A Method of Cell Heat Balance Control to Enable Variable Power Usage by Aluminium Smelters

Nick B. Depree, Yashuang Gao, Mark P. Taylor, and John J. J. Chen

Abstract

Smelters worldwide face increasing challenges regarding power cost, flexibility requirements from power grids, and emission reduction from fossil-fuelled generation. Smelters can become responsible energy users by employing EnPot technology to proactively act as 'batteries' in power grids, to shed load and avoid coal/gas generation when renewables are insufficient, or take on extra load when excess power is available to increase production. The uncontrolled nature of cell heat loss has previously prohibited variable energy usage, however, EnPot can enable this with a complete heat balance of the cell. An analysis of typical heat loss distributions for 160 to 390 kA cells justifies how significantly reduced/increased power operation is achievable through control of cell heat losses. Further benefits of controlled heat loss are also described including benefits to cell control and life, as well as the uses of the waste heat collected.

Keywords

Aluminium smelting • Power modulation • Demand side response • Heat balance • Flexibility

Introduction

A worldwide trend continues to develop whereby power supply for aluminium smelters is becoming increasingly contested, insecure, politicised, or otherwise in need of better fitting in with other grid users at local, national, and international levels. This increasing uncertainty of power availability and pricing can not only be a threat to smelter operation and longevity, but also an opportunity for those smelters that are best able to become flexible power users [1]. These smelters may take advantage of variable power pricing, and provide extremely valuable backup services to grid generators, particularly as penetration of variable renewable energy (VRE) increases, also resulting in a significant reduction in scope 2 carbon emissions caused by the power supply to smelters [2]. EnPot is an enabling technology for this purpose, to allow smelters to increase their operating windows, and overcome the existing challenges regarding cell design and natural heat loss which otherwise prevent flexibility [3–5]. This is particularly applicable in cases where smelters are being incentivised to significantly reduce consumption for extended periods of time that occur during dry periods for hydropower generation.

The Current Situation

Smelting cells are designed for very high rates of heat loss from the sides and top of the pot, as controlled by the cell cathode and lining design, side fins and sometimes cooling networks on the shell, and high suction draught rates. This strategy enables the highest amperage operation, and therefore, maximizes the volume of metal produced, while also reducing fugitive emissions from the top of the pot. Effectively there is little focus on reducing variation in either pot shell design tolerances, e.g., for fins and cradles and shell surfaces, or in the draught that flows through each pot as long as it is sufficient to prevent loss of emissions through gaps in the hoods [6, 7].

Recent investigations have shown significant variability in the key aspects of side and top heat loss in many smelting cell designs, which is a clear risk factor when considering variation in power input while still needing to maintain heat balance and cell integrity. Changes in power input will cause

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some cells to heat/cool much faster than others, and some cells will, therefore, either fail early or else limit the range of power variation that can be safely tolerated on the rest of the potline. Variation in cell draught has not been regularly studied but has been shown to vary by 20–40% in some potlines [7], and hence the top heat loss via convection varies similarly with the changes in flow rate [6]. Recent investigations on 300 kA cell sidewall temperatures have also shown that the pot-to-pot and the position-to-position variability of shell heat loss is also routinely in the range of 20–40% (measured temperatures from 245–360 °C), despite the existence of forced sidewall cooling on every pot in these potlines. Investigations at 345–380 kA without forced cooling have shown average upper sidewall temperatures varying from 275–400 °C, with local hotspots as high as 520 °C [8], which is a clear limitation on increasing power consumption and hence heat generation.

Some smelters are conducting limited power modulation, particularly for short timescales such as full potline shutdowns for one hour when there are shortages or emergencies in the power grid [9], or day/night and weekend modulation rhythms [10]. In these cases, the shell cooling is still uncontrolled, and so there is a limit on allowable modulations and a need to have matching power increases to prevent long-term cooling and pot failures [10, 11].

In order to improve cell modulation ability, heat losses must now be controlled directly rather than the existing uncontrolled natural heat loss. In this way, heat losses can be reduced to match reduced heat generation, and preserve cell heat balance, or conversely increased to match higher line current and heat generation. Shell heat losses can be controlled via forced convection to air, where the airflow rate can be adjusted to suit the required heat transfer. This ‘Shell Heat Exchanger’ (SHE) technology has been developed at the University of Auckland specifically to suit the typical ambient conditions and mechanical and safety restrictions present for aluminium smelting cells [4, 5] and commercialised by EnPot [12].

