Essential Readings in Light Metals: Aluminum Reduction Technology.
Edited by Geoff Bearne, Marc Dupuis and Gary Tarcy.
© 2013 The Minerals, Metals & Materials Society. Published 2013 by John Wiley & Sons, Inc.

OPERATIONAL AND CONTROL IMPROVEMENTS IN REDUCTION LINES AT ALUMINIUM DELFZIJL

Marco A. Stam[1)], Mark P. Taylor[2)], John J.J. Chen[2)], Sikke van Dellen[1)]

[1)] Aluminium Delfzijl B.V., P.O. Box 133, 9930 AC Delfzijl, the Netherlands
[2)] The Light Metals Research Centre, University of Auckland, Private Bag 92019, New Zealand

Keywords: Process Control, Cell Behaviour, Operational Practices

Abstract

Nowadays viability of smelters requires operation of cells at or beyond known performance limits. At Aldel over the last ten years the intensity of electrical energy dissipation and alumina dissolution per cubic centimeter of liquid bath have increased by 50% as production (+40%) and specific energy consumption (-6%) have improved. The cell imbalances resulting from this increased intensity must be sensed quickly and their causes corrected or removed to maintain the cells in their most efficient operating zone. This defines a new control objective for smelting relating to diagnosis of causes of abnormality in strongly interactive multivariate processes. Timely identification of these causes of variation is linked to operational practice improvement and better control decisions in reduction lines.

This paper describes smelter based improvement of operational practices and control decisions using the above objective. Statistical multivariate control surfaces are presented for operating cells and identified abnormal behaviours are discussed.

Introduction

Aluminium Delfzijl B.V. is a subsidiary of the Corus Group plc and operates with 2 reduction lines of Alusuisse prebake end-to-end technology. During a major modernisation step (retrofit) between 1996 and 1998 both potlines were upgraded with 304 new cradle shells, a dense phase system for alumina transport, alumina and AlF_3 point feeders, individual pot controllers, and Hoogovens dry-scrubber technology. Nowadays the pots are running at a line current of 140 kA without any magnetic field modifications to the bus bar configuration. The original design value of the new pots is 120 kA, but in a boosted section of 10 pots a current of 150 kA is tested. Today the annual production of high-quality rolling slabs and extrusion billets is 160,000 tons, which are produced from 115,000 tons of primary metal, topped up with recycled scrap and cold metal.

Ten Years Continuous Improvement

Improving process control has become a major issue at aluminium smelters everywhere, and especially in Western Europe, due to the deterioration of the economical circumstances combined with an increase in environmental constraints. Recent developments concerning the average energy prices have directly led to the closure of a number of good performing smelters. Therefore, after the implementation of the retrofit project at Aldel a challenging continuous improvement program was formulated in order to reduce the operating costs (€/tonnes Al). The main focus of the project is to improve the capital productivity (tonnes Al/pot-day), and to reduce the consumption of energy, gross carbon, and fluorides (per tonnes Al). In spite of this a significant reduction of labour and maintenance costs has been realized. The human productivity has been doubled to a level of 700 tonnes of Al per person. In figure 1 the results of 10 years continuous improvement at the Aldel smelter are presented as a percentage of the total cost reduction of 404 €/tonnes Al.

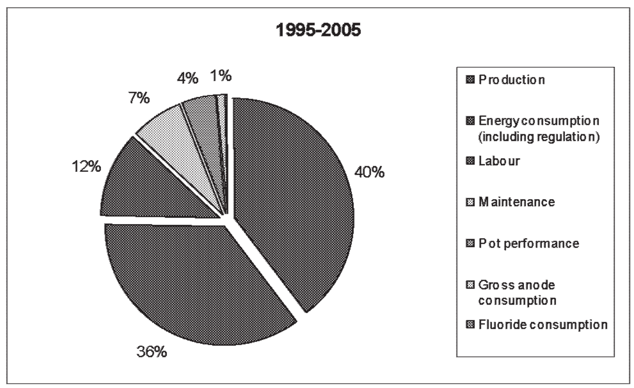

Figure 1: Continuous Improvement Program Aldel

More than 80% of the reduction of the aluminium conversion cost is related to the improvement of the controllability of the reduction process. As the central part of the improvement program Aldel is concentrating on the development of a new progressive process control model, which is coupled with more sophisticated use of the individual pot controllers and alumina and AlF_3 point feeders.

