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Multi-objective Optimization of Aluminum Anode Baking Process Employing a Response Surface Methodology

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Abstract

In the aluminum anode baking furnace, the operational parameters have a significant influence on the furnace performance and the resulting anode quality. For this furnace, an important parameter is the fire-cycle, which determines the production rate of the baking kiln and the anodes quality. Shorter fire-cycle results in a higher furnace production rate and a higher fuel consumption (same anode temperature should be obtained in a shorter time). For a particular fire-cycle, flue-gas soaking temperature and soaking time are the other two key parameters that affect anode temperature distribution and furnace energy consumption. Limited studies in the literature focused on employing the traditional one-factor-a-time (OFAT) method to investigate the effect of these factors. Based on a simplified multi-physics model, a high-fidelity computational tool named ABKA (anode baking kiln analysis) software is developed to investigate the effects of these key operational parameters on the anode baking furnace heating performance. ABKA is employed to conduct a three-factors, two-level full factorial design, with a center point, to investigate the effects of varying fire-cycle, soaking temperature, and soaking time on furnace production rate, fuel consumption, and anode maximum, minimum and average temperature. The advantage of the present approach compared to the traditional one-factor-a-time (OFAT) method is that it can provide adequate information on interactions of different input variables, to effectively estimate the significance level of each factor, and to identify clear optimal settings of the three variables. Using ANOVA (analysis of variance), the effect and significance level of each factor and their interactions are effectively estimated. It is observed that soaking temperature has the highest impact on the final anode temperature distribution. Considering the furnace fuel consumption as a response, it is perceived that soaking time and soaking temperature jointly are as significant. Finally, employing RSM (response surface methodology), conducting multi-objective optimization, the optimal settings of the soaking time and soaking temperature for different production rates (fire-cycle values) are also estimated.

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Keywords: Anode baking furnace; factorial design; multi-objective optimization; fire-cycle time; soaking temperature; soaking time.

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1. Introduction

Green (unbaked) anodes should be baked (heat treated) to obtain desired mechanical, thermal and electrical properties that make them suitable to be used as anodes in the aluminum production. In the overall anode manufacturing process, baking contributes to ~ 44 % of the total processing cost. In the anode baking process, generally energy provided by the methane/natural gas combustion is employed for the heat treatment. Heating by flame jets are widely used in many applications and they are preferred over the induction heating techniques because of their high convective heat transfer, faster heating response time, saving the energy by switching on the burners only when heat is demanded and starting up and cooling down periods are much shorter which also result in energy saving [1-4]. The main drawback of the heating/baking by flame jets is non-uniform heat flux distribution which results in variability of anodes properties such as electrical resistivity, air and CO_2 reactivity, thermal shock resistance and density. The operational parameters have a significant influence on the anode baking furnace (ABF) performance and the anode quality. Computational modeling is imperative to investigate the effects of such parameters. Anode baking modeling approaches can be broadly categorized as the ABF design/CFD modeling [5-12] and ABF process modeling [13-19]. ABF CFD modeling is very expensive computationally. ABF process models fully represent the ABF including all the sections and provide valuable information on the furnace operation with an acceptable accuracy and affordable computational cost. As shown in Figure 1, a fire group usually consists of three preheating sections, three firing sections, four to six cooling sections. After each fire-cycle, the fire equipment (the exhaust ramps, burner ramps, cooling ramps) must be moved one section forward in the direction of the fire advance for the next section. Fire-cycle determines the production rate of the baking kiln and the anode quality.

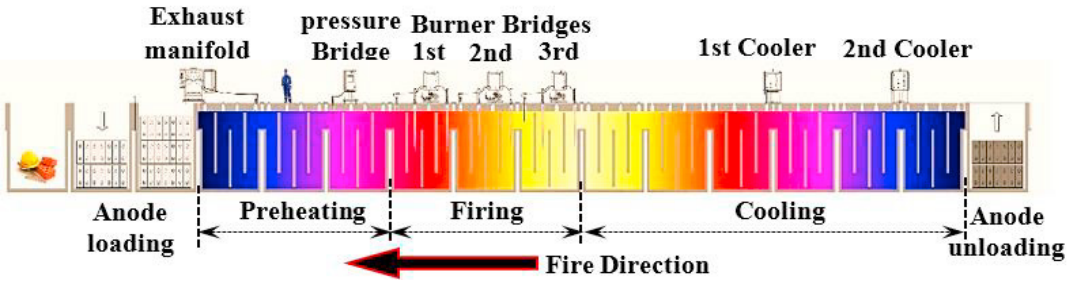


Figure 1.Longitudinal view of a complete fire [17].

