NEW TECHNOLOGY FOR INDIRECT THICK SLURRY HEATING SYSTEM

Edwards M*, Kelly R and DeBoer D

Hatch Associates Ltd, Perth, WA, Australia

Abstract

In the pre-desilication of Bayer bauxite slurries, the first step is to heat the slurry to ~100°C. Direct steam injection adds unwanted dilution that has to be removed by additional evaporation, resulting in capital and operating cost impacts, and production losses.

With indirect heating, the nature of thick, viscous slurries can lead to accelerated scaling on tube walls and rapid reduction in heat transfer resulting in short operating cycles. Blockages and/or excess scale also create high heater cleaning maintenance. Often these fundamental issues render indirect heating uneconomic against direct steam injection.

This paper describes a new technology developed and patented by Hatch for Indirect Heating of Thick Slurry, which overcomes all of the issues above. This technology has been successfully trialled using a full size pilot plant and the first commercial scale project is in operation with a second commercial scale project in progress. The safety, technical, operational and cost advantages are discussed.

1. Introduction

Process efficiency requirements normally dictate that bauxite slurry be ground and desilicated at as high a slurry density as can be practically handled by the slurry pumping and agitation equipment. Typically slurry density ranges from around 35% by weight to as high as 60% by weight, depending on the bauxite. These slurries are termed 'thick slurries' in this paper.

There are two basic modes of heating thick slurries in the alumina industry, direct heating and indirect heating.

For direct heating, steam or vapour is injected directly into the slurry. This form of heating is often used because the equipment required is simple and avoids a number of serious problems associated with the more complex heat transfer equipment utilised in indirect heating of thick, viscous slurries. These issues apply equally to thinner slurries such as in Digestion.

For indirect heating, heat exchangers with relatively complex piping, instrumentation, controls and maintenance are required to keep the heating medium separate from the slurry stream. This paper outlines innovations that address a number of fundamental issues associated with successfully designing and operating an indirect thick slurry heating system, namely:

- Controlling scaling rate
- Maintaining high Heat Transfer Coefficient (HTC)
- Long term heater durability and wear resistance
- Increased heater cleaning cycle
- Ease of cleaning and maintenance.

The mechanical design of the heater is combined with an integrated instrument control system that inhibits scaling and maximises heater performance and life. The technology has been successfully trialled at an alumina refinery in Western Australia in 2005 and commercially installed at a Queensland refinery in 2007. These innovations are patent protected [1, 2].

1.1 Thick Slurry Heating Issues

The Bayer process stream is a recirculating flow that must be maintained at a certain caustic concentration. A major disadvantage of direct heating is that it adds steam to the process stream and thereby dilutes it. Any water added to the process must be removed by expensive forced evaporation in other parts of the Bayer process. Dilution also reduces the production capacity of the plant where flow limitations exist. Indirect heating is therefore the preferred method of heating provided technical and maintenance issues can be overcome.

The main problem to date associated with indirect thick slurry heating has been the poor heat transfer coefficients that are obtained leading to large heat transfer areas and high capital costs. Thick slurry heating is often unreliable as tubes tend to scale and wear rapidly, requiring frequent cleaning and/or replacement. The reasons for this are:

- Firstly, thick bauxite slurries typically containing 35–60% solids by weight exhibit highly non-Newtonian behaviour. They are extremely viscous. Flow within heater tubes is outside a simple laminar regime and tends towards plug flow. There is little turbulence and consequently little mixing between the heated boundary layer and the bulk of the flow, leading to an increase in slurry temperature along the tube wall relative to the bulk volume contained within the tube. This reduces the effective temperature difference between the heating medium and the fluid being heated and is a major contributing factor to the poor heat transfer achieved in indirect thick slurry heating to date.
- Secondly, a major factor is the pressure regime at which typical thick slurry heating installations operate. The slurry is usually discharged at or near the atmospheric boiling point to a slurry storage or desilication tank. Pump heads are therefore relatively low. Temperature of the heating medium (generally steam) outside the tubes is well above the boiling point of the slurry, and the tendency for the heat to concentrate in the boundary layer at the tube wall makes it highly likely that this layer exceeds boiling point and bakes within the tubes, increasing scaling rate.
- Thirdly, tube wall scaling has a dramatic effect on decreasing the HTC of the heater. Scale thermal conductivity is very low so minimisation of scale growth is particularly important. Techniques on controlling scale growth have not been incorporated in traditional designs.
- Finally, an additional problem with indirect slurry heating by means of traditional shell and tube heaters has been rapid wear at the tube entrance due to the high percentage of solids. Where standard 'gauge' heater tubes are used, eroded tubes must be frequently replaced. This rapid wear is to a large extent due to the profile of the entry, which is normally square. A square entry results in concentrated wear at the entry itself and causes considerably higher than

