EXCESS ALF$_3$ CONCENTRATION IN BATH CONTROL LOGIC

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Introduction

In order to operate at maximum efficiency, aluminium reduction cells must be operated in a tight temperature range. This in turn leads to the need to operate the cells with a tight control on the cell bath chemistry.

Contrary to alumina concentration, which is constantly monitored through the cell resistance control logic, excess AlF_3 concentration, which has a huge influence on the resulting cell operating temperature, is only monitored very sporadically by taking and analyzing bath samples. Furthermore, results of the bath sample analysis are only available for feedback control after a significant time lag, which typically results in a very inefficient control of the excess AlF_3 concentration in the bath [1].

AlF_3 mass balance

Excess AlF_3 concentration in the bath is hard to control because, on a short time span, it is affected by many cell parameters which themselves fluctuate rapidly. Globally, AlF_3 is continuously lost by a mix of evaporation and entrainment that is called evolution [2]. For the 300 kA demonstration cell for which modeling results will be presented here, the rate of AlF_3 evolution is 33.8 kg F/ton of Al produced or

$$33.8 \times \frac{93.13}{1000} \times \frac{84}{57} = 4.64 \frac{kg}{hr} AlF_3$$

for that 300 kA cell producing 91.13 kg Al per hour. A big fraction of that AlF_3 is coming back from the scrubber in the secondary alumina fed to the cell. The nominal rate of pure alumina feeding for that cell is 175.9 kg of alumina per hour. If we assume that instead of feeding pure alumina, we are feeding a mixture containing 2% AlF_3, we are feeding back through secondary alumina

$$\frac{2}{102} \times 175.9 = 3.45 \frac{kg}{hr} AlF_3$$

If we neglect for simplicity reason the Na also present in the alumina and the Na absorbed by the cell lining, this leaves a deficit of 1.19 kg per hour that needs to be fed directly to the cell in order to maintain the excess AlF_3 concentration in the bath constant.

Of course, the short term AlF_3 evolution depends on the short term bath temperature and chemistry and the short term concentration of AlF_3 in the secondary alumina depends on the short term scrubber operation. Yet, as long as the average values are not drifting away for some fundamental reason, the only way to maintain, on the long run, the target excess AlF_3 concentration in the bath is to feed the long term cell requirement disregarding any short term change as process operation noise.

AlF_3 deposit

In [1], the observed time lag between the time of the direct AlF_3 addition and its impact on the excess AlF_3 concentration in the bath is explained by a form of AlF_3 "deposit". If we assume that AlF_3, like alumina, when added to the cell forms first a dispersed phase in the bath before dissolving, it is also normal to assume that that dispersed phase can also like alumina settle down as sludge on the cathode surface (see Figure 1).

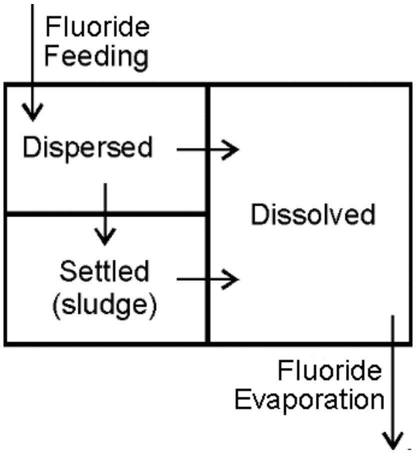

Figure 1. Assumed AlF_3 phases in the cell

There is a very high probability that AlF_3 sludge is the AlF_3 "deposit" that needs to be invoked to explain the time lag between the AlF_3 addition and its impact on the bath chemistry.

Figure 2 presents the results of the addition of 100 kg of AlF_3 assuming a realistic very fast dissolution rate but also assuming a very fast feeding rate and a sludge back dissolution efficiency of 5%. In such conditions, we can observe that the full impact of the 100 kg addition took more than a day to show up in the bath chemistry.

