at temperature higher then 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 (bar) | ~ 10 | ~ 3 |
| Cost of all hex's for all three production lines, incl. steel construction, inner connecting piping, steam-flash vapour- condensate manifold and relevant instrumentation | ~ US $ 30,000,000 | ~ US $ 9,000,000 |

Of course, it can be stated that the conventional heat exchangers should be designed multi-pass, which would limit the number of bundles in series significantly. This may be possible for a slurry with 32% of solid as has been experienced in Western Australia, but it is still a risky choice, with a lot of potential for problems caused by shear thinning and, consequently, preferential flow which then could result in an uneven distribution of the slurry over the tubes.

Realizing that there will always be a trend to increase the solid concentration of the slurry to 38%, 40% or even higher percentages to save on autoclave capital cost, for the conventional heat exchanger, this will result in substantially higher viscosities, lower heat transfer coefficients due to laminar flow, a higher fouling rate and the fact that at the end only single-pass heat exchangers can be used. Tendencies for preferential flow due to shear thinning of highly viscous slurries may become so strong that it could even become a problem for single-pass conventional heat exchangers to achieve an even distribution of the slurry over the tubes.

For the self-cleaning fluidized bed heat exchanger, experiments have shown that these negative effects on viscosity and heat transfer coefficients due to increased solids concentration are much fewer compared to conventional heat exchangers. Moreover, for the self-cleaning fluidized bed heat exchanger, an uneven distribution of the slurry over the tubes is impossible, because its design and working principle are based on achieving equal distribution of slurry and particles over multi-parallel tubes.

From the above, it can be concluded that the occurrence of fouling should not even be a determining factor for the choice of fluidized bed heat exchangers over conventional heat exchangers. If the solid concentrations of the slurry increase to values of 38%, 40% or higher, the slurry viscosity will dramatically increase and as a result of laminar flow, the ‘clean’ heat transfer coefficients of conventional heat exchangers may easily drop to values of 400 W/($m^2$·K) or even less. However, at a higher concentration of solids, the heat transfer coefficient of the fluidized bed heat exchanger will be much less influenced by this increased viscosity and, as a consequence, the fluidized bed heat exchanger could still operate with heat transfer coefficients between 1,500 W/($m^2$·K) and 1,750 W/($m^2$·K).

## INSTALLATION OF SELF-CLEANING HEAT EXCHANGERS IN EXISTING HPAL PLANTS

A new indirect heat exchange technology can be introduced in an existing directly heated plant using the following approaches:

- Small-scale pilot-plant testing with the purpose of building a completely new full-size installation based on the newly developed technology.
- Installation of a full-size ‘test installation’ based on the new technology in parallel with the existing installation.

As, for this particular application, a rather thick slurry has to be handled in combination with external circulation of rather large particles through a downcomer, a small-scale pilot-plant requires a minimum diameter of a downcomer in order to prevent jamming of the particles in the downcomer. This minimum diameter corresponds with a minimum number of heat exchange tubes, i.e. for this application 50 to 60 tubes. These tubes should be able to handle a slurry flow of approximately 100 $m^3$/h.

A full-size plant handles between 250 $m^3/h$ and 350 $m^3/h$ and, therefore, for economic reasons, it seems to be justified to prefer ‘a test installation’ which actually is a full-size installation parallel to the existing installation. In case of problems with this ‘test installation’ an easy return from the ‘new’ technology to the ‘old’ technology of the existing installation is possible. Also in case of modifications and/or improvements of this indirectly heated ‘test installation’, the ‘test installation’ can be put off line, while operation of the HPAL plant at its normal capacity can be continued by the existing directly heated installation.

Investment cost for the complete full-size ‘test installation’ with approx. 120 tubes are very likely only 50% higher than these costs for the small-scale pilot still containing 50 to 60 tubes. However, in case of successful operation, the benefits of the ‘test installation’ would contribute substantially to the savings of the plant.

Figure 5 shows the existing directly heated HPAL in parallel with the indirectly heated flow paths of the slurry employing heat exchangers. If during operation, the directly heated flow paths are closed and all the slurry is heated in the heat exchangers, the direct heating of the slurry has been changed into indirect heating.

Figure 6 presents a more detailed flow diagram for indirect heating of the slurry parallel to the direct heating of the slurry at the low temperature end of the installation, i.e. the second stage. The dimensions follow from Table II and yield a total tube length of 6 m for this particular stage and a shell diameter of 960 mm. For the first stage and the final heating stage, the principal and required installed components are the same and dimensions again follow from Table II, i.e. total tube length for the first stage and final heater 6 m and 12 m respectively, with shell diameters of 960 mm.