average velocities a short distance downstream from the entry, where the incoming stream of slurry contracts.

1.2 Thick Slurry Heating Design Innovations (Figure 1)

The process design innovations utilise 3 key principles:

1. Maintain the Reynolds number of flow through the tubes as high as practicable, in order to keep the flow regime in the turbulent regime and maintain a reasonable level of natural mixing by some means of frequent in-line mixing, or by utilising short tubes (more channel sections), in order to average the slurry temperature.
2. Control slurry pressure relative to the temperature of the heating medium to ensure slurry cannot boil within the tubes, eliminating slurry baking on the tubes.
3. Optimise tube velocity as high as possible (balance with tube wear), reduce heat flux (balance with heating area required) and ensure ongoing pressure control (balance with supply pump head/power) to reduce scale growth.

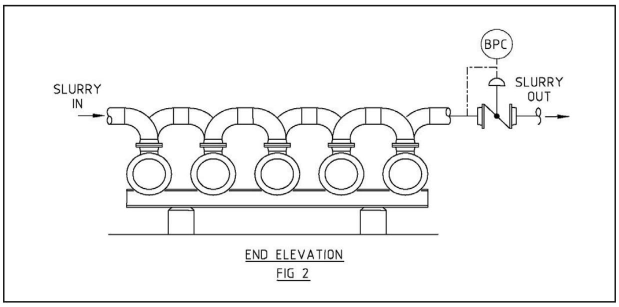


Figure 1. Basic Elevation Schematic of Heating System

In terms of mechanical design, the problem of tube entrance wear and tube replacement is addressed by utilising a wear plate and pipe (instead of 'gauge' heater tube) for heater construction:

- By selecting a pipe diameter somewhat larger than standard heat exchanger tubes, Reynolds number can be increased and turbulence in the slurry enhanced to some degree.
- Pipe has the advantage of a greater wall thickness well in excess of the thickness required for pressure containment and therefore provides more material for potential erosion.
- Larger diameter, thick walled pipes minimise tube blockages and prevent damage when mechanical cleaning.
- A wear plate has sufficient thickness to allow entries to be rounded at the tube plate. Such rounding reduces both the concentration of velocity at the edge of the entry and at the downstream contraction of flow. High wear and high downstream velocities are thereby abated.

1.3 Thick Slurry Heating Construction Innovations (Figure 2)

Apart from design considerations, resolving maintenance issues is also critical to making a heating system viable:

- The new heaters are single pass for simplicity, ease of construction and cleaning. While this results in a larger number of heaters than conventional shell and tube heating systems, this system is devised as a modular set of simple heater units. Additional duty, any changes to process conditions that reduce the heater performance, or even under-designed systems do not require heaters to be replaced as an additional heater can be readily added to make up the shortfall in duty.

