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Statistical Evaluation and Modeling of the Link between Anode Effects and Bath Height, and Implications for the ALPSYS Pot Control System

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Abstract

While anode effect benchmarks show that the near zero anode effect target is achievable using up-to-date process control logic, increasing constraints ranging from far lower ACD, power modulation to operational disturbances have led to a recent surge of PFC emissions in modern smelters pushing their technology towards the limits.

After achieving a significant reduction in anode effect rate and increased current efficiency by introducing the new auto-adaptive alumina control logic presented in 2010, the ALPSYS R&D team has identified bath management as a priority to further improving control robustness.

This paper recalls the main factors affecting bath height and the direct link between bath height and anode effects. It then shows the results of improved bath height management and the implications for process control procedures such as alumina control, instability treatment and power modulation.

Introduction

Bath control is known to be a prerequisite to stable pot operation, and justly so, because it influences most of the other cell control loops.

To begin with, bath depth impacts alumina dissolution ability, and thus interferes not only with alumina concentration control, and, more particularly, with anode effects as we will see further on in detail, but also with noise control as undissolved alumina muck may settle on the cathode, thus generating metal pad instability. Bath also interacts with pot chemistry and thermal control, crust formation and gaseous emissions. Finally, it affects metal purity through anode stub or side wall erosion [1].

These interactions suggest that particular attention should be paid to bath control to ensure optimal cell control.

Unfortunately, in most smelters, bath height control remains quite basic with measurements taken manually, and is highly dependent upon cell condition and anode-cathode distance. Moreover, bath adjustment must be fitted into the work cycle [2], which may delay bath addition or removal depending on other operational constraints.

In this paper, we will quantify statistically the influence of bath height on anode effects in order to demonstrate the importance of proper bath control in the reduction of PFC emissions.

Conversely, we will show how a simple bath model helps to predict bath height control efficiency and the associated anode effect rate.

We will present the implications for other control procedures such as alumina control, instability treatment and power modulation, and the results of our plant tests.

Finally, we will outline the improvements to the ALPSYS bath control procedure that incorporates our findings.

Main factors affecting bath height

Bath height depends on many factors. However, before reviewing them, we consider it important to give a precise definition of what is understood by bath height.

Hereafter in this paper, we will distinguish between measured bath height and actual bath height.

Measured bath height is usually entered into the control system in the shift before metal tapping, after a manual bath and metal height measurement using a rod. This value might be corrected according to the resistance of the pot at the time of measurement in order to account for ACD variation impact on bath height.

Actual bath height is the real bath height one could observe on the pot at any time, which coincides with the measured bath height at the time of measurement only.

From a statistical point of view, Tessier et al. [1] used weekly averaged data to show that measured bath height depends on two main factors: power input and anode cover material composition. These long term variations modify the thermal and liquid bath production balance of the pot and have, as can be expected, a significant impact on bath height.

On a shorter term, the operational cycle also has a major impact on actual bath height.

Bath corrections are, of course, an obvious cause of actual bath height variation.

Metal tapping is a less obvious, but also well known, cause of immediate bath height variation due to the ledge profile. The impact of metal tapping and subsequent metal production can easily be calculated using a simple model, taking into account the average ledge profile and the volume available for bath and metal between ledge, anodes and cathode, as shown in Figure 1.

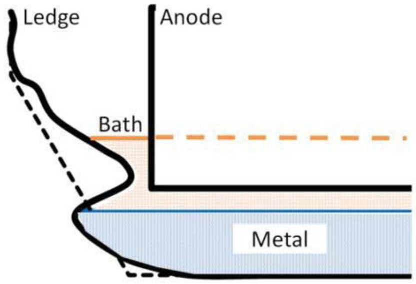

Figure 1: Volume available for bath and metal

A volumetric calculation allows modeling of bath and metal height decrease after metal tapping, as well as the subsequent increase due to metal production, see Figure 2.