As shown in Figure 2, during the baking process, the flue-gas temperature should follow a prescribed temperature history called baking curve (target curve). A shorter fire-cycle time results in a higher furnace production while longer fire-cycle time slows down the production. However, both extremes have limitations, beyond which anode quality and the baking economy (fuel consumption) will suffer. For a particular fire-cycle time, soaking time and soaking temperature are the two main parameters that affect significantly anode temperature distribution and energy consumption.

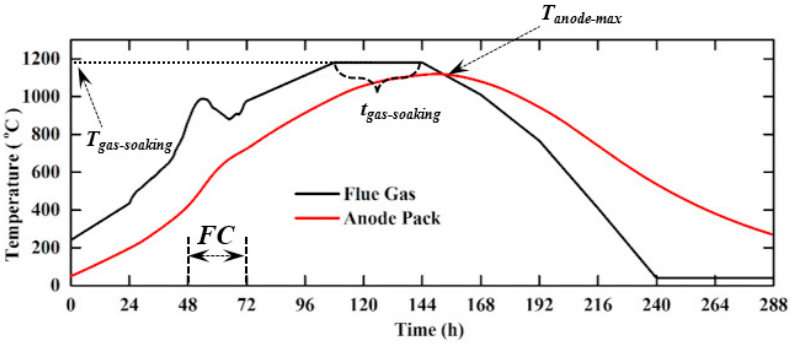


Figure 2. A typical anode baking curve.

Literature review indicates that in the case of ABF process modeling, often the bulk of time and resources are spent on building and validating the model, with a little time to employ the model for decision-making insight such as process optimization. The limited studies on the anode baking process optimization follow two approaches namely best guess approach, and one-factor-at-a-time (OFAT) approach [13-19]. These traditional approaches fail to provide adequate information on interactions of different input variables, or to provide accurate estimates of the effects and significance level of each factor, and to identify clear optimal settings of the factors. In the present study, employing the simulation results obtained from a high-fidelity in-house built computational tool named ABKA (Anode Baking Kiln Analysis) software, a 2-level factorial design is conducted to investigate the effects of varying fire-cycle, soaking temperature, and soaking time on the following responses; furnace production rate, fuel consumption, and anode maximum, minimum and average temperatures. Using ANOVA (analysis of variance), the effect and significance level of each factor and the interactions of these factors are effectively estimated. Finally, employing RSM (response surface methodology), multi-objective optimization of the anode baking process is carried out to identify the optimal settings of fire-cycle time, soaking time and soaking temperature.

2. ABKA Mathematical Formulation and Numerical Implementation

Figure 3-a shows the thermal exchanges in the anode baking furnace for a single pit. Two separate sub-models are considered namely flue and pit. The two sub-models are coupled through an interface. The flue model incorporates the flow of the gas in the flue wall cavity including the volatiles combustion, fuel combustion, heat transfer from flue-gasses to the refractory wall by convection and radiation, air infiltration etc. In the pit model, the transient heat conduction through the solid materials (refractory bricks, packing coke and anodes) is considered including heat loss to the foundation and atmosphere from the pit bottom and top. The equation is the heat balance equation solved for the flue sub-model. As shown in Figure 3-b, for a slice of thickness "dx", the heat balance equation can be written as the total heat coming into the gas control volume is equal to the total heat leaving the control volume.

$$\overbrace{\left(Q_{gas\ inlet}-Q_{gas\ outlet}\right)}^{1.\ heat\ transfer\ from\ gas\ to\ solids}+\overbrace{Q_{fuel}}^{2.\ Heat\ provided\ by\ the\ fuel\ combustion}+\overbrace{Q_{volatile\ gases}}^{3.\ Heat\ provided\ by\ the\ volatiles\ combustion}$$
$$-\overbrace{\left(Q_{foundation}+Q_{atmosphere}\right)}^{4.\ Heat\ loss\ to\ the\ atmosphere\ and\ foundation}-\overbrace{Q_{infiltartion}}^{5.\ infiltrated\ air}-\overbrace{\left(Q_{solids-gas}-Q_{gas-solids}\right)}^{5.\ Heat\ transfer\ from\ flue\ gas\ to\ wall}=0 \quad (1)$$