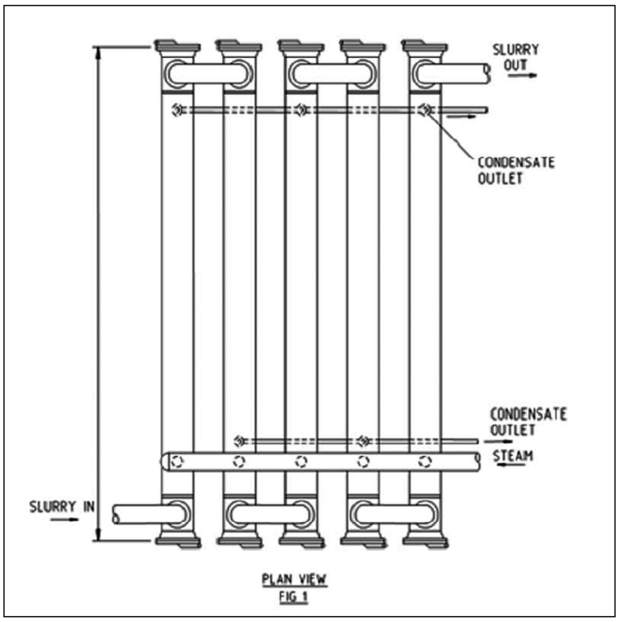


Figure 2. Basic Plan Schematic of Heating System

- The heaters utilise standard size pipes and fittings to fabricate the shell and tubes. Combined with a smaller shell size this creates the opportunity to construct modular units at low cost off site. Modular units can be pre-assembled and shipped to site from the fabrication shop as ready-to-install, skid-mounted units complete with interconnecting pipe work, supporting structure, instrumentation and valves. The advantage of modular units depends on whether a horizontal or vertical orientation layout of the heaters is used.
- Heaters can be arranged in the horizontal or vertical plane depending on footprint restrictions. Horizontal is preferred as it simplifies access, maintenance, piping layouts and reduces potential for tube blockages.

The combination of the above design attributes results in a significantly higher sustainable HTC together with improved reliability and robustness, making these indirect heaters economically viable for replacing direct steam injection heaters.

2. Full Scale Pilot Plant Trial Overview

As part of a refinery expansion study, economic benefits were identified for installing indirect heating for the thick bauxite slurry feed pumped from the grinding mills to the pre-desilication tanks. The existing process used direct steam injection. New indirect heaters would remove significant dilution from the process and allow bauxite slurry to be heated to a higher temperature, further improving pre-desilication. This could eliminate the requirement to install an additional Slurry Storage Tank and allow decommissioning of an Evaporation Unit, significantly enhancing project economics.

2.1 Trial Description

Three heaters were designed and supplied for installation of a full scale pilot plant to take full plant slurry flow for 1 of 5 units. Bauxite slurry properties are summarised in Table I.

For the project to prove viable, the heaters had to maintain above 550 W/m^2°C for at least one month with heater cleaning turnaround being less than 3–4 days.

Once the pilot plant was constructed, performance data on the heaters were collected, including HTC, temperature pick up, pressure and steam consumption. This provided data for the design of a full scale heating facility to replace the existing direct steam heaters.

Table I. Trial Process Data

Parameter	Units	Trial Value
Volumetric Flow	m^3/h	570-730
Solids Concentration	Weight %	44-46
Caustic Concentration	g/L Na_2CO_3	210
Slurry Density	kg/m^3	1650-1780
Slurry Feed Temperature	°C	70-75
Slurry Exit Temperature	°C	90-100
Heater Shell Size	NB	600

After 9 weeks operation and despite the heaters being repeatedly subjected to undesirable process conditions due to plant upsets, HTC was still stable at 1500–1550 $W/m^2{}^\circ C$ (Graph I). HTC regularly recovered after the heaters were left full of slurry during extended shutdowns from other plant problems, demonstrating that the simplified design allows the heater to re-suspend settled solids of its own accord when draining is not done or flow interruptions occur.

When heaters were taken offline and inspected after the 9 weeks operation there was only a thin layer of scale observed in the tubes that was quickly and effectively removed with high-pressure water jet cleaning.

