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THE 'VIRTUAL BATTERY' – OPERATING AN ALUMINIUM SMELTER WITH FLEXIBLE ENERGY INPUT

N. Depree[1], R. Düssel[2], P. Patel[1], T. Reek[2]
[1]Light Metals Research Centre, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
[2]TRIMET Aluminium SE, Aluminiumallee 1 Essen, Germany

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Abstract

TRIMET Aluminium SE operates four smelters in Western Europe. TRIMET has investigated power modulation and opportunities to provide services to the energy grid for several years. The primary aim has been to stay competitive in a geographic zone with above world-average energy prices as well as having to deal with high volatility in energy prices caused by renewable, non-baseload energy sources.

Recent work has seen the implementation of Shell Heat Exchanger (SHE) technology on 12 pots at TRIMET's plant in Essen, Germany. The heat exchangers are capable of boosting sidewall heat extraction or acting as an insulator depending on active air flow or not. The pots have comfortably maintained heat balance with stable ledge when operated within 150 to 180kA for up to 48h. Greater control of heat loss has also enabled operating voltages to be significantly reduced. By being able to operate significantly above or below the conventional design amperage, the smelter can operate as a 'Virtual Battery' to the grid.

Introduction

Germany is striving to increase the share of electricity supplied by renewable sources. While wind and solar power both have significantly reduced CO_2-emissions, they both have a highly volatile nature. This necessitates conventional power plants to operate in standby modes to balance the grid load, negating much of the possible benefits of renewable energy [1]. Making the energy demand more flexible would be a great benefit given the volatile generation system and allow greater integration of renewable energy production.

Primary aluminium production is, however, a highly energy intensive process that traditionally demands a near-constant energy input. Worldwide about 3% of all generated electricity is used to produce 50 million tpy of aluminium. Germany is slightly below this average with 2% of all generated electricity [2].

TRIMET has modified a test section of 12 reduction pots (from a total of 360) located at their Essen plant with Shell Heat Exchanger technology and an optimized bus bar system. A key objective of this is to enable highly flexible energy input of up to ±25% to better align the plant with the realities of the generation system. So far this has enabled the pots to operate with +20/-13% energy input for up to 48h while staying within the optimum process window.

By enabling variation in power consumption at short notice significantly above or below the usual level, the smelter can act as a 'virtual battery' in the electricity grid, 'returning' capacity to the grid at times of high demand and price and preventing the need for equivalent capacity of conventional energy production that otherwise has to be added.

Shell Heat Exchanger Technology

The Shell Heat Exchanger (SHE) Technology is patented and developed by the Light Metals Research Centre (LMRC) of the University of Auckland.

The purpose of the SHE-technology is to allow dynamic control of the sidewall heat loss to help maintain operable heat balance when there are significant changes in a pot's power input. This is achieved by varying the airflow through the individual exchanger units (controlled via a suction fan) to control the heat transfer rate at the sidewall as per the schematic diagram in Figure 1. Airflow above a base demand allows the sidewall heat loss to be increased, which compensates for power increases (eg. upwards modulation) in the pot. Operating with an associated airflow below the base demand reduces the heat loss thereby creating an insulating system that compensates for power decreases in the pot (eg. downwards modulation) [3, 4]. Figure 2 shows the variation in heat extraction achievable with varying flow rates through the system.