Process Control Model

The basic philosophy of the current process control model [1] is to keep the cell within its energy and material balance window in order to achieve the optimum cell performance. Central to this model are bath temperature and liquidus measurements on which pot voltage and AlF_3 additions are calculated. With use of the Heraeus Electro-Nite disposable superheat probe, these automatic adjustments are applied as the primary heat and material balance control mechanism.

Crucially important is a tight superheat control. On the one hand it is necessary to run a cell with sufficient superheat to assure good alumina solubility and avoid bottom freeze. Good control of superheat provides a balanced ledge profile, which minimises turbulence and thermal instabilities. On the other hand the superheat should not be too high that the ledge and a stable top crust cannot be maintained to provide adequate sidewall protection, and good heat balance and environmental performance respectively.

Bath chemistry control is based upon a moving average of the liquidus temperature, which gives information about the overall bath composition including alumina concentration. However, the need for AlF_3 in modern technologies with a dry-scrubber [2] is linked to cell age, the type of cathode blocks used, line current, gas collection (hooding) efficiency and most particularly the soda content of the alumina used. Considerable caution therefore needs to be exercised when AlF_3 additions are also being used to compensate for a change in bath chemistry.

Maximum line current

As every smelter which is searching for its maximum line current, Aldel has gone through a program of substantial amperage increase. In the period after retrofit the line current has gone up 35 kA (figure 2). Although a significant reduction of the energy consumption was realised, the total internal heat generation has gone up by 30% to a level of 319 kW. Due to the implementation of larger anodes in order to keep the anode current density within acceptable operating limits the liquid bath mass has been reduced by 10%. The combination of both changes has led to an increase in the electrical heat dissipation and alumina dissolution per cubic centimetre of liquid bath of 50%.

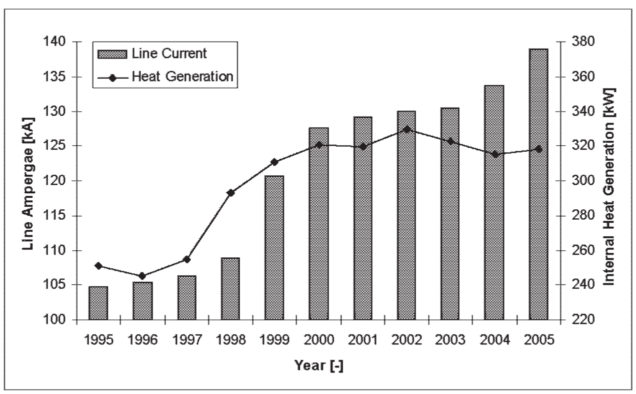

Figure 2: Development of Line Current versus Heat Generation

In a boosted section of 10 pots a current with a maximum of 10 kA above the line current can be tested at Aldel. It is an excellent way of testing new settings for the energy and material balance. With ramping up line current effects on the recycle loop via the dry-scrubber should be monitored closely, because of potential influences on the average fluoride (gaseous and dust) content and in particular carbon content in secondary alumina (see paragraph "anode properties"). The pressure on maximizing the performance of reduction cells requires a new control objective in order to run whole potlines at these new heat dissipation and alumina dissolution 'intensities' continuously.

Energy regulation

The position of aluminium smelters in European countries without governmental regulation in the "energy market" has become very difficult [3], e.g. energy prices have been doubled over the last 3 years in the Netherlands. While energy demand has strong temporal variation (from minutes up to seasonal effects) these circumstances have led to the development of advanced energy regulation strategies. For several years Aldel has built up a power management strategy in order to reduce its overall energy costs.