Deep Modulation Technology

EnPot is a mature technology that has been industrially implemented at Trimet Essen smelter [3, 10, 13] with the aim of controlling sidewall heat losses to enable both upwards and downwards power modulation while maintaining existing cell heat balance and avoiding long-term overheating or cooling (freezing) problems. This technology provides part of the heat balance solution, however, it is also vital to consider and balance heat losses from the top of the cell particularly, where around 50% of total heat is lost. EnPot cannot be considered as a simple hardware addition, but a complete strategy to understand and manage key heat losses in a power modulation technology package.

Long term or compounding modulation changes will also affect plant operational scheduling and work practice requirements around tapping and anode changes, as well as require strict control over cell hood condition and regularity (hooding standards), and good condition of alumina feedings and anode covering and crust integrity.

For a smelter to operate with flexible power consumption, within a reasonable window of around ±20% power, the key factors are:

1. Sidewall and endwall heat loss control—via EnPot technology for sidewalls, also with some consideration of endwall losses via heat exchangers or insulating material.
2. Top Heat Loss control—by duct draught control, and hooding tightness control.
3. Standardisation of side and top heat losses from pot to pot on the potline—a periodic practice involving duct flow measurement and adjustment.
4. Automated feedback from each pot about the longer-term impact of deep modulation such as cathode temperature.
5. Effective process control results in bath temperature and ledge thickness stability, preventing overheating and sidewall damage, or cooling and poor performance.

The EnPot hardware covers the upper sidewalls of each pot, with the potential to reduce the sidewall heat losses by up to 70% in the case of cell power reduction [4, 10]. While only part of the upper sidewall is covered, the area affected by EnPot is that with the greatest heat loss (the hottest area), and which has the most effect on cell internal condition and thickness of frozen ledge (adjacent to the bath-metal interface). EnPot furthermore becomes the controlling factor of sidewall heat loss by disruption of existing convective and radiative heat transfer. A schematic view of the EnPot system is given in Fig. 1, and a photograph of the pot-side equipment installed at Trimet Essen is shown in Fig. 2. It can be seen that the heat exchangers cover a significant area of the sidewall heat transfer area, and extend down the length of the pot with a manifold system for zonally controlling heat flows.

Top heat loss can be adjusted by reducing draft rates roughly in proportion to the cell power reduction, assuming the hooding condition is sufficient to maintain fume collection. Similarly, in the case of increased power generation, the heat losses from the sidewalls and top can be increased to match, given sufficient additional capacity of GTC suction.

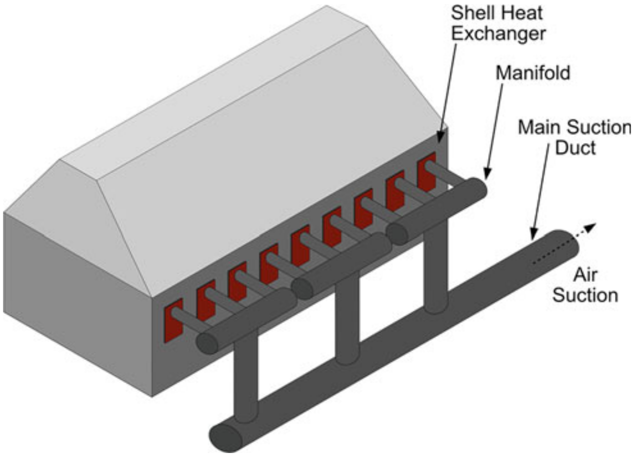

Fig. 1 Schematic of pot-side equipment for EnPot system

Heat Balance Calculations for Downward Modulation

The adjustment of cell heat balance along with changes in power input has been previously investigated for a range of cell designs and line currents. The development of the EnPot system in practice included trials on plants ranging from 160–300 kA, in particular Trimet Essen with a base line current of 164 kA [3]. Beyond this, cells of 360–390 kA at low current density similar to modern Chinese cell designs have been studied in both static and dynamic models [14, 15]. The gist of this present research is to demonstrate via simple calculations that the magnitude of heat balance changes required is similar, and practical, for both low (160 kA) and high (390 kA) current cell designs.