Control logic based on bath sampling

In modern cell technology where AlF_3 is fed on a continuous basic using a point breaker feeding system, time lag response due to AlF_3 "deposit" is very doubtful. Yet, this has not necessary solved the issue of poor excess AlF_3 control in all those modern smelters as it is not the only time lag present in the feedback control loop.

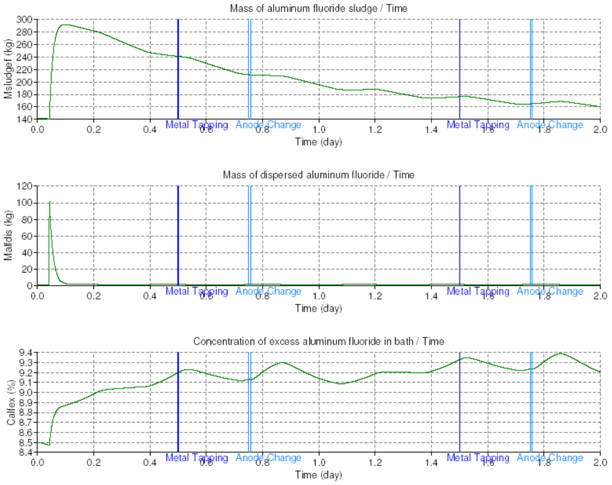

Figure 2. Cell response to a 100 kg AlF_3 addition

As we will see below, the time lag between the collection of the bath sample and the introduction of the results in the cell controller database can also lead to significant oscillations in the excess AlF_3 concentration in the bath.

Case no 1: 100 days response without feedback control

In Figure 3, we can see the 100 days cell response to a constant 1.2 kg per hour direct AlF_3 feeding rate. Since 1.2 kg per hour is a bit more than what the cell needs to maintain a 8.5% excess AlF_3 concentration, that concentration increases for about 50 days before an equilibrium at 9.2% is reached.

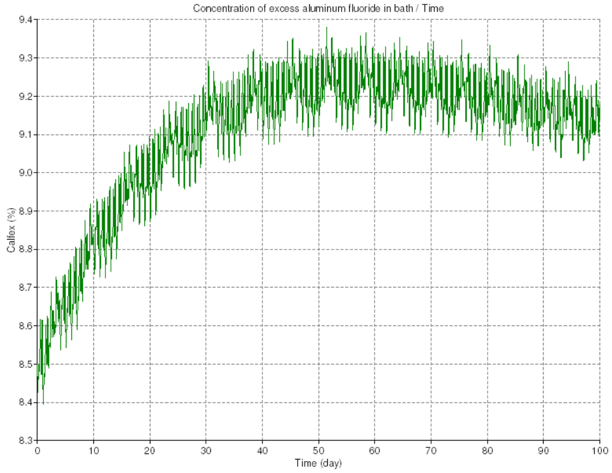

Figure 3. 100 days response without feedback control

Case no 2: Integral control, 1 sample per day, 1 day delay

Continuously readjusting the base direct AlF_3 feeding rate every day based on the results of the analysis of the previous day sample analysis is an example of integral control feedback loop with a time lag. As we can see in Figure 4, when a 10% adjustment is made on the base direct AlF_3 feeding rate each day for each 1% excess AlF_3 concentration offset for the bath sample of the previous day, an oscillation pattern emerges.

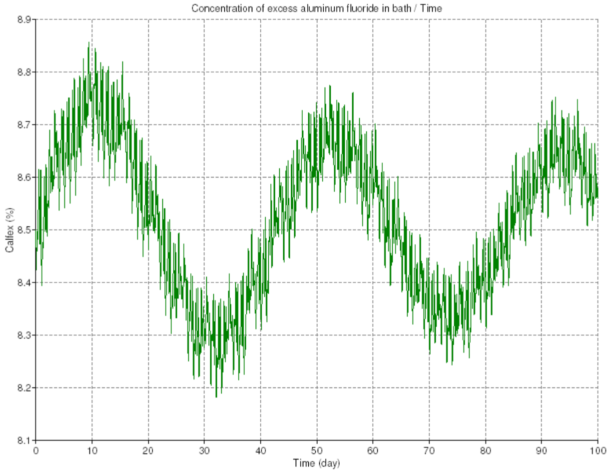

Figure 4. Integral control, 1 sample per day, 1 day delay.