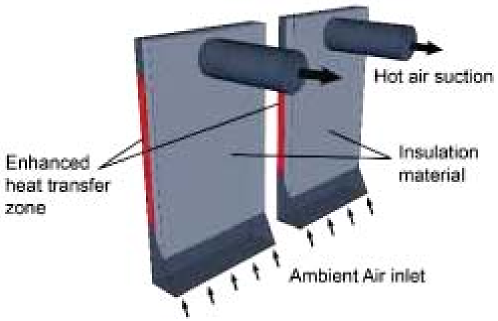


Figure 1 - Schematic of Shell Heat Exchanger (SHE) Concept

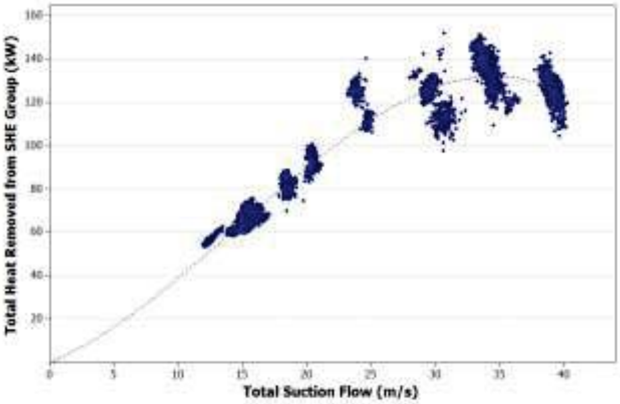
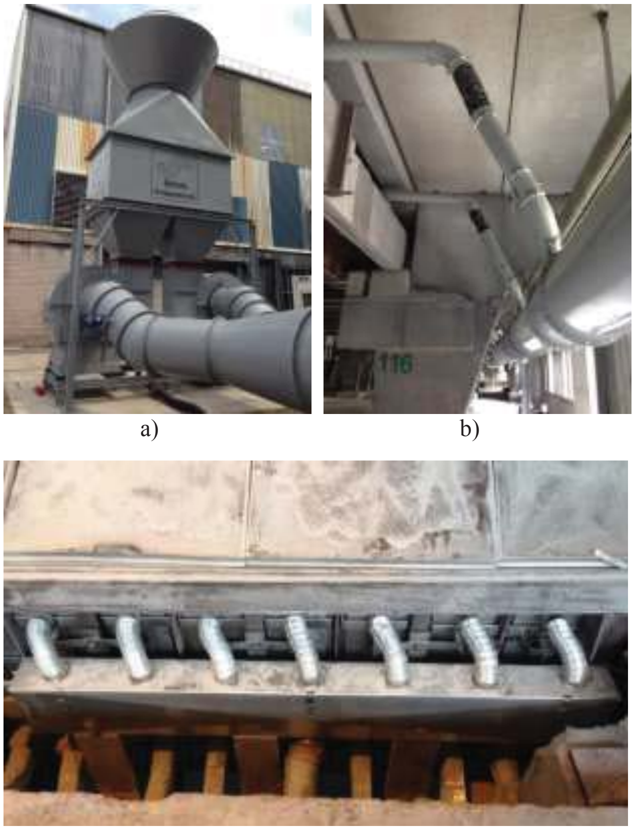


Figure 2- Total heat extraction from the booster group as a function of airflow rate through the SHE system.

Installation and Design

The SHE trial is installed on a mid-line booster group of 12 pots, with capability of increasing current by up to 25kA above the rest of the line. The current of the booster section cannot be reduced independently below the base line current without also reducing current on the rest of the pots in the line, however, which is not possible in a safe manner for more than short periods. For this reason, most trials have involved upwards modulation from the base line current and downwards modulations starting from an elevated state down to the base line current. Some trials have involved reducing the whole line current for up to two days, with additional voltage applied to non-SHE pots.



a) b)

c)

Figure 3- SHE trial installation details showing a) Redundant dual-fan system and exhaust stack with silencer, b) branch ducts to pot side in basement, c) SHE units connected to distribution manifold box on pot sidewall

The current 12-pot trial follows an earlier one-pot test design and was installed over 12 days in June 2014. The required ducting and fans were placed ahead of time so that each pot could immediately be connected to the suction flow to prevent overheating. The system comprises of four main ducts and each duct is connected to one side of a pot row down each side of the electrolysis hall equipped with end-to-end pots. The branch ducts are connected to a redundant setup of two fans located on a plinth outside the potroom, with an adjacent control room for fan control and temperature monitoring equipment. The main ducts are connected to three smaller branch ducts per pot-side, which are in turn connected to three manifold boxes mounted above the cathode collector bars adjacent to the shell.

Each manifold box provides suction for 7-8 SHE units, with a total of 44 units per pot. The SHE units are mounted to the wall of a pot shell, one in each inter-cradle space, using a spring loaded clamping system. The ducting and SHE mounting system is completely reversible with no welding or permanent attachment required. The SHE units were installed in-situ while the line was operational, but disconnection of the branch ducts enables the entire pot to be removed to reconstruction with the SHE attached for easier removal later.

Instrumentation consists of 12 thermocouples per pot, at upper- and lower-sidewall positions at the centre and ends of each side, as well as air suction temperature at each pot, and air duct temperatures and flowrates at several locations in the main duct. Two pots have additional instrumentation of 48 thermocouples for more detailed study. Temperatures and airflows are all logged at high frequency (between 1 and 600s) in the monitoring software. High and low temperature alarms are used on all thermocouple measurements to help control sidewall temperatures within target ranges and prevent excess ledge freezing or melting and associated sidewall damage. Currently fan control is manual and alarms alert to when manual fan changes may be required.