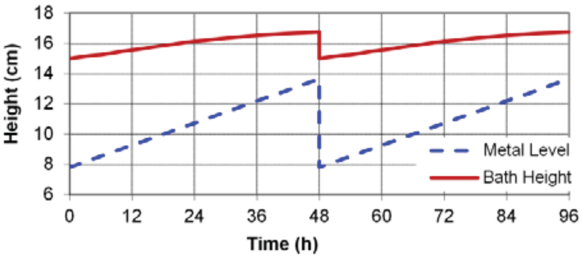

Figure 2: Bath height and metal level variation over a 48-hours metal tapping cycle

According to the bath model, using the example of a 48-h metal tapping cycle, tapping induces a metal level decrease of 6 cm, but also a bath height decrease of almost 2 cm. The latter is due to the fact that, even though ACD remains constant during tapping, bath flows to wider areas of the ledge, formerly occupied by the metal: thus the bath needs less height for the same volume. These results are consistent with measurements before and after tapping performed on pots.

The model is also used to calculate the so called “piston effect”, i.e. the ratio between ACD movement and bath height variation. This allows comparison of bath height variation due to usual additional resistances (e.g. for instability treatment) to bath height variation due to metal tapping. Our findings show that both of these bath height variations have the same order of magnitude.

Finally, the bath model can calculate over time the impact on actual bath height of bath production or consumption, as well as the impact of bath addition or bath tapping.

Combining the long term statistics with the short term information given by the bath model, we can sum up the main factors affecting actual bath height:

- Bath corrections
- Bath production or consumption trend
- Metal tapping
- Metal height evolution
- ACD change

Actual bath height estimation

The bath model described above estimates the actual bath height of each pot over time. Inputs to the model are:

- Measured bath and metal height as a starting point
- Bath correction events
- Bath production / consumption trend
- Metal tapping events
- Metal production trend
- Additional resistances

Figure 3 shows a bath and metal height estimation example over a 4-day period. After each new bath or metal height measurement, the estimation is reinitialized, which accounts for adjustment steps in the curves due to model imprecision or measurement quality.

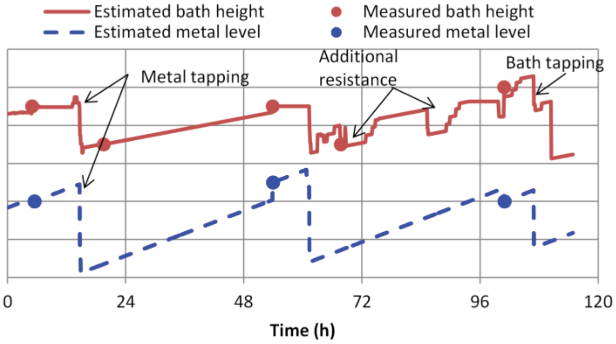

Figure 3: Bath and metal height estimations and measurements

Despite model or measurement inaccuracies, using the bath model outputs over time instead of the measured value provides far better knowledge of the actual bath height variations, and thus proves a powerful tool for further statistical investigations and improved bath control.

Actual bath height and anode effects

In particular, the above bath model estimates the actual bath height at the time of specific events such as anode effects.

The relationship between anode effects and measured bath height is already well known. This justifies the emphasis that should always be placed on bath management.

However, the actual bath height estimation gives a new insight into the importance of permanent bath control, i.e. control not just at the time of measurement.

Figure 4 compares the average anode effect rate for different bath heights, using bath height measurement versus actual bath height estimation, on a group of 200 pots during 3 months. To highlight the difference, these anode effect rates were divided by the average anode effect rate for all bath heights over the same period.

Both curves match expectations, i.e. a marked increase in anode effect rate at low bath heights, a minimum anode effect rate near target bath height, and an increase in anode effect rate at higher bath heights. The interesting difference is that the curve established using measured bath height suggests that anode effect rate around target bath height (green zone between 15 cm and 18 cm) is only slightly below global average anode effect rate.

In reality, the curve established using estimated actual bath height shows that the anode effect rate around target bath height is less than twice average anode effect rate. This shows that, although bath height management was already considered to be a high priority with respect to anode effects, its importance is even greater than expected. This also opens up opportunities for dividing anode effect rate by a factor of two, provided that bath height control procedures manage to keep actual bath height continuously within the optimal zone.