Case no 3: Proportional control, 1 sample per day, 1 day delay

Clearly, it is better to keep the base direct AlF_3 feeding rate constant over time and rather make a one time adjustment proportional to the current concentration offset. Figure 5 presents the obtained results, there are no more oscillations but by using a proportional 1 kg/hr% proportional adjustment constant on a base 1.2 kg/hr feeding rate, we are ending up with a 0.5% permanent error as with a proportional only control mode, it takes an offset to make a correction.

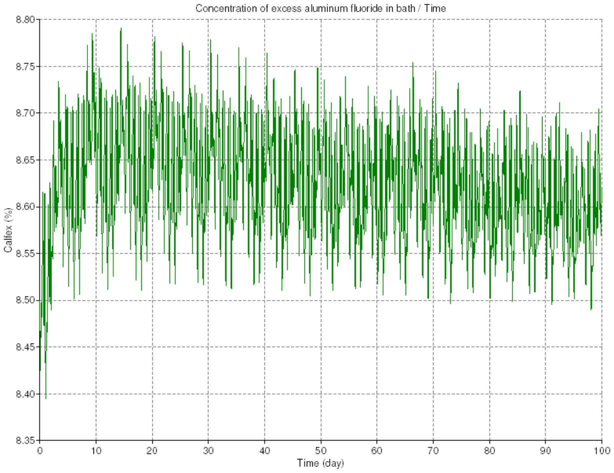

Figure 5. Proportional control, 1 sample per day, 1 day delay.

Case no 4: PI control, 1 sample per day, 1 day delay

As it is presented in Figure 6, the permanent error can be eliminated by reintroducing the integral part of the feedback control (i.e. readjusting the base feeding rate at each feedback loop). This PI feedback control works so well that that could very well be the end of the story! Unfortunately, it relies on the fact that we are taking 1 bath sample per cell per day and that the results are available to the cell controller in 24 hours. Many smelters cannot keep up with this kind of schedule, so they have to reduce the bath sampling frequency introducing a longer time lag in the control feedback loop.

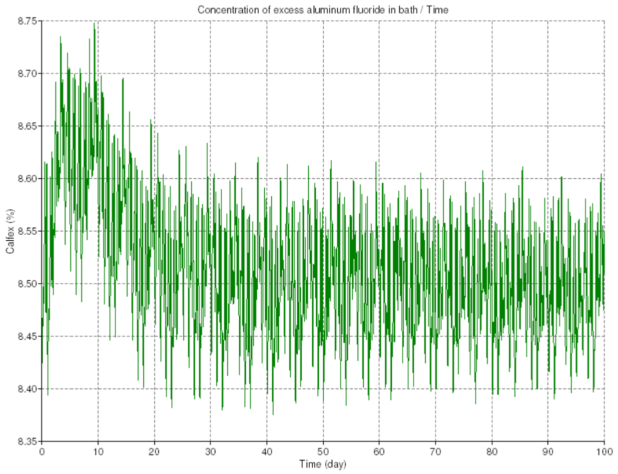

Figure 6. PI control, 1 sample per day, 1 day delay

Case no 5: Proportional control, 1 sample per 2 days, 2 days delay

As we can see in Figure 7, the pure proportional feedback control loop is not too much affected by the decrease of the sampling frequency and the corresponding increase of the time lag. On the long term, it is stabilizing to the same permanent error after a more significant overshoot. Of course, as it is leaving a permanent offset, the proportional only feedback control is not the best option.