Fig. 2 Shell heat exchangers and manifolds installed at trimet essen

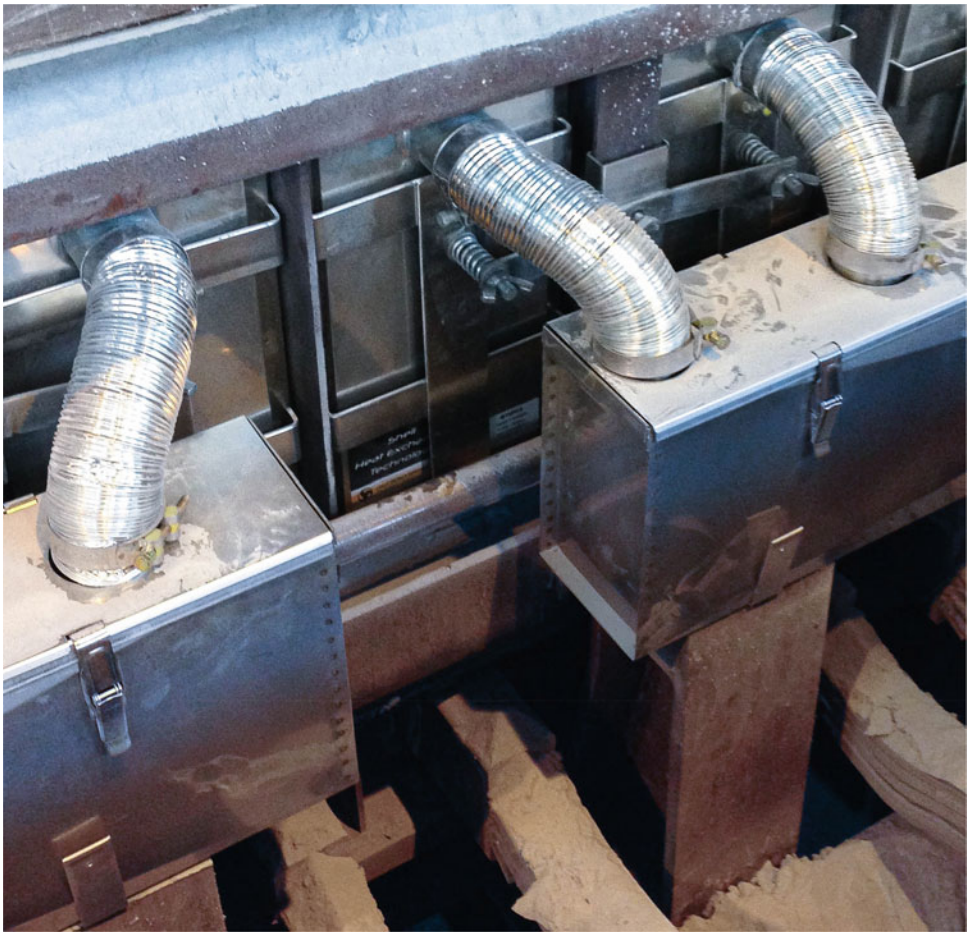

Table 1 Input heat balance data

Input data	Low current cell	High current cell
Line current (kA)	160	390
Cell voltage (V)	4.35	3.95
External voltage (V)	0.12	0.2
Current efficiency (%)	93	92
Reaction voltage (V)	2.03	2.03
Heat balance distribution		
Total heat dissipation (kW)	347	684
Top heat loss (kW)	132 (38%)	357 (52%)
Sidewall heat loss (kW)	137 (39%)	199 (29%)
Endwall heat loss (kW)	28 (8%)	48 (7%)
Collector bars (kW)	24 (7%)	34 (5%)
Bottom heat loss (kW)	28 (8%)	48 (7%)

A key input into these calculations is the in-situ measurement or calculation of heat balance distribution of these cell designs, along with key operating data including cell metered and external voltage, and current efficiency. These measurements and input data are shown in Table 1. Previous publications have investigated the 390 kA case [15], hence we consider the following procedure to investigate the 160 kA case in detail, and compare the summary of both cases in Tables 3 and 4.

Two options for downwards modulation can be considered, where either (a) only sidewall heat losses are reduced 70% via EnPot, and (b) additional changes are made to reduce endwall heat losses by 50%, plus top heat losses reduced by 20%. This shows both the potential for rapid modulation changes, and larger changes possible with complete control of the cell heat balance following a deep modulation technology design. The new heat balances are shown in Table 2, targeting line current changes of −20% and −30% respectively.