The airflow to each manifold of 7-8 SHE units is balanced via damper valves, where the individual SHEs tend to be self-balancing due to pressure drop. The main duct branches are also balanced via damper valves. The main suction flow rate is controlled via a variable speed drive on each fan, with the fan flow rates currently being set manually for each modulation and referenced against pot temperatures.

Heat Balance Control

A key aspect of the SHE system is to allow operation at the existing or as-designed pot heat balance, as well as opening the window for upwards and downwards modulation. Pots equipped with the SHE should be able to run permanently with minimal change in existing procedures or process control even though the energy input is varied significantly. This requires sufficient flexibility in the system to allow both higher heat extraction through increased airflow and also an insulation capability to reduce sidewall heat loss when required. A key stage of commissioning is to find the balance in this heat insulation/extraction range where the pot heat balance can be maintained as prior to SHE installation. This typically requires a moderate suction airflow to compensate for the insulating effects of the SHE.

As the temperatures measured outside the cell are continuously available, suction calibration can be achieved quickly, although some longer term monitoring is required due to the slow speed of changes in ledge profile and heat transfer. Suction calibration also involves flow balancing of the ductwork by manipulation of the damper butterfly valves, both around the main branch ducts and also the flow to each manifold box individually. This can also involve monitoring of temperatures over an extended period of time to ensure the temperature profile is even and stable i.e. the corners especially are neither too hot nor cold.

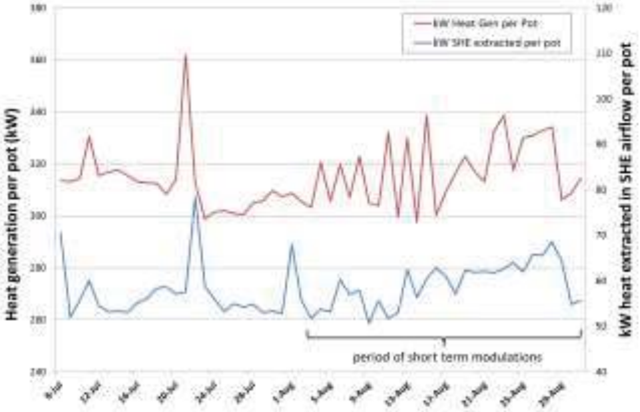


Figure 4 - Pot heat generation and heat extraction from SHE

Balancing of airflow is the main practical difficulty in commissioning, as all dampers are controlled manually. The changes in airflow can be interacting and nonlinear. Once a suitable balance has been found, however, the dampers usually do not need to be adjusted again. As small irregularities in airflow tend to magnify as the airflow is increased it is better to perform flow balancing at a relatively high flowrate. In practice it is difficult to balance the main branch flows to less than 10-20% difference using manual dampers. Otherwise, the airflow distribution has proven to be consistent over one year of modulation trials.

The SHE airflow is currently controlled by regulating the suction fan manually to maintain approximately stable shell temperatures during modulations. This has proven to be easy and stable in operation with only limited adjustment needed. The calculated heat extraction vs pot heat generation is shown in Figure 4, based on measured outlet air temperature and suction rate in the SHE main ducts.

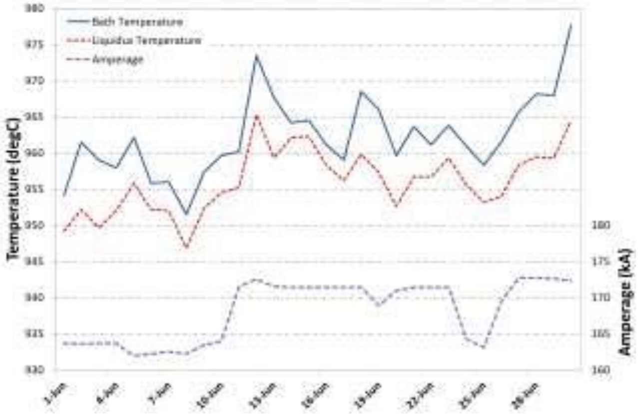


Figure 5 - Long term trial of +10kA for three weeks showing line current, average bath and liquidus temperatures of 12 pots

Further changes in pot heat balance may be required depending on the ultimate goals of power consumption, modulation magnitude and pattern. This may involve long-term changes in the average anode cover level or material mix, including yoke assembly temperature monitoring and auditing of covering practices, changes to average pot exhaust draught rates to the gas treatment center, or bath chemistry changes.