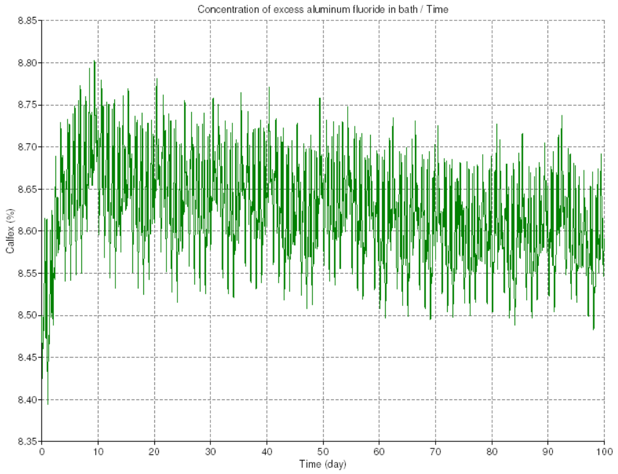

Figure 7. Proportional control, 1 sample per 2 days, 2 days delay

Case no 6: PI control, 1 sample per 2 days, 2 days delay

By comparing Figure 8 to Figure 6, we can see that the doubling of the time lag had some destabilizing effect on the feedback response. But considering that the laboratory bath sample analysis expenses have been cut by half, that little negative impact on the process may well be small enough to lead to a positive economical impact for the smelter.

Case no 7: Proportional control, 1 sample per 3 days, 3 days delay

For some reason, this is no longer the case when the sampling frequency is further decreased to 1 sample per 3 days with a corresponding 3 days time lag in reporting the results to the cell controller.

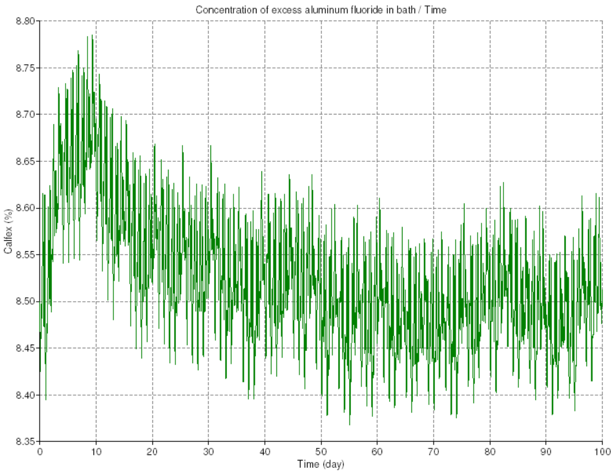

Figure 8. PI control, 1 sample per 2 days, 2 days delay

By keeping the same 1 kg/hr% proportional adjustment constant, as we can see in Figure 9, even the pure proportional feedback control mode is destabilized enough to exhibit permanent oscillations in addition to a permanent error. That proportional adjustment constant is now too big considering the 3 days time lag in the feedback control loop.

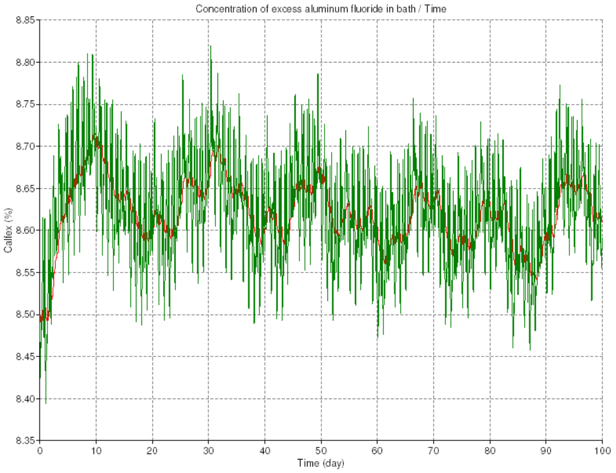

Figure 9. Proportional control, 1 sample per 3 days, 3 days delay

Case no 8: PI control, 1 sample per 3 days, 3 days delay

Of course, adding integral feedback to a constantly overshooting proportional controller only contributes to destabilize more the system as we can see in Figure 10. This time, we have a truly unstable feedback control that will need to be reinitialized frequently before it diverges completely!