For example, assuming that we reduce the amperage down to 128 kA in the short term, or 112 kA in the long term, the operating voltage to maintain constant heat balance is calculated to be:

$$\begin{aligned}\text{New Cell Voltage}\,(128\,\text{kA}) &= (256\,\text{kW}/128\,\text{kA}) + 2.03V_{\text{reaction}}\\ &\quad + 0.12(128/160V_{\text{ext}})\\ &= 4.13\,\text{V}\end{aligned}$$

$$\begin{aligned}\text{New Cell Voltage}\,(112\,\text{kA}) &= (215\,\text{kW}/112\,\text{kA}) + 2.03V_{\text{reaction}}\\ &\quad + 0.12 * (112/160V_{\text{ext}})\\ &= 4.13\,\text{V}\end{aligned}$$

These new cell operating voltages represent constant heat balance scenarios, but a constant ACD scenario can realise significantly greater power savings, notwithstanding the minimum ACD required for magnetic stability. The following calculation shows the calculated cell operating voltage at 128 kA when utilizing the same pseudo resistance (comparable to constant ACD) as a cell operating at 160 kA and 4.35 V.

$$\begin{aligned}\text{Pseudo resistance}\,(160\,\text{kA}) &= (4.35\,\text{V} - 1.65\,\text{V})/160000\,\text{A}\\ &= 16.88\,\mu\Omega\end{aligned}$$

$$\begin{aligned}\text{New Cell Voltage}\,(128\,\text{kA}) &= (16.88\,\mu\Omega \times 128000\,\text{A}) + 1.65\,\text{V}\\ &= 3.81\,\text{V}\end{aligned}$$

Table 2 New heat loss distribution for 160 kA

New heat balance distribution	Sidewall only	Complete
Target line current (kA)	128 (−20%)	112 (−30%)
Total heat dissipation (kW)	256	215
Top heat loss (kW)	134	106 (−20%)
Sidewall heat loss (kW)	37 (−70%)	37 (−70%)
Endwall heat loss (kW)	42	21 (−50%)
Collector bars (kW)	25	25
Bottom heat loss (kW)	28	28

Table 3 Heat balance results for 160 kA cell

160 kA cell		Base	(a) Const HB	(a) Const ACD	(b) Const HB	(b) Const ACD
Heat Dissipation	kW	352	256	256	215	215
Amperage	kA	160	128	138	112	128
Voltage	V	4.35	4.13	4.00	4.03	3.83
Power Usage	%	100.0	−24%	−20%	−35%	−30%
Specific Power	kWhr/kg	13.8	13.2	12.7	12.9	12.1

Table 4 Heat balance results for 390 kA cell

390 kA cell		Base	(a) Const HB	(a) Const ACD	(b) Const HB	(b) Const ACD
Heat Dissipation	kW	687	555	555	432	432
Amperage	kA	390	312	355	273	318
Voltage	V	3.95	3.90	3.74	3.78	3.58
Power usage	%	100.0	−21%	−14%	−33%	−27%
Specific power	kWhr/kg	12.8	12.8	12.2	12.2	11.5

The total heat rejection at constant ACD of 228 kW is much lower than the specified 256 kW for constant heat balance. To achieve constant heat balance at constant ACD we can iterate the calculations and find instead 4.00 V at 138 kA, for the same 20% reduction in power consumption. As these constant ACD voltages are well below the constant heat balance voltages, the ACD will not need to be squeezed in order to reduce the power input to the cell. In fact we have room to increase the ACD if required. This calculation shows that with the Shell Heat Exchanger technology and the right top heat loss control it is possible to reduce amperage in the cell whilst still maintaining heat balance and ACD.

The complete results for a 160 kA cell are given in Table 3, and a 390 kA cell in Table 4, for cases of a) sidewall heat loss control only, and b) complete heat loss control, showing that in all cases operable combinations of cell line current and voltage can be found to give approximately 20% and 30% reduction in cell power consumption respectively.

It can also be seen in each table that operating at reduced line current gives good savings in specific power consumption, with energy usage reducing from 13.8 kWhr/kg in the 160 kA cell down to 12.1 kWhr/kg with the largest line current reduction, and from 12.8 to 11.5 kWhr/kg in the 390 kA cell.