In general this regulation comprises a few different scenarios. On the one hand a day-night rhythm is actively used, which results in a continuous difference in base load over the lines of 5 kA between the day and night. As presented in figure 3 the difference in line amperage results in a variation in both bath temperature and liquidus of 5°C. It is also evident from these measurements that the reaction in the rise of bath temperature is predominant, and initiates a temporary rise of the cell superheat.

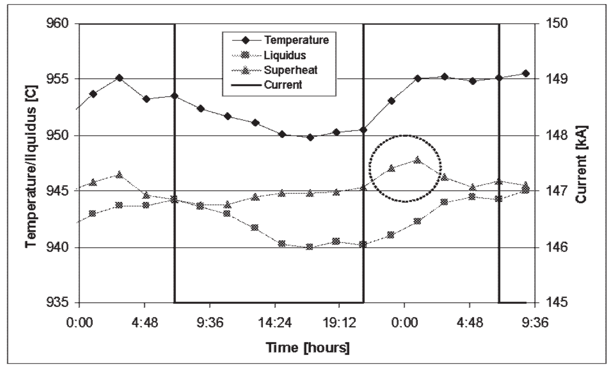

Figure 3: Impact of Day-Night Rhythm

Other energy management scenarios are related to real-time energy market circumstances and contains amperage reduction and/or outages at a frequency of once per 3.3 days (on average) and a range of 15 MWh/day up to 560 MWh/day (with and without a pre-warning). Existing control models compute a long-term material and energy balance for the cells under these testing and unpredictable scenarios. As discussed previously in the context of continual line amperage increase, power modulation above a certain intensity (up to 7% of the average daily cell heat input is frequently lost) also calls for a fresh control objective.

Environmental performance

At Aldel, the improvement of the environmental performance (e.g. SPL, and fluoride and fluorcarbon emissions) of the smelter is part of sustainable business operation. In order to reduce spent pot lining an intensive research program has been set up to improve the average lifetime of a cell. Beside adjustments to the design and construction of the pots the process model has been successful in a tight superheat control, which assures a stable side wall ledge protection.

The ventilation and therefore the cooling characteristics along the cells are of equal importance. A reduction of the air and steel temperature of 77°C and 98°C respectively were reached with a new ventilation design (figure 4). Beside that the direction of the airflow along the pots has been changed in the way that the heat dissipation through the holes is forced away from the side of the cell, which is a better design in respect to gas collection efficiency [4, 5]. The new design has resulted in a growth of the average side ledge thickness (+16%) due to better cooling. As result of these improvements the predicted average failure age of the first generation pots has reached a level of 2300 days, which is 15%

higher than benchmark figures of identical glued cathode block technology.

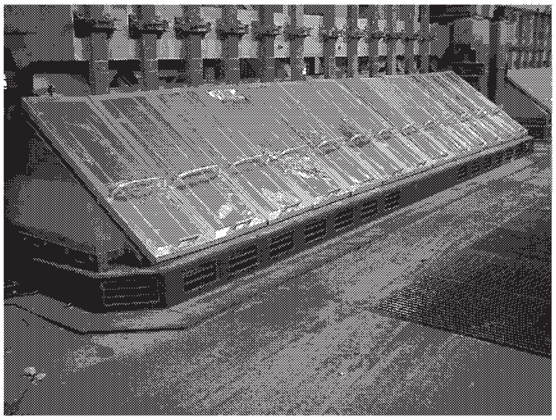

Figure 4: Improved Cell Ventilation Design

After the implementation of both the process control model and the new ventilation design, a program of further current increase has led to an overall reduction of the specific energy consumption. During the ramp up of the line amperage, a clear relation was found between the reduction of the total heat dissipation into the potrooms (calculated from the cell heat loss minus the heat extraction by the dry-scrubber) and the average airflow through the roof (figure 5).