## OPERATION OF THE SELF-CLEANING HEAT EXCHANGER IN PARALLEL WITH THE EXISTING DIRECTLY HEATED FLOW PATH

For a successful operation of the self-cleaning heat exchanger, it is important that attention is paid to the varying properties of the slurry such as density and viscosity supplied to the heat exchanger with respect to its operation. The non-Newtonian behaviour of the slurry and the ‘shear-thinning’ behaviour of the slurry in the presence of a fluidized bed are properties, which have great influence on the fluidization and the transport of the cleaning particles through the tubes of the heat exchanger. The ‘actual viscosity’ of the slurry in the channels and tubes of the exchanger is very much influenced by the ‘shear-thinning’ experienced by the slurry due to the turbulence created by the fluidized cleaning particles. A patented measurement device has been developed which makes it possible to determine the value for the ‘actual’ viscosity of the slurry upstream of the exchanger. If this value is known, it is possible to distribute the slurry flow in such a way that almost all the slurry will pass through the heat exchanger.

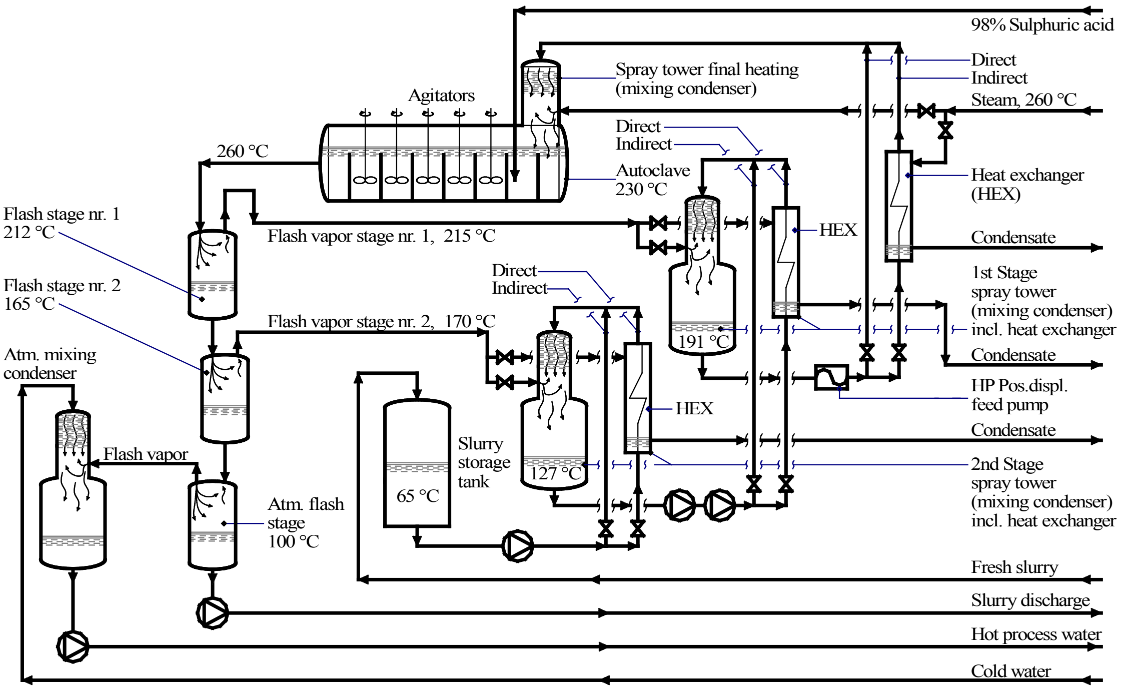

Figure 5 – HPAL for Laterite Nickel Employing Direct Heat Transfer Revamped into Indirect Heated Configuration.

Operation of the self-cleaning heat exchangers can be best explained by describing a start-up of the installation as shown in Figure 6. In case of a start-up, the best way to start is to use only the direct heating flow path while adjusting the concentration of the slurry, including its viscosity, to its desired values. If the operating parameters are stable and the density and the viscosity of the slurry are known and remain constant, the slurry flow through the exchanger is put into operation by opening the required valves. Then the main flow and the control flow are adjusted in such a way that the hydraulic operation of the self-cleaning heat exchanger takes place according to plan. Maybe, in the final situation, Y $m^3$/h or 90% of the slurry flow passes through the exchanger and only X $m^3$/h or 10% of the slurry flow by-passes the heat exchanger. However, after both the flow through the exchanger and the bypass flow join one another to (X+Y) $m^3$/h, all heating of the slurry still occurs by supplying the steam in the spray tower or mixing condenser. As a next step, the steam valve to the shell of the exchanger should be opened and the steam supply for the indirect heating of the slurry increases while the steam supply to the mixing condenser governing the direct heating decreases. The final situation could be that 90% of the slurry is heated indirectly and only 10% is heated directly. This of course, dramatically reduces the dilution of the slurry, because, now 90% of the supplied steam is condensed in the shell of the self-cleaning heat exchanger and removed as condensate without diluting the slurry flow. Fine-tuning of the operation may result in a situation that, finally, all slurry passes through the exchanger and, therefore, is heated indirectly with zero dilution of the slurry by the condensate.