These results are conservative when compared with Taylor and Chen [14] where a 25% reduction in line current from 390 to 290 kA was considered for this same cell condition. In this case the line current change was specified, and the heat balance changes needed to maintain thermal stability were calculated by detailed dynamic models as opposed to static calculations. Here, a total reduction in sidewall heat losses by 60–70% was needed, with a 30% reduction in top heat losses. The resulting model gave a 46% reduction in total power usage, with specific power consumption reducing to 10.5 kWhr/kg.

Results presented here, and by Taylor and Chen [14] show the great benefit of utilising a deep modulation technique in smelters, as in the case where there are power shortages or mandated power reductions, such that power usage could be reduced by 20–30% or more for a long period. The production rate of the smelter is of course reduced in proportion to the line current reduction, but the metal produced at this time is done so more efficiently at lower specific energy consumption. This power reduction is most needed when the energy is more expensive than usual, or more valued by grid operators elsewhere, and the smelter may also receive additional benefits by not using this energy, with appropriate contractual arrangements in place [2].

Dynamic modelling results [14] show that a drop in line current from 390 to 290 kA with simultaneous reduction in heat loss by sidewall insulation and reduced draught will reach a minimum temperature after 2.3 h, but continue to recover afterwards, as shown in Fig. 3. This required a 70% reduction in side and 30% reduction in top heat loss. The full time to reach a new equilibrium is not clearly known, and should be studied in practice, as it may affect the frequency and duration of large modulation changes made to the cells. Without sufficient temperature (external and internal)

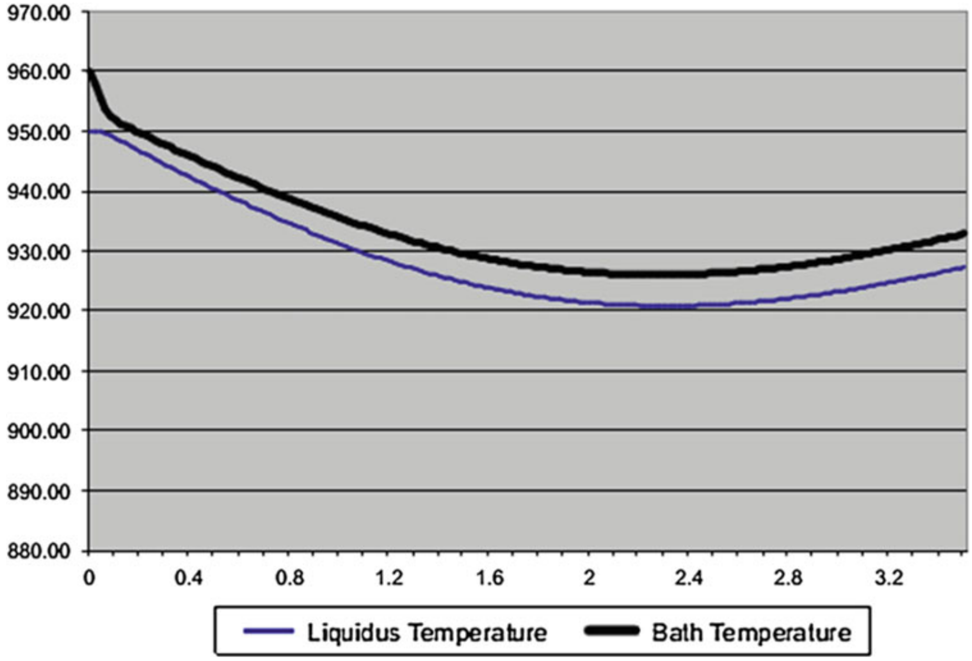

Fig. 3 Dynamic model result for 390 kA reduction to 290 kA with 70% side and 30% top insulation [14]

monitoring or improved understanding, successive modulation changes may outpace the ability of the cell to respond, and the thermal state may become out of control. This may be an issue for intra-day modulations, but does not affect long-term changes such as power reductions for long periods during times of high power price or low availability, such as dry seasons for hydro generation.

Upwards Modulations Calculations

A similar calculation is followed to find a stable heat balance operating point for upwards power modulation, however there are many other operational considerations when increasing power usage. These include the additional fan and scrubbing capacity needed at the GTC to allow for more airflow. An increase in power usage will also result in a corresponding increase in current density in the anodes, and demands on the anode quality, rods and transition joints, and require sufficient capacity in bus bars and power supply, and considerations of maintaining $n + 1$ rectifier redundancy.