	Heat Dissipation Per Pot [MWh/day]	Air Velocity Roof [m/s]
2001	6.33	0.723
2002	6.37	0.788
2003	6.32	0.720
2004	6.11	0.590
2005	6.04	0.476
R^2	0.9678	

Figure 5: Heat Dissipation versus Roof Airflow

Adjacent to this a better cover of the reduction cells was formed due to bigger anodes, which gave an increase of anode table with 12%. Finally, a better control of the individual gas suction rate per pot has been introduced and the overall cell hooding efficiency has been improved by the implementation of extra shielding. The specific fluoride emissions through the roof is dropped down by a factor of 2 (figure 6).

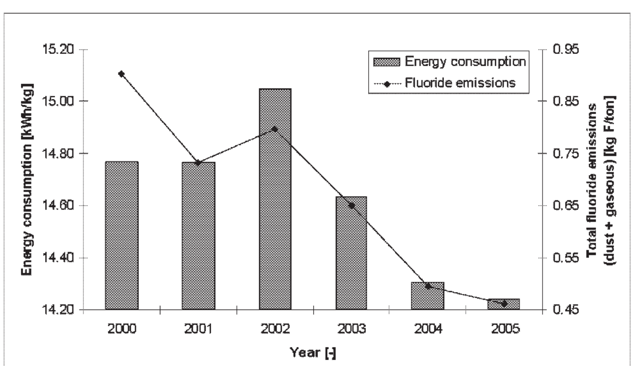

Figure 6: Specific Energy Consumption vs. Fluoride Emissions

After the retrofit project the anode effect frequency was reduced from 0.43 to 0.050 AE/pot-day. The anode effect energy has also come down to 100 kWh per anode effect with an emission of 0.30 kg fluorcarbon per anode effect in the ratio CF_4:C_2F_6 of 25:1 [6]. At the moment more than half of the anode effects are related to current reduction and/or outages. The anode effect frequency under "normal" process conditions has come down to 0.020 AE/pot-day. Further improvement of the anode effect frequency is complicated due to energy regulation, and it is necessary to investigate new advanced process control.

Anode Properties

Adjacent to the flattening of the overall performance related to maximizing line amperage, better environmental performance and convenient energy regulation the deterioration of anode quality is of significant concern in further development and in reaching a next level of controllability. Most of the old technologies, partly due to side feed origin, have their weak point connected to the heat balance in the upper part of the cell and need big investments for an upgrade of their anode assembly. As Aldel has no anode manufacturing facilities, anodes are purchased from different sources, and are treated separately in the potlines. In figure 7 the development of carbon dust generation is presented [7].

	Supplier A			Supplier B		
	CO_2 Dust	Air Dust	Total Dust	CO_2 Dust	Air Dust	Total Dust
2004	5.9	0.3	6.2	2.7	1.3	4.0
2005	4.7	0.5	5.2	3.1	2.0	5.1
2006	3.5	1.0	4.5	4.0	3.5	7.5

Figure 7: Propensity to Carbon Dust Generation [kg C/ton Al]

The results of better anode baking of Supplier "A" are noticeable, and the decline of the overall anode quality of Supplier "B" leads to enlarged operational problems. The average carbon content in secondary alumina has gone up by a factor of 2.5. In combination with the reduction of the average anode cathode distance (higher line current) and unpredictable interruptions in the cell heat input, the number of anode spikes in one potroom have been increased by 75%. The current through a spiked anode is approximately double of the nominal current, and due to shortcutting this part of the line current is not contributing to the electrolysis process. Being aware of this, there is a potential of improving the overall current efficiency by another 0.5%.