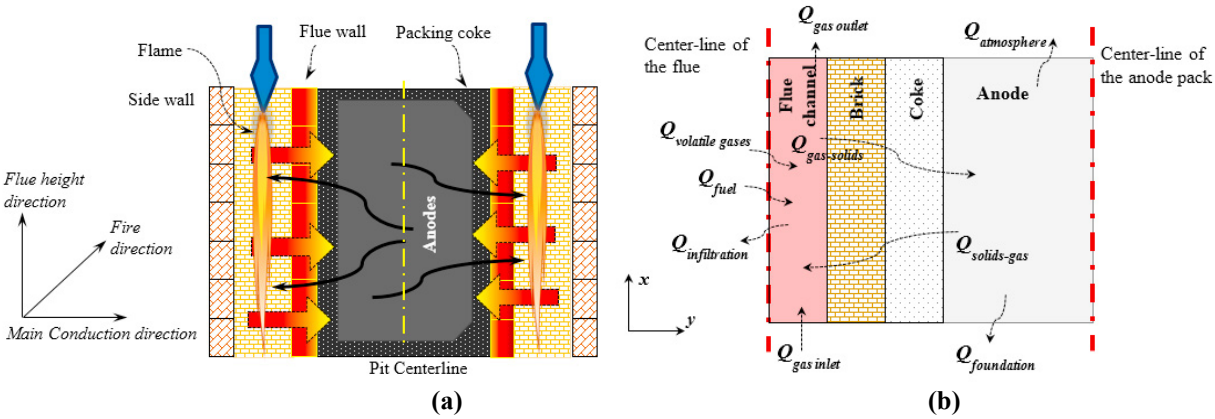


Figure 3. a) Thermal exchanges in a single pit, b) Schematic of the energy balance control volume.

Substituting the physical expression of the terms mentioned in the Eq.(1), it can be expressed as:

1. For the preheating sections

$$\overbrace{\dot{m}_g C_{pg} \frac{dT_g}{dx}}^{flue\ gas} + \overbrace{\left(\dot{m}_{tar} H_{tar} + \dot{m}_{CH_4} H_{CH_4} + \dot{m}_{H_2} H_{H_2}\right)}^{Heat\ provided\ by\ the\ volatiles\ combusted}$$
$$- \overbrace{\dot{m}_n C_{pg} (\mathrm{T}_g - \mathrm{T}_\infty)}^{\text{infiltrated air}} - \overbrace{2\,\mathrm{h}_T \mathrm{D}_{\text{flue}} (\mathrm{T}_g - \mathrm{T}_w)}^{Heat\ transfer\ from\ flue\ gas\ to\ wall} - \overbrace{W h_{equiv} (\mathrm{T}_g - \mathrm{T}_\infty)}^{Heat\ loss\ to\ atmosphere\ and\ foundation} = 0 \quad (2)$$

2. For the firing sections

$$\overbrace{\dot{m}_g C_{pg} \frac{dT_g}{dx}}^{flue\ gas} + \overbrace{\eta\, \dot{\mathrm{m}}_f H_f}^{Heat\ provided\ by\ the\ fuel} - \overbrace{\dot{m}_n C_{pg} (\mathrm{T}_g - \mathrm{T}_\infty)}^{\text{infiltrated air}} - \overbrace{2\,\mathrm{h}_T \mathrm{D}_{\text{flue}} (\mathrm{T}_g - \mathrm{T}_w)}^{Heat\ transfer\ from\ flue\ gas\ to\ wall} - \overbrace{W h_{equiv} (\mathrm{T}_g - \mathrm{T}_\infty)}^{Heat\ loss\ to\ atmosphere\ and\ foundation} = 0 \quad (3)$$

3. For the cooling sections

$$\overbrace{\dot{m}_g C_{pg} \frac{dT_g}{dx}}^{flue\ gas} - \overbrace{2\,\mathrm{h}_T \mathrm{D}_{\text{flue}} (\mathrm{T}_g - \mathrm{T}_w)}^{Heat\ transfer\ from\ flue\ gas\ to\ wall} - \overbrace{W h_{equiv} (\mathrm{T}_g - \mathrm{T}_\infty)}^{Heat\ loss\ to\ atmosphere\ and\ foundation} = 0 \quad (4)$$