Modulation Trial Design

The initial design of the SHE system was to allow for significant, sustained upwards modulations in line current, using the SHE primarily to increase heat extraction from the sidewall. However, political and economic opportunities have shown that there is potentially more benefit to downwards modulations for power-cutting purposes, on both short and long time scales, which allows the smelter to be used as a 'virtual battery' and release power to the grid for distribution elsewhere in times of peak demand (and cost).

Downward modulations require that line current be significantly reduced from base load, which is not easily possible on a trial group without adversely affecting the entire line. For this reason, most trials were of upwards modulation, or downward modulations from an initially raised base point down to the normal line average. Modulations are tested both with rapid changes over short periods (hours) and sustained changes over long periods (weeks).

The prior single-pot trials had shown stable operation at high heat extraction using both increased booster current and additional voltage for heat generation. The first 12-pot trial consisted of a sustained increase of +10kA for several weeks as shown in Figure 5. While the EPT14 pot design is robust and may cope with this increase without SHE units installed, this system gives much greater flexibility in the timing and method of modulation as well as enabling much larger modulations than without SHE.

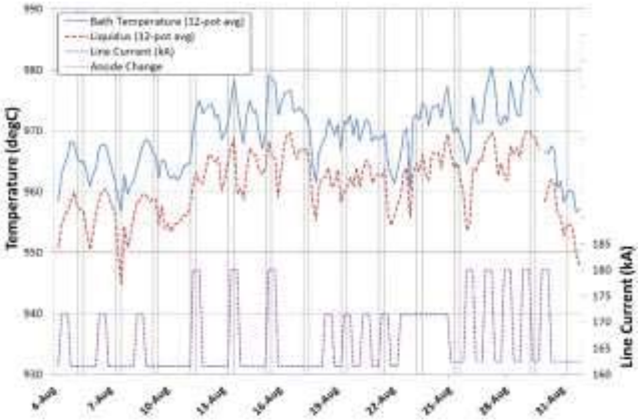


Figure 6 - short term modulations of +10kA and +18kA showing anode change periods and bath and liquidus temperature averages for 12 pots (even side).

The long-term scenario was followed by short-term modulations to simulate rapid response to electricity price spreads e.g. daily/nightly changes. These involved increases of +10kA and +18kA for 8-24hr periods, with normal periods in between to represent periods of regular energy prices.

After this, the pots were allowed to stabilize at +10kA line current as a new 'base' state on the booster group. Short-term downwards modulations of -10kA – which were essentially returning to normal line current – and upwards modulations of +8kA were then tested at short intervals from this new base current. Bath and liquidus temperature responses to modulation are shown in Figure 6 and superheat in Figure 7, also showing the approximate timing of anode changes.

Even larger downwards modulations were then performed by reducing current of the entire line, and adding compensatory voltage to the non-SHE installed pots to maintain heat balance, however, these were limited to periods of maximum 48h to keep the impact on the unmodified rest of the reduction line under control. As a result of this experiment it was found that the pots with compensated voltage required additional heat equal to 0.8 kWh/kg higher energy consumption, while the boosted group with shell heat exchangers was able to keep the same energy consumption as previously. The higher energy consumption was due to both increased cell voltage as well as lower current efficiency, as will be examined later in the paper.

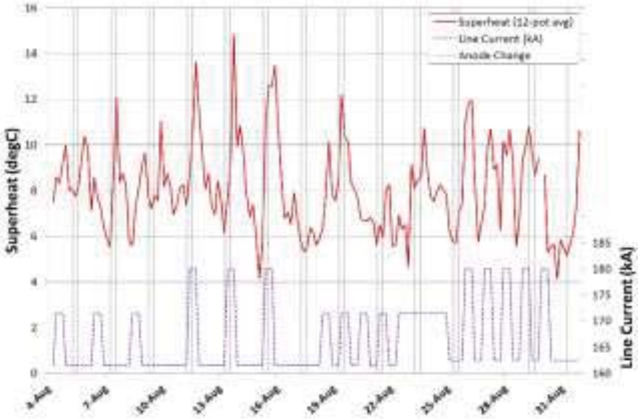


Figure 7 - short term modulations of +10kA and +18kA showing anode change periods and superheat temperature averages for 6 pots (anode change subsection).