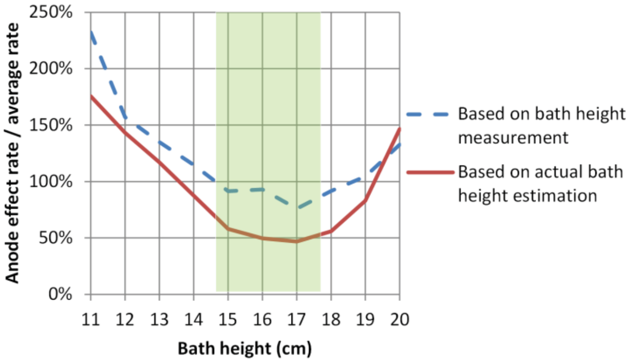

Figure 4: Anode effect rate variation based on measured / estimated bath height

The link between anode effects and bath height is usually attributed to the capacity of bath to dissolve alumina. This is certainly the case for low bath heights, where the alumina shot does not have enough bath volume and time to dissolve completely before reaching the metal pad and sinking to the cathode.

Another interesting perspective is given by Thonstad et al. [3]: when alumina concentration decreases towards the anode effect, current distribution under the anodes is shifted to the vertical sides of the anodes. This current side shift depends on bath height, leading to an increased anode effect risk for pots with low bath height.

In the case of bath heights above target, the explanation for the increase in anode effect rate is probably more related to alumina control logic than to dissolution: an increasing bath volume combined with extra alumina dissolved from the crust directly impacts slope control logic, and may counter-intuitively lead to lower alumina concentrations, as described in [4], thus increasing the anode effect risk.

Whatever the reasons linking bath height to anode effects, the above observations show that maintaining actual bath height within the optimal range (15-18 cm in the above example) throughout the operational cycle is a key factor to strongly reducing the anode effect rate.

In order to develop bath height control strategies aiming at avoiding anode effects, in the following paragraphs we will study in more details the influence of specific bath variation causes: metal tapping, bath production or consumption, but also power modulation.

Anode effects after metal tapping

One of the most convincing proofs of the link between actual bath height and anode effects is the metal tapping operation, which leads to a bath height decrease of 3 cm on the potline studied.

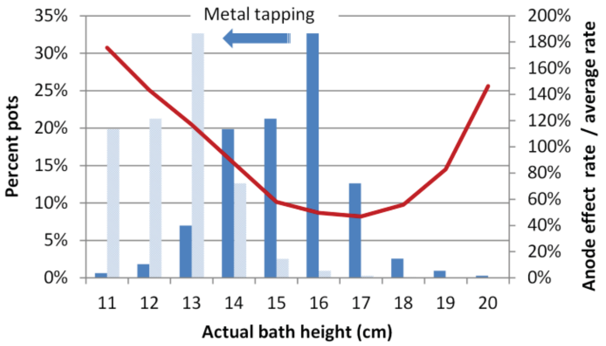

Figure 5: Bath height distribution

Starting with the measured bath height distribution before metal tapping (dark histogram), the distribution can be shifted by -3 cm to predict the new distribution just after tapping (light histogram), and then be shifted back progressively to predict global actual bath height evolution over time, as shown in Figure 5. Note that this prediction is not comprehensive, because possible bath corrections are not taken into account. Using the anode effect rate according to actual bath height from Figure 4, the average anode effect rate variation can be predicted over time, provided that bath variation really is the key factor affecting anode effect rate.

Figure 6 represents the predicted anode effect rate variation compared to the measured anode effect rate evolution over a 32-hour tapping cycle.

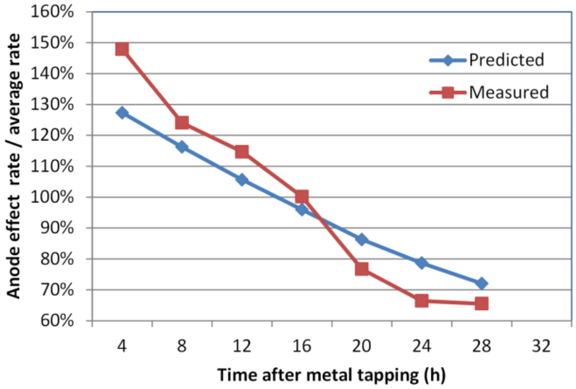

Figure 6: Anode effect rate evolution after metal tapping

From the above curves we can see that more than 50% of all anode effects occur within the first 12 hours after tapping, and that the bath height model is a fairly good predictor of anode effect rate, highlighting once again the direct link between actual bath height and anode effects.