New control objective for aluminium smelters

As described in the previous paragraphs there is an absolute need for development of new generation of process control models. The requirement of operating reduction cells at or beyond known performance limits is a new challenge for the aluminium industry. In collaboration with the Light Metals Research Centre at the University of Auckland, a research project has been set up to improve the understanding and controllability of the aluminium reduction process. Because of the multivariate characteristics of the process, an important part of the work will be focused on improving the quality of decision-making within the control and associated operating strategy. Most existing control systems are based on compensatory control actions with a short-term focus to move the controlled variable(s) back into the optimum region. New control systems should be based on multivariate principles and they should be capable of addressing root causes in order to come to corrective control actions which reduce the process variability (and the number of causes acting) continuously, day by day.

Current Cell Behaviour

In order to obtain an initial characterization of the cell behaviour under the conditions now prevailing, a study was carried out on pot performance related to energy regulation. A first level of understanding of the effect of different energy management scenarios is evident in the large pot temperature and superheat responses during and after these energy imbalances. The impact of these power interruptions, depending on duration, frequency and intensity, can also lead to a long-term shift in bath chemistry.

The most frequent tendency after power modulation is a rapid decrease of the bath temperature (T_B) in combination with a larger decrease of the liquidus point (T_L). This trend is mostly observed together with an increase in alumina additions to the pot and occasionally with a decrease of bath levels, which is an indication of sludge formation (figure 8).

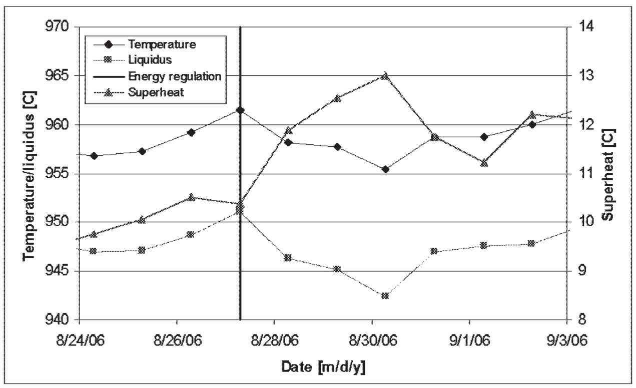

Figure 8: Decrease of T_B with a Predominant Decrease of T_L

Due to ensuing control actions [1] a decrease in AlF_3 additions and at times an increase in the set point voltage over several days can be observed. Over a period of 10 days approximately 2 tons of extra alumina (equals one normal day addition) is fed to the pot. Besides an alumina build-up in the system, almost 30 kg of AlF_3-equivalent via secondary alumina (equals two daily additions) is added to the pots. This could be the trigger of a self-accelerating cooling trend of a) sludge formation, b) increase of the total mass of alumina and fluorides in the system, c) increase of the cell resistance, d) a lower ACD with constant cell voltage, e) higher alumina concentration and therefore a decrease of the liquidus point.

More detailed investigation of the cusum of the energy input into the cell, the liquidus temperature and the total amount of alumina fed to the cell shows a clear cyclic behaviour of the aluminium reduction process (figure 9). Although most of the changes in the direction and/or the magnitude of the slope are directly linked to severe energy regulations (>100 MWh/day), there are indications of a predominant effect from the alumina additions resulting in a long-term process shift. In general the alumina additions and the liquidus temperature behave in an opposed manner as described previously in the mechanism of sludge formation. Based on the comparison between the bath temperature and liquidus point measurements over the last 3 years, it can be concluded that the controllability of the liquidus point is slightly worse than the bath temperature ($\Delta\sigma$ = 1.5°C). Beside the impact of working practices related to cover integrity (holes in the crust can doubled the fluoride emissions from a cell), the alumina feeding controllability is crucial in relation to constant mass and energy balance conditions.