Key metrics monitored throughout the trials were the bath temperature, liquidus and superheat as measured using a Heraeus Fibrelab instrument, as well as pot voltage and noise. The current modulation scheme is shown in Figure **Error! Reference source not found.**8, with the responses in bath and liquidus temperatures shown in Figure 9. Shell temperatures were monitored carefully both to avoid short term hot- or cold-spots and to ensure the long-term average remained steady.

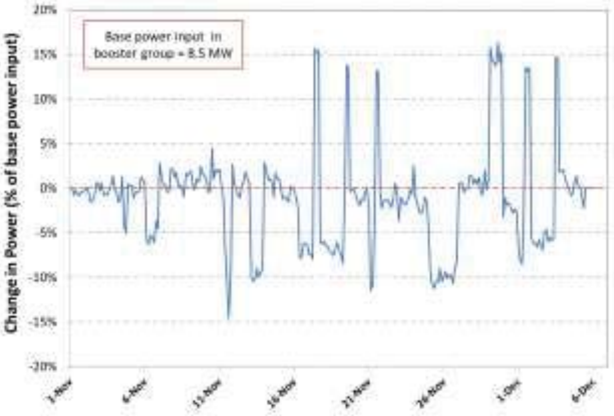


Figure 8 - Repeated downwards and upwards modulations from base line current using corrective voltage on non-SHE pots

Modulation Trial Results

The longer term trials went smoothly, with the pots quickly returning to a steady operating state after 24h at approximately normal temperature, superheat and noise levels. The short term trials, however, were of too fast frequency that the pots were not reaching steady states before successive changes in line current. A key finding is the rapid rise in bath and superheat temperatures at the time of upwards modulation measured by 4-hourly Fibrelab measurement. This is in contrast to the relatively slower fall in temperature following downwards modulation (or removal of upwards modulation/heat generation).

This caused long term increases in bath temperature shown in Figure **Error! Reference source not found.**6, which also resulted in decreasing measured ledge thickness. This needs to be considered carefully in future, such as by using an ‘energy counter’ to integrate net energy input changes, which could be compensated using changes in SHE airflow (additional cooling or insulation) i.e. by maintaining increased forced cooling for a period after upwards modulation. Anode changes had large impact on superheat, especially if changed shortly after upwards modulation to reduce the increase in temperature, with a smaller effect if changed before modulation. Anode changes could be leveraged better to reduce heat at desirable times, or by not adding additional anode-setting voltage when superheat is already high.

Pot shell temperatures were well controlled at all times and the surface temperatures responded quickly to changes in suction airflow, although these changes take a long time to propagate to new stable ledge positions. The SHE system does, however, allow for stable operation with thinner than normal ledge thickness due to the forced cooling through the sidewall. Importantly, no damage or increases in metal silicon content were observed, which would indicate sidewall brick erosion.

Bath and superheat temperatures will naturally become higher when operating at high heat input. As sidewall heat loss comprises only approximately 40% of the total heat loss as measured on these pots, it is difficult to entirely control bath temperature via SHE adjustment only. It is estimated that the SHE system can provide around 50% of any additional heat loss/conservation required. A long term strategy will therefore involve careful consideration of factors such as suitable bath composition to maintain alumina dissolution at lower superheats and the overall impact of the entire heat loss of the pot. For example, the next step is to get more control over the top heat loss. Top heat loss can be regulated on the long term through changes in covering practice and cover material properties, but can also be more dynamically controlled through changes in suction rate towards the GTC. However, when varying suction towards the GTC the challenge will be to do so without compromising environmental regulations and therefore this needs to be investigated carefully.

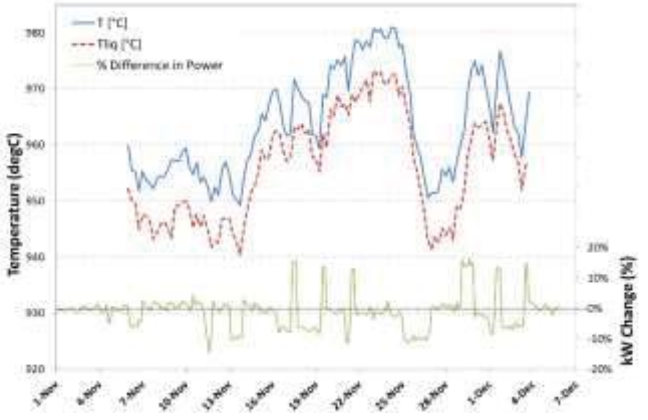


*Figure 9 - Bath and liquidus temperature trends over period of upwards and downwards modulations**Error! Reference source not found.**.*

Operating Voltage Reduction

In addition to gains in power input flexibility, improvements in energy efficiency have also been made in this trail group when running at the normal operating amperage of 162 kA.