As metal tapping is not avoidable on most pot technologies, the main lever in reducing actual bath height variation due to tapping at pot level is to have shorter tapping cycles.

For a given tapping cycle, the other lever, at potline level, is to reduce measured bath height variation among pots.

We will now study the impact of bath production or consumption on measured bath height variation, and its consequences on anode effects.

Impact of bath production or consumption on anode effects

Bath height control usually relies on a proportional correction table, see Figure 7.

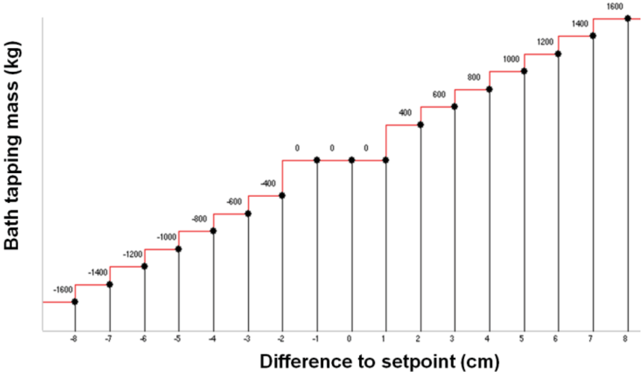

Figure 7: Typical bath correction table

Corrections are made manually using a bath tapping ladle. Minor corrections around set point are avoided to reduce ladle handling and bath freeze. Depending on the pot trend which either produces or consumes liquid bath, bath mass evolves continuously over time, with regular stepwise corrections according to the above table. Bath corrections only occur when a difference to set point is measured, which creates a steady state error. For example, a pot producing 100 kg of liquid bath a day will only be corrected after a bath height increase of 2 cm (400 kg produced in 4 days), which creates an average bath height steady state error of 1 cm compared to set point.

Figure 8 shows anode effect rate and average measured bath height according to average daily bath production, measured on 100 pots in another potline.

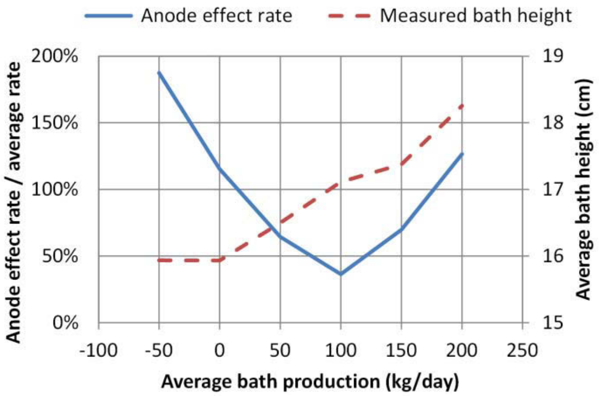

Figure 8: Impact of liquid bath production/consumption on anode effect rate and measured bath height

As expected, average measured bath height depends on average bath production: the steady-state error is up to +/- 1cm around set point, bath consumer pots are on average always under target, and bath producer pots are above target.

The graph also shows that the minimum anode effect rate is reached for pots producing some liquid bath (50-100 kg/day) but not too much: liquid bath production steadily limits the risk of falling into the very low bath height / high anode effect rate zone. Pots consuming liquid bath have a much higher anode effect rate: these pots rely on manual bath additions, which are dependent on other operational priorities.

These observations are in accordance with Tessier et al. [1]: liquid bath production or consumption depends on anode cover composition and power input to the pot, and have a strong impact on measured bath height. However, it is important to remember that the link between measured bath height and liquid bath production is mainly due to the steady state error of the proportional control algorithm.