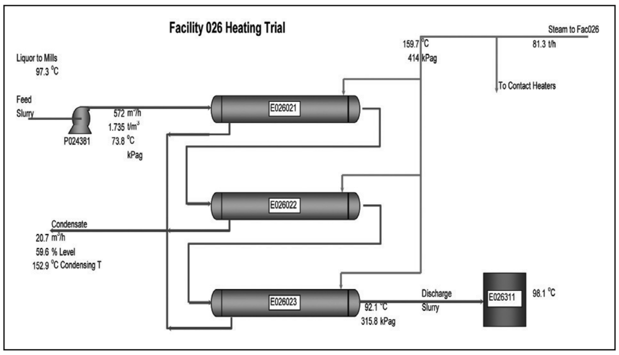
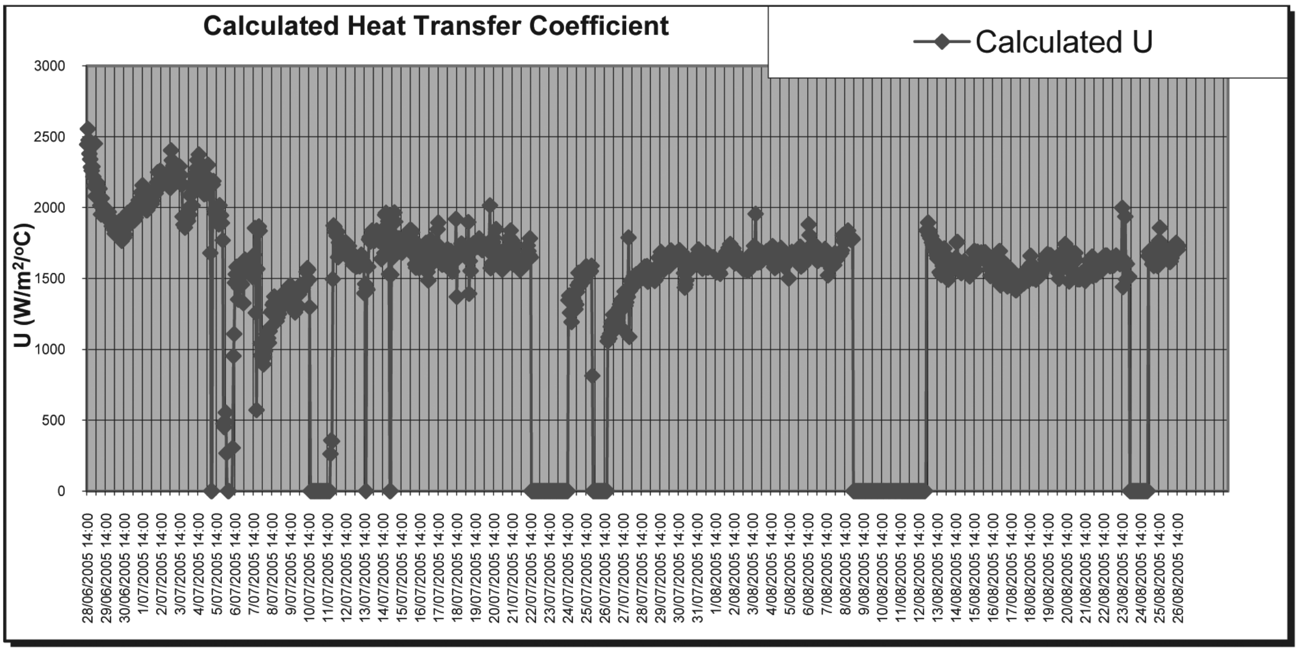


Figure 3. Trial Process Schematic

2.2 Technical Challenges and Sensitivity to Process Parameters

Design of the new bauxite slurry heating system addresses technical challenges associated with key process parameters that are important in the design but difficult to accurately establish:

- Expected heater cleaning cycle required
- Scale Thermal Conductivity
- Shell Side Fouling Factor
- Rate of decline of HTC or Scaling Rate
- Bauxite characteristics (including slurry rheology)



Graph 1. Full Scale Trial Heat Transfer Coefficient – Refinery 1

Based on on-site observations of the cleaning process, it was estimated the three heaters could all be cleaned within 3–4 hours. The reduced scale thickness may mean only a high velocity liquor flush on occasions, a major improvement on existing designs.

Note that due to the high HTC maintained, cleaning was not necessary but performed as a trial only, in fact it is more beneficial to leave a slight scale film on the tubes as this will protect the tube wall from long term wear.