Case no 9: Proportional control, 1 sample per 3 days, 3 days delay

Fortunately, when a proportional controller overshoots, there is a simple remedy to the problem, the proportional feedback constant simply needs to be reduced. While keeping the 3 days sampling frequency, simply reducing the proportional feedback constant to 0.5 kg/hr% completely re-stabilizes the system, obviously the price to pay is the doubling of the permanent error as we can see in Figure 11.

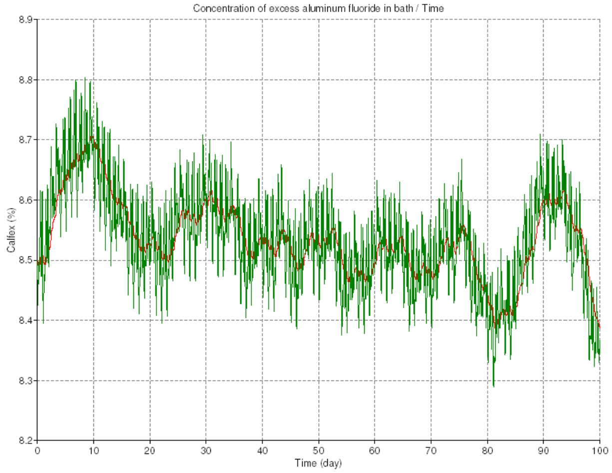

Figure 10. PI control, 1 sample per 3 days, 3 days delay.

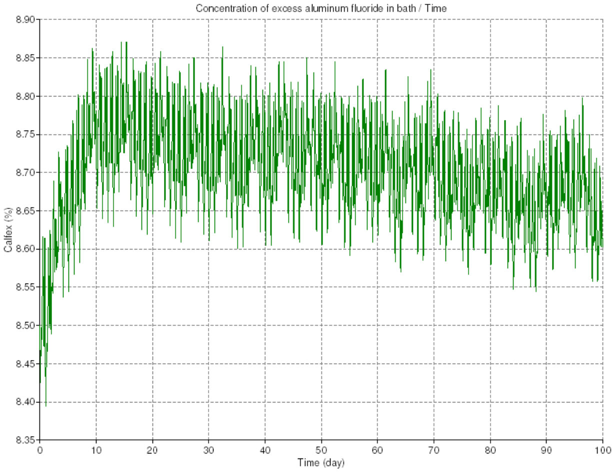

Figure 11. Proportional control, 1 sample per 3 days, 3 days delay

Case no 10: PI control, 1 sample per 3 days, 3 days delay

Again, fortunately, now that the proportional feedback has been re-stabilized, adding the integral feedback control will eliminate back the permanent error as we can see in Figure 12. This time, this could very well be the end on the story!

Control logic based on bath temperature measurement

In order to avoid completely having to do all those bath sample analysis on a continuous basis and to have to suffer the impact of the time lag in the feedback control, Desclaux [3] proposed to control the bath chemistry based on the feedback from the cell operating temperature.

As demonstrated by Desclaux, there is a very strong correlation between the excess AlF_3 concentration in the bath and the cell operating temperature as shown in Figure 13. That correlation is established through the relation that exists between the bath chemistry and its liquidus temperature and the fact that there is a strong correlation between the bath liquidus temperature and the cell operating temperature through the cell superheat.