To reduce anode effects, the most efficient solution is probably to find a proper thermal balance allowing pots to produce a little liquid bath, but not too much, so as to limit bath tapping operations. However, this task is not always simple, especially during amperage increase phases, where older linings work for a while near newer ones at the same amperage. Another solution is to improve the control algorithm to take into account the production trend of each pot.

An improved bath control procedure

From the above study, it is now clear that proportional bath control relying only on measured bath height cannot ensure that bath height remains within an optimal range to minimize anode effects.

The objective of an improved bath control procedure is to control both bath mass and bath height while minimizing bath transfers.

In order to do so, measured bath heights can be corrected according to ACD and to the metal tapping cycle, to estimate bath mass and allow better control.

Liquid bath production or consumption is estimated over a large number of tapping cycles in order to correct the steady state error of traditional proportional control.

Actual bath height, estimated in real time, can be combined with chisel-bath contact [5] information to detect high anode effect risk situations and to trigger associated alarms.

These improvements provide a framework for far better bath control, and are an important support tool for reducing anode effects. However, unlike core control procedures such as resistance control or alumina control which run most of the time automatically, bath control relies strongly on operational priority given to bath tapping: perfect tapping requests without timely tapping will have little effect on bath height standard deviation and on anode effect rates.

Figure 9 shows the simulated anode effect rate according to liquid bath production/consumption and bath transfer rate.

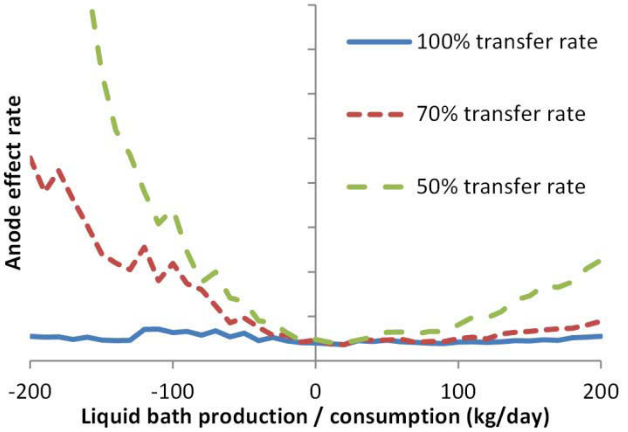

Figure 9: Simulated anode effect rate according to liquid bath production and bath transfer rate

The simulation uses the bath model, the new bath control procedure as well as the anode effect statistics according to actual bath height. The result shows that the new procedure can keep actual bath height within the optimal range to avoid anode effects whatever the bath production, provided that all transfers are carried out. However, once the transfer rate deteriorates, it is no surprise to see that optimal actual bath height and anode effect rate cannot be kept under control.

Implications for other control procedures

Real time knowledge of actual bath height and bath mass is a key factor for other control procedures.

The importance of bath for the alumina concentration control procedure is well known from a dissolution perspective, but also from a control logic perspective, see [4].

We have also shown that additional resistances can reduce bath height significantly and should therefore be used with parsimony on pots already low on bath height to avoid anode effects.

This is true for the automatic instability treatment procedure, which generally relies on an additional resistance to stabilize the metal pad.

Another example is the control of power modulation events. In one of the smelters we studied, the energy contract includes a large number of power modulations every year (amperage halved for one hour), which resulted in an increased anode effect rate.

A statistical study of actual bath height before amperage modulation showed that the pots causing the increase in anode effect rate were the pots which were already low on bath before the event, as shown in Figure 10: bath cooling during power modulation induces a decrease in global bath height particularly affecting pots with very low bath heights.

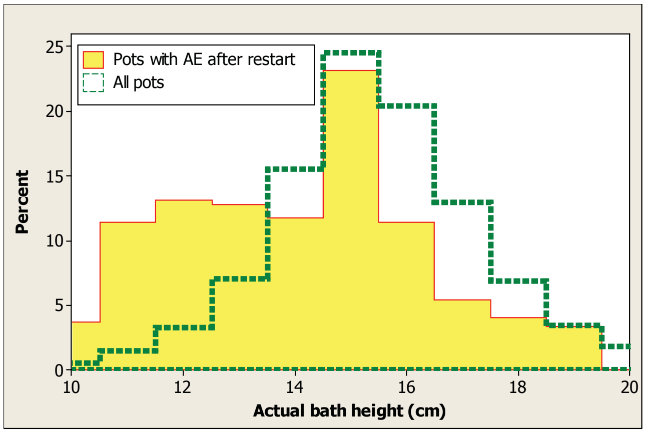

Figure 10: Histogram of pots with an anode effect after restart

This observation allowed us to reduce the anode effect rate significantly after power modulation by improving bath control, and in particular by reducing additional resistances after restart.