If this information is not available or there is concern over the accuracy or relevance of the data that are available, data can be extrapolated from other sources to develop values suitable for design. However, this approach introduces a degree of uncertainty to the design.

While use of actual data is preferred, it is also recognised that measurement of some of the above parameters in laboratory test work or even existing plant operations has limitations. This uncertainty can lead to a belief that pilot testing is necessary.

The 'modular' component of the new heating system design enables uncertainty in parameters to be managed in a cost effective manner by allowing additional heaters to be incorporated into the design or added at a later stage. Due to the simplicity of the heaters, the cost of doing this is in the order of USD 100–150K per heater, which is much lower than the cost of a pilot trial.

The following sensitivity analysis shows how uncertainty in the parameters can be assessed to enable a manageable level of risk to be selected in design.

A target temperature of 105 °C and 12 weeks cleaning cycle were selected as the base case.

Scale Thickness

Scale thickness is proportional to scaling rate, hence the time between cleaning cycles is related to the change in scaling rate:

- To maintain 105 °C, a 20% increase in scaling rate reduces life from 12 to 10 weeks, a 17% decrease in cleaning cycle.
- To maintain 12 weeks life, a 20% increase in scaling rate reduces exit temperature from 105 °C to 102.5 °C.

Slurry Rheology

Accuracy of slurry rheology values can be expected to vary by 50–100% due to the difficulty of measurement in the laboratory, although the impact on design will be significantly less:

- To maintain 105 °C, a 100% increase in slurry viscosity from base value only reduces life from 12 to 10.4 weeks, a 13% decrease in cleaning cycle.
- To maintain 12 weeks life, a 100% increase in slurry viscosity from base value only reduces exit temperature from 105 °C to 103 °C.

Scale Thermal Conductivity (Base value 1.0 W/m^2 °C)

This potentially has the greatest impact as there is a wide range of values reported for different bauxites and refineries:

- To maintain 105 °C, a scale conductivity value of 0.3 W/m^2 °C reduces life from 12 weeks to 3 weeks, a 75% decrease in cleaning cycle.
- To maintain 105 °C, a conductivity value of 1.73 W/m^2 °C increases life from 12 weeks to 23.2 weeks, an increase of 93% in cleaning cycle.
- To maintain 12 weeks life, a scale conductivity value of 0.3 W/m^2 °C reduces exit temperature from 105 °C to 85.1 °C, a decrease of 20 °C.

Shell Side Fouling

The quality of steam should be clean to prevent scaling inside the shell. Fouling factor can be predicted accurately and will not change significantly over time provided steam quality is maintained:

- To maintain 105 °C, a 100% increase in shell side fouling only decreases cleaning cycle from 12 weeks to 10 weeks, a 17% decrease in cleaning cycle.
- To maintain 12 weeks life, a 100% increase in shell side fouling only reduces end temperature from 105 °C to 102.7 °C.

The example analysis above demonstrates that process parameters will have varying degrees of effect on the heating performance. Some will counteract the effect of others. Except for scale thermal conductivity, even relatively large variations in expected values of key parameters generally result in only small variations in heating system design, that is, a variation of one or two heaters which can be added following commissioning if it is found that the design parameters used were not fully valid. This is a key benefit of the new modular design.

Since scale thermal conductivity is the main factor that can have a significant impact on number of heaters or life cycle, it is preferable to establish at least an approximate value from laboratory tests to reduce technical risk. Samples taken from existing desilication or digestion heating equipment utilising the bauxite under consideration can be measured.

The technical challenges can be overcome when the issues and relevance to the system performance is properly understood.

2.4 Methodology for Design

Each type of bauxite and scale exhibit different properties under different process conditions. The conservative way to obtain definitive data for actual slurries to be heated is to conduct pilot plant trials or undertake bench-scale testing. While bench-scale testing of thick slurries may be less costly, accuracy of the data obtained may not add any technical value.