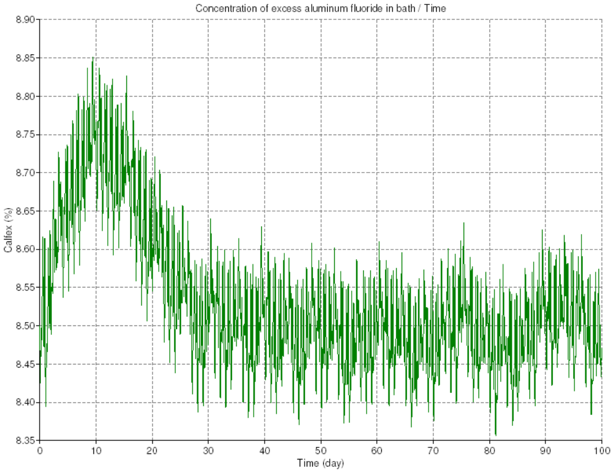

Figure 12. PI control, 1 sample per 3 days, 3 days delay.

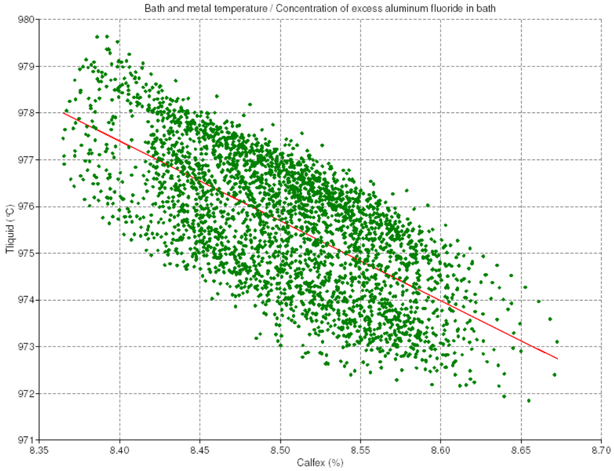

Figure 13. Correlation between excess AlF_3 temperature and bath temperature

Unfortunately, on short periods of time, that correlation is not as strong as there are many short term events that influence the cell instantaneous cell superheat like the alumina feeding regime (overfeeding or underfeeding) and events like anode change, anode effect, noise treatment, etc. Furthermore, other bath additives like alumina and CaF_2 also influence the bath liquidus temperature.

As a result, using the cell operating temperature as feedback to control the excess AlF_3 concentration, although it eliminates the time lag, does introduce significant noise that destabilize the feedback response as we will see below.

Case no 1: Proportional control, 1 measure per day, no delay

Figure 14 presents the feedback response obtained when using a 0.1 kg/hrºC proportional constant. Even with that quite small proportional constant leaving a huge permanent error, we can see that the extensive temperature noise has introduced some non negligible instability in the response. Furthermore, the constant is so small that the response is not so different from the case presented in Figure 3 where there is no control at all.

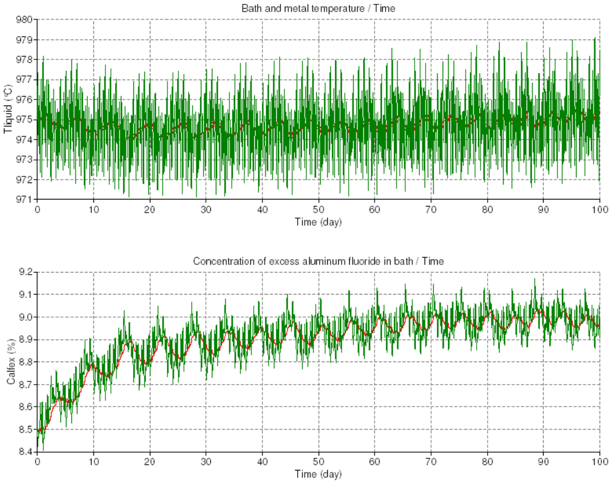

Figure 14. Proportional control, 1 measure per day, no delay

Case no 2: Proportional control, 1 measure per day, no delay

Using a 0.3 kg/hrºC proportional constant reduces slightly that permanent error but increased significantly the oscillation in the response as we can see in Figure 15.