Initial results

Although improving bath height control is no easy task as it relies on the human factor and not solely on an automatic procedure, the above statistics gave to one of the smelters we worked with sufficient reasons to refocus its priorities on bath height management in order to reduce anode effects.

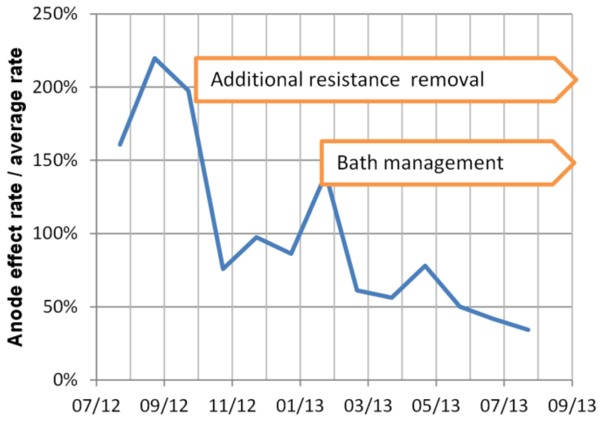

Figure 11: Anode effect rate evolution

The results of the field test confirm the efficiency of the improvements suggested by the statistical analysis, as shown in Figure 11. After power modulation, this smelter normally fitted an additional resistance to increase power input to the pot and facilitate return to normal temperatures. Unfortunately, the associated decrease in bath height generated too many anode effects. The first step was to remove the additional resistance after restart, which reduced the anode effect rate significantly. The potline then began to progressively improve bath height management practices, which led to the current situation, with an anode effect rate under control, despite further power modulation events.

From R&D to operation through ALPSYS enhancements

As demonstrated in this paper, reducing anode effect rate is possible thanks to improved and tighter bath height management and control. This implies taking into account a larger array of additional process parameters as well as operational considerations. Imbedding these improvements into the control system is key to achieving these results consistently and sustainably.

Following the demonstration of the benefits of the presented improvements, the ALPSYS R&D and product development teams have worked together on industrializing and integrating them into the latest version of the ALPSYS product which now includes enhanced bath management functions and features.

The ALPSYS system calculates, in real time, an actual bath height based on a measured bath height corrected to take into account the influence of metal height, bath corrections and actual ACD. For this correction to be reliable, precise and rigorous, knowing the exact time of the bath height measurement is key.

The system enables measured bath height to be captured either through smart work floor measurement acquisition devices or by directly entering them at the level-1 pot controller (Potmicro). Corrected, as well as raw, before and after, bath correction values are stored in a database to facilitate statistical analysis and further tuning of the bath model.

As an updated actual bath height is permanently available, it’s used to detect and notify the operators in a more timely and reliable manner when pots exit the acceptable bath height range.

Thanks to the enhanced noise analysis separating metal pad noise (cathodic noise) from other types of noise (anodic noise), unnecessary unsqueezing is avoided, thus contributing to maintain bath height, in addition to saving energy.

Finally, the corrected bath height is used to determine the bath correction operations target, which is the key factor in keeping a tighter control of the bath mass in the pot.

Conclusion

Good bath height control is known to be a requirement for stable pot operation. A simple bath model coupled with a statistical analysis helped us to understand in greater detail the direct relationship between actual bath height and anode effects, and to find the optimal bath height range to minimize anode effects. The new ALPSYS bath control procedure is designed to estimate in real time the actual bath height, and to ensure that excursions out of the safe range are avoided, or at least signaled. This procedure is a key tool for operations aiming at benchmark anode effect rates, provided that bath control gets the priority it deserves.

Acknowledgements

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