Assuming these challenges can be solved, or are economic to upgrade given a potentially greater income from metal production at times of low power cost, an upwards modulation scenario is calculated for the 390 kA cell, which has low current density design of around 0.75 A/cm^2 in normal operation. In this case, it is assumed that heat extraction from the sidewalls can be increased by 50% over existing, and top heat losses increased by 20% via increased suction draft, giving a possible heat rejection of 859 kW.

Calculation results in Table 5 show that the increase in heat rejection would be comparable to a 26% increase in line current at the same voltage, however this is clearly a large squeeze in ACD, and plant-specific investigations would be needed to find the lowest stable ACD for any particular cell technology, including ledge thickness and homogenisation benefits possible from controlled sidewall heat loss, which may give a lower minimum ACD than currently possible.

A more conservative scenario involves a constant ACD calculation, where a +17% power consumption is caused by a +10% line current at higher voltage. In this case the specific power consumption increased from 12.8 to 13.5

Table 5 Upwards modulation results for 390 kA cell

390 kA cell		Base	Const HB	Const ACD
Heat dissipation	kW	687	859	859
Amperage	kA	390	487	431
Voltage	V	3.95	4.00	4.18
Power usage	%	100.0	+26%	+17%
Specific power/kg	kWhr/kg	12.8	12.8	13.5

kWhr/kg, which however may be economic at times where metal prices are high, or power supply cheap, giving overall greater advantage.

In each case, the increases in cell heat rejection possible by controlled cooling are large, compared to likely tolerance of the rest of the plant i.e. a 25% increase in productivity is not likely if the anodes, bus bars, GTC, and rectifiers are not similarly oversized. Demonstrating the thermal limits of the cell with controlled cooling however may lead to a business case for other plant upgrades to match.

Additional Benefits

In order to successfully modulate power usage at a smelter, it is necessary to understand and standardise the natural heat losses around the pot such as by improving hooding condition and suction flow balancing. Furthermore, heat balance control using the EnPot system includes continuous measurement of shell temperatures at many points around the pot perimeter, and enables temperature and heat balance stabilisation by adjustments in local cooling zonally around the pot.

Standardisation of heat balance including top and side heat losses for every pot will have a good improvement in standardisation of control outcomes, such as homogenisation and control of ledge thickness around the pot, the ability to reduce ACD and pot energy consumption, and potentially improved feeding and chemistry control outcomes, and improved current efficiency, as demonstrated in plant trials [3]. Continuous shell temperature monitoring and the ability to act directly on hot temperatures will give a benefit to cell life, with problem cells identified earlier and sidewall damage able to be prevented directly by enhanced targeted cooling. Sidewall insulation will also extend the time a potline is recoverable following unforeseen power disruptions [16].

Waste heat usage is another consideration providing additional benefits from controlled cell heat losses. Typical temperature of air exiting EnPot shell heat exchangers adjacent to the pot shell is around 150–200 °C, depending on the average shell temperature and air flow rate. There may be significant temperature loss by the time the air exits the potroom at an external fan, such that usable air is around 100–150 °C. Furthermore, the air flow rates are largest when the temperature is coolest, and highest only at very low flow rates when the shell is insulated.

In some locations, particularly those with colder winter conditions, using waste heat in a connected residential district cooling system or locally at the smelter is an efficient use of the low-grade hot air. Electricity generation from the waste heat may be a possibility given recent advances in efficiency of these systems. The most widely applicable use of the waste heat however appears to be raw material preheating, saving energy efficiency in the smelting cells, such as via preheating of anodes immediately before being installed in the pot. EnPot continues to work on development of waste usage solutions and support smelters to improve energy efficiency.

Conclusions

Becoming flexible power consumers will become highly advantageous or even necessary for smelters in future, however heat balance control is the limiting factor regarding the magnitude of response that can be safely sustained. In this paper we demonstrate that both small (old) and large (modern) pots similarly benefit from external heat balance control, and that sensible operating points can be found both when increasing and decreasing power consumption by 20–30%. This relies however on fully understanding and controlling heat losses from the pot. EnPot is the key enabling technology to control heat flows from the upper sidewall, which is the critical location regarding heat transfer from the molten bath and sustaining the frozen ledge, however larger modulations are possible when top heat losses are also managed. This includes balancing and changing of draught rates, but also operational improvements such as maintaining hooding tightness to prevent emissions. Beyond modulation, there are also significant operational benefits to be realised by reducing pot-to-pot variations, and measurement and control of heat losses.

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