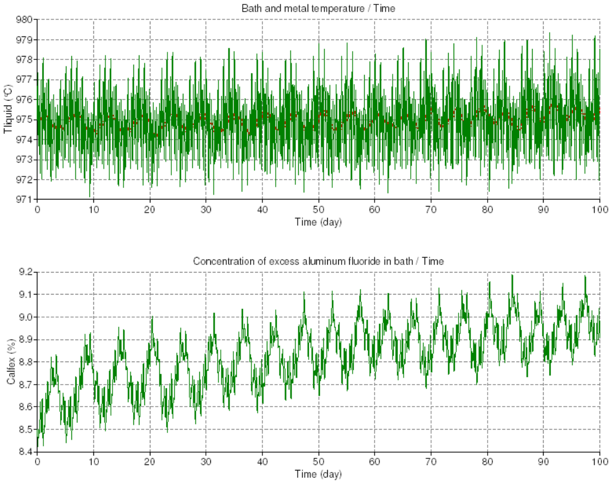

Figure 15. Proportional control, 1 measure per day, no delay

Clearly, controlling the excess AlF_3 concentration using only bath temperature measurement even with one measurement per cell per day and without any time delay is not as stable as using bath sampling even with a much lower feedback control frequency and a quite significant time lag.

Control logic based on both bath sampling and bath temperature measurement

Many modern bath excess AlF_3 concentration control strategies [4,5] are using both the time lagged bath sample analysis and the bath temperature in their control feedback loop. Is this a good idea?

Case no 1: PI mixed control, 1 sample per day, 1 day delay, 1 temperature measurement per day, no delay

Figure 16 presents one of the best possible feedback control response that can be obtained using that mixed control strategy. The bath temperature target is set to 975ºC, which is compatible with a 8.5% excess AlF_3 concentration target for that demonstration cell operating at that current superheat and average alumina and CaF_2 concentrations. All those factors are important as the correlation presented in Figure 13 only holds in those conditions.

Furthermore, the bath sample analysis results are only lagging the temperature measurement by 1 day reducing the risk of being out of phase and hence inconsistent for the cell controller to act upon. The proportional constants are set to 1 kg/hr% and 0.3 kg/hrºC respectively.

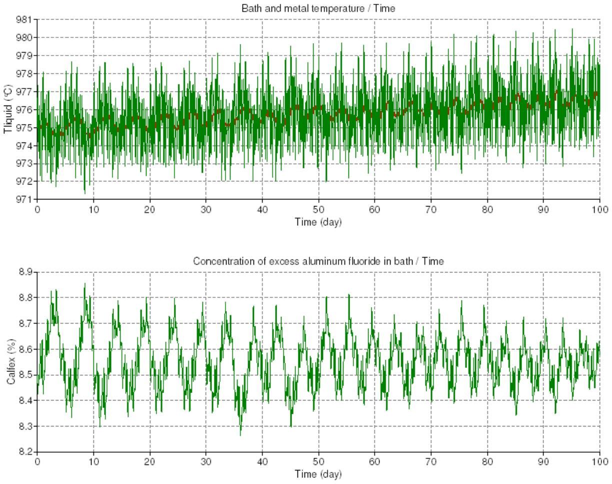

Figure 16. PI mixed control, 1 sample per day, 1 day delay, 1 temperature measurement per day, no delay

Clearly when compared with the response of Figure 6, using the bath temperature in addition to the bath sample analysis only adds instability to the response.

Case no 2: PI mixed control, 1 sample per day, 1 day delay, 1 temperature measurement per day, no delay using inconsistent targets

It is important to notice that this is one of the best possible feedback responses possible. A more probable response would be the feedback response resulting from the tug of war itself resulting from setting inconsistent targets between the 2 parts of the controller.