Figure 10 shows the results of an Anode-Cathode Distance (ACD) vs pot stability test carried out on a typical EPT-14 pot at TRIMET Essen. Figure 10 shows that from the normal operating voltage of approximately 4.4V the ACD could be reduced by an equivalent 500mV before significant instability was recorded. This result indicates that the pot is not ACD limited from a stability point of view and that it therefore has potential for significant voltage reductions through further squeezing of the ACD.

From previous experiences it is known, however, that further ACD squeezing in the long term leads to low pot operating temperatures and greater instability caused by ridging. This confirmed that the pots were heat balance limited and that lower heat generation within the pot could not be sustained with the current pot design.

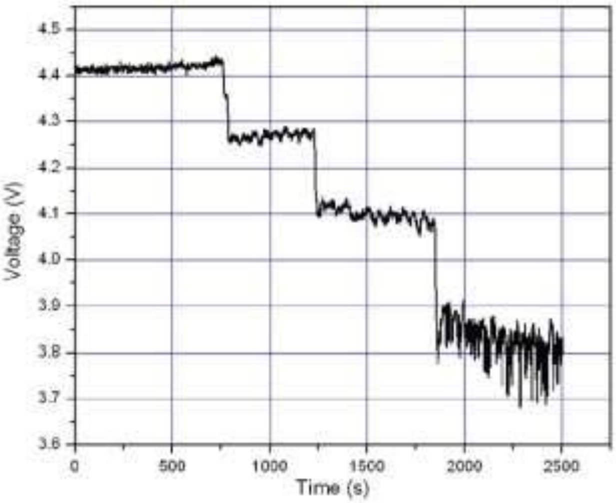


Figure 10 - Impact of ACD reduction on pot stability on a typical EPT-14 pot at TRIMET, Essen.

This heat balance limitation has been partly alleviated through the installation and optimized operation of the Shell Heat Exchangers. Trials were conducted to reduce the ACD (heat generation) whilst concurrently reducing the airflow through the exchangers. Reducing the airflow allowed the heat loss to be controlled to a lower level (operating in a slight insulating mode) which compensated for the lower heat generation in the pot. Initial trials showed that reduction in ACD equivalent to 60mV was easily achieved whilst still providing a long term stable heat balance and operations. This reduction in ACD was also enabled through additional insulation being placed on the shell corners and also having less suction in the exchangers near the corners. These measures have alleviated the significant corner ridging that the cell design is normally prone too. This combined optimization of the heat balance has resulted in more stable operations as ledge and ridge profiles have been able to be controlled. This has resulted in a lower amount of long term pot instability and current efficiencies that are consistently maintained above 93%.

The combination of the reduction in ACD and more stable operation due to optimized heat balance resulted in approximately a 0.25 kWh_{DC}/kg improvement in energy consumption and up to a 0.4% increase in current efficiency in the trial group when compared with the rest of the pots operating in the line at the same amperage (refer to Figure 11 and 12, period April to June 2015).

Overall Performance

Figures 11 and 12 shows the current efficiency and energy consumption of the trial pots in comparison to the rest of the pots in the line since November 2014.

In general it has been found that pots with the SHE Technology are more robust to changes in power input due to modulation. During normal power input operation (162 kA) the trial group maintained current efficiency at a similar level as the rest of the pots in the line (April to date). However, during power modulation it is clear that pots with the SHE maintain current efficiency better than pots without. This is shown in Figure 11 over the November-December modulation trials where it was found that the trial pots were able to maintain current efficiency at up to 1.5% higher over this same power modulation trial period.

Figure 11 - Trial group current efficiency (%) compared to rest-of-line average over extended trial period

The trial group with Shell Heat Exchanger technology had approximately 1.0 kWh_{DC}/kg lower energy consumption than pots modulated without SHE. However, in normal power input conditions (162 kA during April to June 2015) the benefit of the use of SHE's has been measured at 0.25 kWh_{DC}/kg when compared to pots without the SHE Technology due to voltage reductions discussed earlier.