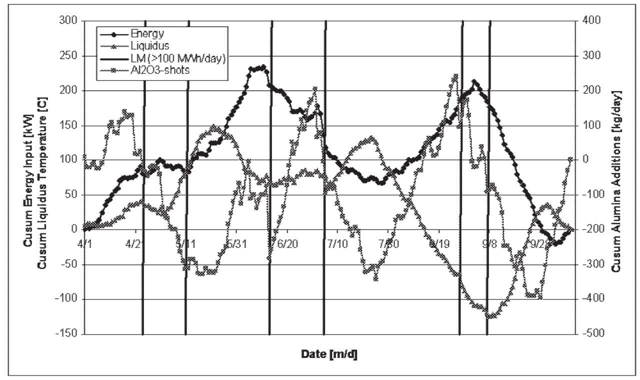

Figure 9: Cusum of Energy Input, Liquidus and Al_2O_3 Additions

Another common trend is a strong increase in bath and liquidus temperature (with or without a cold period before). This behaviour is often found together with an increase in the superheat, a decrease in alumina additions to the pot, with (on average) low noise levels. The combination of these items is most likely an indication of an anode spike. Investigations have shown that some anode pairs are more sensitive to spike formation then others (e.g. corner anodes due to the location of the alumina point feeders in relation to the direction of the metal circulation). The substantial increase of the line current creates a higher sensitivity for energy imbalances due to larger variations in metal inventory, lower liquid bath mass and consequently a heightened sensitivity to anode setting.

In some occasions pots tends to stick around (or slightly below) their target bath temperature for quite a long period. Based on the current control model both cell voltage and alumina additions to the pot show a continuous increase during this period. Especially when this particular trend is found in combination with a decrease of average bath levels, often pots fall into spiking problems.

Sensing and Detection

As a result of the increased sensitivity to energy imbalances of the pots, it is necessary to improve the sensing, analysis and diagnosis of cell abnormalities. The aluminium reduction process has a strongly interactive multivariate characteristic, which requires different methods of problem solving. Due to the fact that bath temperature and liquidus point of a cell are not independent, it has been found that the Hotelling T^2 method [8] is an appropriate multivariate control charting and analysis method to use in these process circumstances. This method can be used in the present investigation of two or higher dimensional systems in order to identify variation which is likely to be related to a single dominant cause in a cell. It is also a powerful tool in the detection of so-called Type I and Type II errors. These types of errors are related to variability that is considered in univariate systems to be in-control, but is in fact outside of statistical control (failed alarm or Type II) or vice versa (false alarm or Type I)

Hotelling T^2 statistics can be calculated for several combinations of interactive parameters, e.g. in analyzing two dimensional systems such as: bath temperature and liquidus point, liquidus point and bath height, liquidus point and alumina feeding, bath height and alumina feeding, and then compared with the computed Hotelling T^2 control limit for a given level of statistical significance. In figure 10 the development of the Hotelling T^2 statistic is presented for a cell approaching a situation of severe power management. As can be concluded from this example the Hotelling statistical is a beneficial tool in the detection of abnormal cell behaviour.

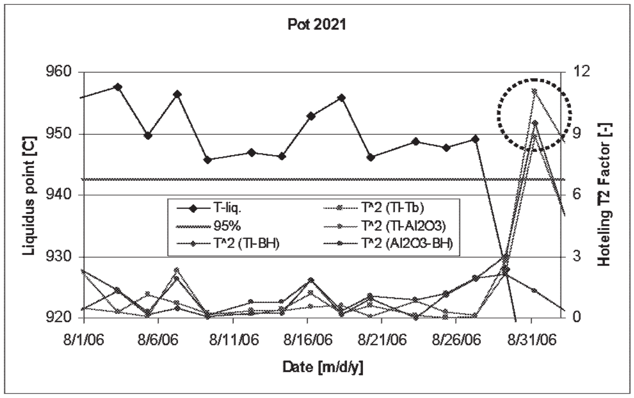

Figure 10: Development of T^2 in Case of Power Modulation

Based on the 95% confidential interval a control ellipse can also be determined for the couple bath temperature and liquidus point variables. This is shown in figure 11 which represents a two dimensional slice through a multi-dimensional cell operating region. On the one hand ordinary control models often make use of fixed targets and sometimes dead-bands. This approach directs in this two dimensional representation to a rectangular target area (yellow surface), which is not inline with the natural process variability and it ends up with incorrect responses.