This is a more likely scenario because there are many factors affecting the correlation between the excess AlF_3 and the bath temperature. As example, Figure 17 presents the modified bath excess AlF_3 vs. bath temperature correlation when the CaF_2 concentration increases from 3% (in figure 13) to 8%.

As we can see, there is about a 5ºC shift down in the obtained correlation. Similar shift in the correlation will occur if the cell superheat is increasing due to cell amperage increase per example. In fact, the list of factors affecting that correlation is extremely long: bath chemistry excluding excess AlF_3, cell amperage, ACD, anode size, anode cover thickness etc.

Any shift in the correlation will mean that if not readjusted, the 2 controller targets will become inconsistents. Case 2 is identical to Case 1 in all aspects except that the bath temperature target has been set to 970ºC instead of 975ºC. Figure 18 presents the resulting tug of war feedback control response. Clearly this is the worst type of control response possible. Unfortunately, this is still a quite common one in the industry even nowadays.

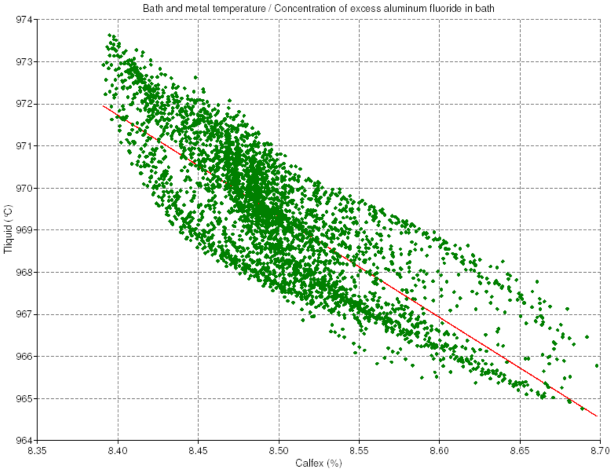

Figure 17. Correlation between excess AlF_3 temperature and bath temperature

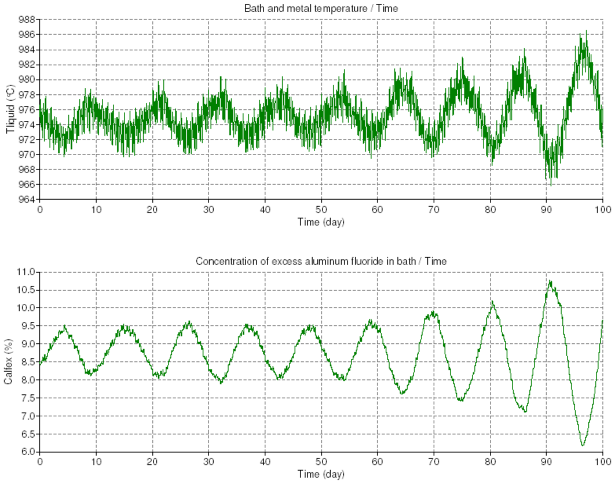

Figure 18. PI mixed control, 1 sample per day, 1 day delay, 1 temperature measurement per day, no delay

Conclusions

Clearly, using a mixed bath sample analysis and bath temperature double targets control strategy like the one presented in [4,5] is a very bad choice of control strategy. Is there any other industrial process that is essentially using 2 controllers to control the same process variable?

Using the cell operating temperature alone to control the excess AlF_3 concentration in the bath is not very efficient either as the daily evolution of the bath temperature is much more influenced by other parameters like feeding regime than it is affected by the excess AlF_3 concentration in the bath.

Directly using the bath sample analysis results seems to be the most effective control strategy despite the fact that it involves the introduction of a time lag in the feedback loop.

A time lag of up to 3 days between the sample collection and the report of the results is even manageable if the proportional constant is set appropriately in order to avoid overshooting.

References

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