It should be noted that from June to August 2015, the significant reduction in energy consumption seen in Figure 12 is due implementation of magnetic compensation in trial group, which has allowed further voltage reductions. This will be discussed in more detail in future publications.

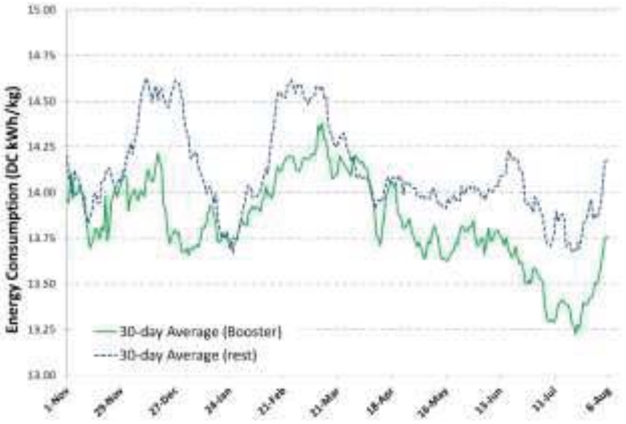


Figure 12 - Trial group energy consumption (DC kWhr/kg Al) compared to rest-of-line average over extended trial period

Also, it should be noted that decreases in current efficiency and increases in energy consumption over the period of January to March 2015 were mainly due to anode quality related issues and not a result of any of the ‘virtual battery’ trials.

Future Trial Plans

The SHE trial booster group pots have been operated for significant periods of up to 48h stably with +20% and -13% power input compared to base load. The goal for future trials is to achieve a variation in power input of ± 25% for 48 hours.

An advanced ‘energy counter’ for heat balance control is currently being developed, which will help to achieve this goal. The energy counter is being tested on pots with almost 100 thermocouples each to compare pot shell temperatures all around including dry scrubber flows and SHE air suction rates as well as air temperatures. This should allow better understanding and thus better control over the pot heat balance during energy modulations, especially for larger and longer modulations. This may prevent excessive ledge freezing or melting and promote stability, hence giving the lowest energy consumption and highest current efficiency during flexible operation as well as during traditional, constant operation.

Temperature measurement and bath chemistry control processes will also be investigated further, as these can vary significantly depending on time and location of measurement in the bath, and should be considered in conjunction with any rapid changes in power input.

Further trials also involve newly-installed magnetic compensation at these pots, and further optimization of pot control parameters. It is expected that ACD can be stably lowered significantly further on pots with SHE than pots without, giving even further advantages in energy consumption.

Conclusions

The Shell Heat Exchanger technology tested on 12 pots at TRIMET Essen gave much greater flexibility in energy input to and dissipation from the pots. This opens up a wider operating window for line current while still maintaining stable operation over both short term rapid modulations and long term sustained modulations, which can be highly advantageous given the electricity market in Germany, and particularly the continuing reliance on volatile renewable generation.

The trials performed to date gave good performance at energy inputs -13% to +20% from normal base conditions and provided significant improvements in both current efficiency and energy consumption due to ledge and heat transfer stability improvements. It is planned to push this to ±25% energy flexibility in the near future, although this may require a larger (line-wide) trial to enable significant current reductions without adversely affecting other pots without SHE. This flexibility will give significant ability for the TRIMET Essen plant to act as a ‘virtual battery’ on the power distribution grid, reducing their power consumption in times of peak demand and price, and reducing the need for further installed back-up power generation capacity in Germany.

A major improvement for future trials will involve a sophisticated energy counter, including existing pot data as well as shell and airflow temperature measurements. This will allow for better long-term control of heat balance and bath temperatures during periods of varying modulations, as trials have shown long term trends due to limited manual control. Modulation changes may also be aligned better with anode changes, as this operation also has a significant and rapid effect on bath and superheat temperature. This necessitates rethinking of standard working procedures if moved beyond the scope of a small test group.

A key outcome of an installed SHE system is that flexible adjustment of pot energy input is no longer counteracted by unstable pot energy balance or increased specific energy consumption. If this ‘virtual battery’ system is applied to all three TRIMET plants in Germany then the storage capacity energy availability of the grid could increase by 7700 MWh, nearly as much as the largest German pump storage power plant. Almost 40% of this could be achieved solely by installation at Essen.

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