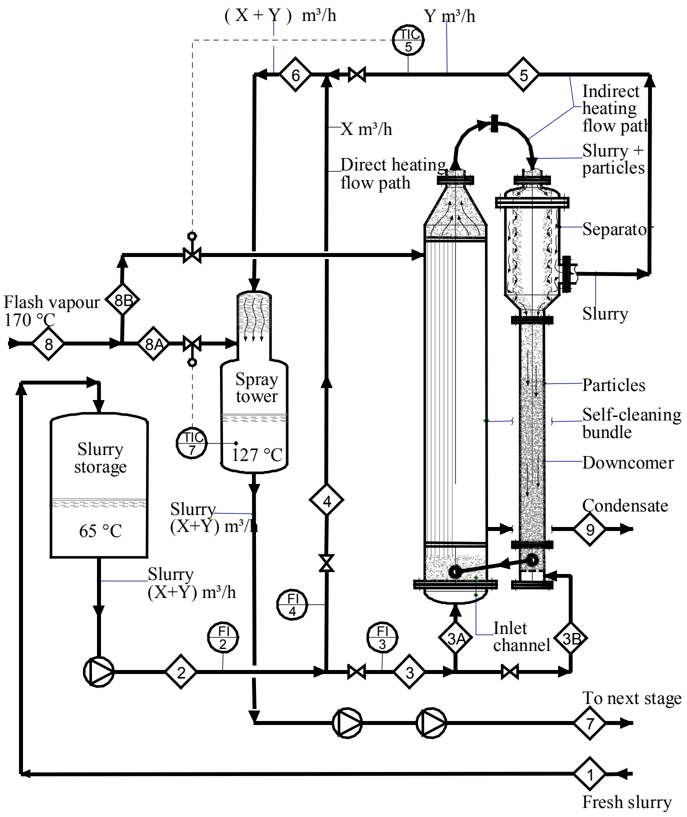

Figure 6 – Detail of Flow Diagram Direct/Indirect Heating Flow Path.

In case of a shut-down of the indirect heating using the self-cleaning heat exchanger, the various steps to be taken are reverse to the ones described above. First, the steam flow to the exchanger is gradually shut down, while the steam flow to the mixing condenser is increased to maintain the required outlet temperature. If all steam is supplied to the mixing condenser, the flow through the heat exchanger is gradually reduced to zero while the flow through the directly heated flow path is increased accordingly.

No doubt, that the presence of a directly heated flow path parallel to the indirectly heated flow path creates a unique flexibility in the operation of the plant and, therefore, is very much recommended, even in case of the construction of new HPAL plants.

## CONCLUSIONS

Indirect heating of slurries in HPAL for the processing of laterites for the production of nickel and cobalt is to be preferred over direct heat transfer. The advantage of indirect heating, employing self-cleaning shell and tube heat exchangers, is a dramatic reduction of dilution of the slurry by the condensate, which results in a higher utilization of high-pressure autoclaves allowing an increased nickel and cobalt throughput per cubic metre of autoclave volume in addition to reduced acid and water consumption along with increased water recoveries.

A comparison between conventional shell and tube heat exchangers and self-cleaning fluidized bed exchangers show that performance and price of the self-cleaning fluidized bed heat exchangers cannot be matched by the conventional exchangers. Moreover, if the trend in HPAL for a higher solid concentration of the slurries, and consequently more viscous slurries, continues, the self-cleaning fluidized bed heat exchanger may become the only alternative for indirect heating.

An elegant method has been presented to modify existing directly heated laterite nickel processing plants into an indirectly heated configuration employing self-cleaning heat exchangers. Installing the indirectly heated flow path employing self-cleaning heat exchangers parallel to the existing directly heated flow path creates a unique flexibility in the operation of the plant enabling an easy return or fall-back from the 'new' technology on the 'old' technology, if necessary.

Because of the increased reliability of the self-cleaning heat exchangers, the fall-back possibility from 'new' on 'old' technology and the large benefits which can be achieved by the operation of the indirectly heated self-cleaning exchangers, this article recommends the installation of full-size self-cleaning heat exchangers parallel to the existing directly heated installation, instead of rather costly small-scale pilot-plant testing prior to the installation of full-size self-cleaning heat exchangers.

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