As found in the project outlined above, neither the cost nor time delays associated with plant trials or bench-scale testing are generally considered justified given the alternative approach utilised below. A design methodology has been developed that generates information from existing plant data and other sources to perform design without the need for pilot testing:

- **Scaling Rate.** HTC curves are generated and scaling rates estimated from plant data and used to estimate the life cycle of the Thick Slurry Heaters. While this method is subject to inaccuracy, it provides some basis for estimation in the absence of a pilot trial.
- **Slurry Rheology**. Shear stress – shear rate rheograms are developed.
- **Scale Thermal Conductivity**. Laboratory measurements are made and compared to values of the in-house database.

General heat exchanger design principles are well documented [3,4,5] and can be applied to optimise the performance. The relative benefits of design enhancements versus additional capital costs required should be considered to ensure efficient and effective use of capital spending.

3. 1st Full Scale Facility Installation Results

A full scale design for heating full plant flow for a new pre-desilication facility was recently commissioned in Australia. The heating system consists of 10 heaters, 8 duty and 2 spares. Since there is only one incoming feed, piping layout allowed any pair of heaters to be taken out of service for cleaning.

Initially the design was restricted to 85 °C rather than 105 °C due to process and equipment concerns in Digestion. With the modular design, this allowed the number of heaters online to be adjusted to suit the much lower duty.

The system was commissioned in late 2007 with relative ease and site personnel have indicated that operations and maintenance found the system easy to operate and clean.

The HTC graph for the heating system performance is given in Graph 2. This plant slurry exhibits a more viscous nature, significantly higher silica content and lower tube velocities than the slurry used in the Pilot Plant Trial resulting in a lower design HTC target of ~840 W/m^2 °C.

This graph indicates performance is close to target. Importantly, it was discovered on inspection that there was little or no tube scale and the performance drop off was due to tube blockages, some due to large pieces of scale (50mm+) from an unknown source. The lack of tube scale again indicates the technology to be sound. Monitoring is ongoing to optimise the performances and was in progress during the writing of this paper.

3.1 Investment Payback Period

Payback for the capital investment required to install the new system to replace existing direct steam injection has been analysed for a number of refinery sizes and configurations using typical energy costs. The analyses indicated:

- Capital costs ranged from USD 2.2–3.7 million
- Annual energy savings ranged from USD 2.0–5.7 million
- Payback ranged from 8–14 months.

3.2 Other Applications

Application of this heating system was originally designed to resolve the problems associated with indirect heating of thick bauxite slurries. However, the design can potentially be applied to any industry heating thick or thin slurries or liquor where scaling occurs. For example, alumina hydrate precipitator inter-stage coolers are typically plate heat exchangers. They have a high volume and low thermal exchange of typically only 5–10 °C per heater.

These heaters are notorious for high scaling and blocking issues and high maintenance to keep clean. The application of this heating system can be extended to several larger heaters that offer a more robust and easily maintainable heating system. The single pass tubes will be less susceptible to blockages and easier to clean. The control system should also reduce the scaling rate, extending the cleaning cycle.