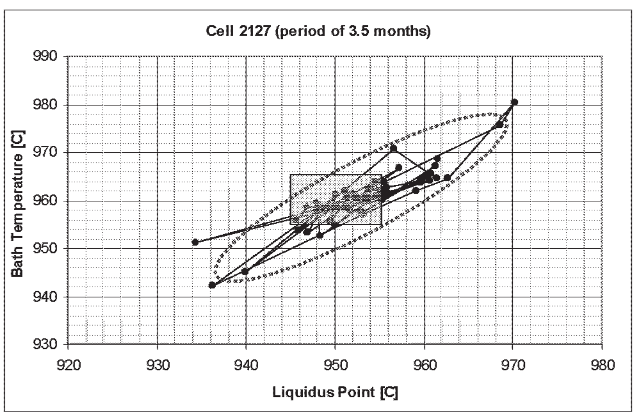

Figure 11: Temperature-Liquidus Control Ellipse

Beside this the points outside the control ellipse are an indication of abnormal statistical cell behaviour. Not only the position of a cell in relation to the control surface is important, however trending of the cell through the ellipse, or very rapid movements of the cell between one position and another can also constitute out of control behaviour. In fact in the latter case and combined with a crosscheck of process data (e.g. alumina additions and cell noise levels) a tool is available for the detection of anode spikes.

The present research program will be focused on the development of a new generation of process control models, which uses the multivariate characteristics of the aluminium reduction process, supported by measurements of the bath temperature and liquidus point including the alumina feeding control features.

Conclusions

Ten years of continuous improvement at the Aldel smelter has led to a significant increase of the capital productivity (tonnes Al/pot-day) and a major reduction of the overall operating costs (€/tonnes Al). It is found that the effectiveness of such a program is strongly linked to a good understanding of the relation between different "independent" subjects and project. As discussed the progress in the environmental performance could only be achieved due to the combination of the development of a process control model, new ventilation design along the cell, and improvements of the overall cell hooding efficiency. After the described implementation Aldel is facing a new operational plateau, which automatically leads to the definition of a new research program.

In order to be able to operate reduction cells at or beyond known performance limits continuously, it is necessary to define a new control objective relating to diagnosis of causes of abnormality in strongly interactive multivariate processes. With the requirement of maximizing cell productivity and the implementation of energy regulation strategies to reduce overall costs timely identification of these causes of variation is essential and linked to operational practice improvement and better control decisions in reduction lines. In this paper current Aldel cell behaviour is being discussed and several tools of sensing and detection of abnormalities are presented.

References

1. M.A. Stam, K.R. Kloetstra, "Development of an Advanced Process Control Strategy at Aluminium Delfzijl", Proceedings 8th Australasian Aluminium Smelting Workshop, 2004
2. M. Iffert, M. Kuenkel, M. Skyllas-Kazacos, B.J. Welch, "Reduction of HF Emissions from the TRIMET Aluminium Smelter", Light Metals, 2006
3. H. Kruse, "The German Power Market - The Final Countdown for the Aluminium Smelters", Proceedings 8th Australasian Aluminium Smelting Workshop, 2004
4. E. Dernedde, "Estimation of Fluoride Emissions to the Atmosphere", Light Metals, 1998
5. M. Karlsen, V. Lielland, H. Kvande, S.B. Vestre, "Factors Influencing Cell Hooding and Gas Collection Efficiencies", Light Metals, 1998
6. I. Berge, R. Huglen, M. Brugge, J, Lindstrom, T.I. Roe, "Measurement and Characterization of Fluorcarbon Emissions from Aluminium Reduction Cells", Light Metals 1994.
7. R&D Carbon, "Anodes for the Aluminium Industry", 1st Edition, 1995.
8. J.J.J. Chen, M.P. Taylor, "Control of Temperature and Aluminium Fluoride in Aluminium Reduction", Aluminium, 2006.