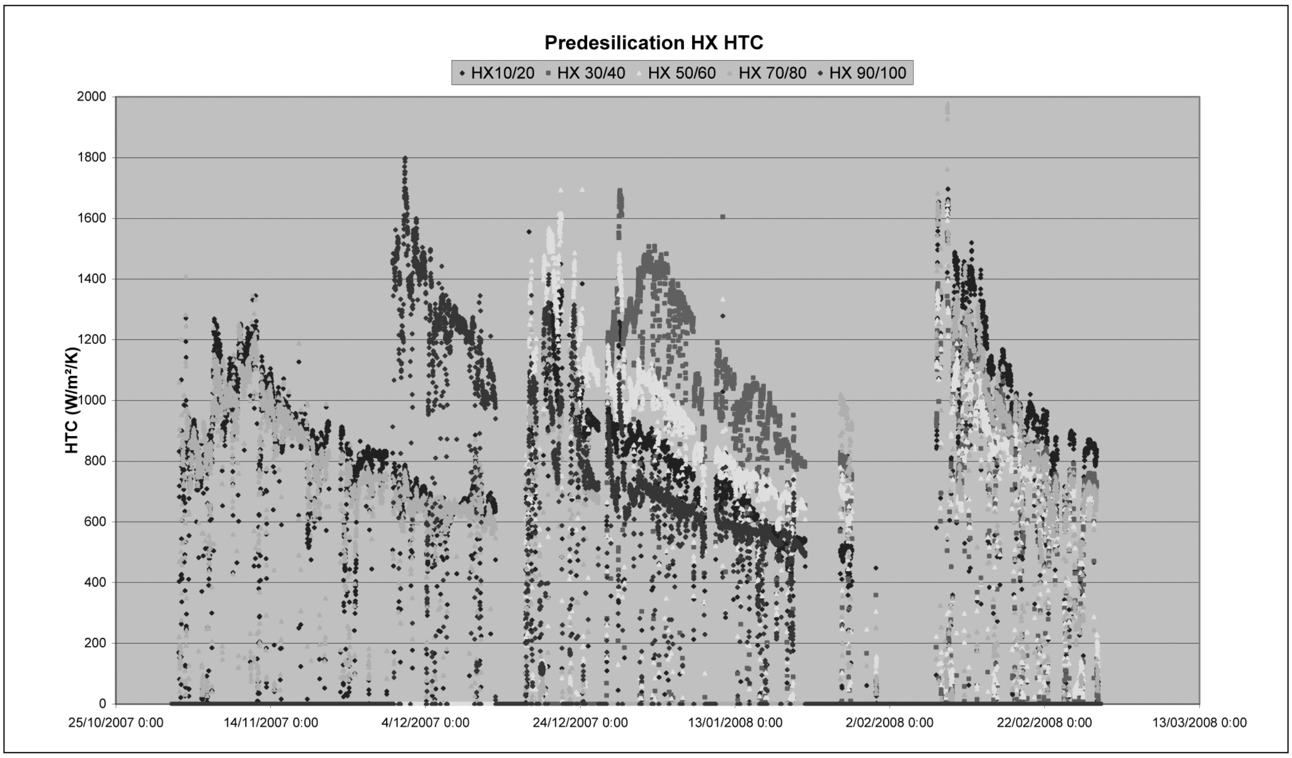
By applying similar design principles, the advantages of this heating system can be translated to many different applications.

4. Conclusions

Providing indirect pre-heating of slurry prior to Digestion and elimination of dilution from the process generally has a significant cost saving for any refinery, and particularly for a refinery with limited evaporation and plant capacity.

A successful indirect heating system is dependent on resolving the process and design parameters, mechanical design and maintenance issues associated with this type of heater. The new design has been developed to address all these aspects.

In the absence of accurate process data, the modular design reduces technical risk and hence reduces capital risk and potentially eliminates the need for expensive and time-consuming pilot testing. The savings resulting from achieving the benefits from the new indirect heating system earlier by avoiding project delays due to pilot testing more than outweigh the cost of including or adding additional heaters later if found to be required



Graph 2: Full Scale Project Heat Transfer Coefficient – Refinery 2

The simplicity of the mechanical design addresses the maintenance and mechanical issues. The integrated control system and backpressure control system addresses the scaling problem.

The pilot trial and new facility installation to date has successfully proven the technology is sound, and further commercial installations will establish the robustness of the design for a range of bauxites and process conditions. The commercial installations will also provide additional information on the potential application of this technology to any thick or thin mineral slurry heating process in alumina refineries and other industries.

References

1. International Publication Number WO 2005/119154 A1 (2005), Thick Slurry Heating System.
2. D Deboer, M Edwards, R Kelly, P McIntosh (TMS 2007), New Technology for Indirect Thick Slurry Heating.
3. D.A. Donohue (1949), Heat Transfer and Pressure Drop in Heat Exchangers, Industrial and Engineering Chemistry Vol 41, No 11.
4. D.Q. Kern (1965), Process Heat Transfer, McGraw-Hill.
5. Tubular Exchanger Manufacturers Association, Inc (1999), Standards of the Tubular Exchanger Manufacturers Association, Eighth Edition.