Where,

η : Combustion efficiency

W : Flue width

P_{flue} : The equivalent perimeter of the flue

T_g : Gas temperature

h_T : Total heat transfer coefficient (Convective and Radiative)

$\dot{m}_g$: Gas mass flow in the flue

$\dot{m}_f$: Fuel injection per unit furnace length

$\dot{m}_v$: Volatiles release rate per unit furnace length

C_{pg} : Specific heat of the gas

T_w : Wall temperature

H_f and H_v : Fuel and volatiles gases heats of reaction

h_{equiv} : Equivalent heat transfer coefficient; considering the conductive resistance of the top and bottom solid materials, and convective- radiative heat transfer from the top and bottom

The first term is the enthalpy change of flue-gas. The second and third terms represent the heat added by the fuel and volatile combustion, respectively. The fourth term illustrates the heat loss to the foundation and the atmosphere. The fifth term shows heat loss due to air infiltration. The last term represents the heat transfer to the wall by flue-gas during preheating and firing sections and vice versa for the cooling sections. For the pit sub-model, heat transfer from flue gasses to fire bricks, then to the packing coke and finally to the anodes is incorporated by solving two-dimensional transient heat conduction equation. The directions for heat conduction are considered as the width and height of the pit (y, z), which are perpendicular to the fire direction (x).

$$\rho_s C_{ps} \frac{\partial T_s}{\partial t} = \frac{\partial}{\partial y}\left(k_s \frac{\partial T_s}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_s \frac{\partial T_s}{\partial z}\right) - Q_{p-lost} \quad (5)$$

Where k_s, C_{ps} *and* ρ_s are the thermal conductivity, specific heat and density of the solids (refractory wall, packing coke and anodes), T_s is the solids temperature and Q_{P-lost} is the heat loss to the foundation to the atmosphere from bottom and top of the pit.

3. Response Surface Methodology

Response surface methodology (RSM) is a collection of mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data. In the present study, the simulations result provided by the ABKA software. In the optimization of the anode baking process, multi-objective optimization has to be conducted. The objective is to simultaneously minimize the fuel consumption, maximize the furnace productivity, to meet a target anode average temperature and to minimize the non-uniformity of anode temperature. To test if the alteration in one of the levels or interaction is significant, a hypothesis test for the average response can be conducted by conducting ANOVA (analysis of variance). Table 1 shows ANOVA parameters that should be calculated for a two factors full factorial design. The same can be extended to three factors. Equation (7) demonstrates the expression for the total sum of squares, which is simply the sum of all the other four entries in that column. As provided in Table 1, the total degrees of freedom is the sum of all the other four entries in that particular column. For the cases that $F > F_0$, that particular main effect or interaction is considered to be significant.

$$y = \underbrace{\beta_0}_{Mean} + \underbrace{\sum_{i=1}^{k} \beta_i x_i}_{Linear\ term} + \underbrace{\sum_{\substack{j=1 \\ j<i}}^{k} \sum_{i=1}^{k} \beta_{ij} x_i x_j}_{Intraction\ term} + \underbrace{h.o.t.}_{Model\ error} + \underbrace{\varepsilon}_{Residual\ error} \tag{6}$$

Table 1. ANOVA table for a two-factor factorial design.

Source of variation	Sum of Squares	Degrees of freedom	Mean Squares	F	F_0
A	SS_A	$a-1$	$MS_A = SS_A/(a-1)$	$F = MS_A/MS_E$	$F_{(1-\alpha),a-1,ab(n-1)}$
B	SS_B	$b-1$	$MS_B = SS_B/(b-1)$	$F = MS_B/MS_E$	$F_{(1-\alpha),b-1,ab(n-1)}$
AB	SS_{AB}	$(a-1)(b-1)$	$MS_{AB} = SS_{AB}/(a-1)(b-1)$	$F = MS_{AB}/MS_E$	$F_{(1-\alpha),(a-1)(b-1),ab(n-1)}$
Error	SS_E	$ab(n-1)$	$MS_E = SS_E/ab(n-1)$		
Total	SS_T	$abn-1$	***NB: For a 2-level factorial design, a=b=2. Thus, dof =1 for each term.***		

$$\underbrace{\bar{y}_i = \frac{1}{bn}\sum_{j=1}^{b}\sum_{k=1}^{n} y_{ijk}}_{Average\ effect\ of\ Input\ A};\ \underbrace{\bar{y}_j = \frac{1}{an}\sum_{i=1}^{a}\sum_{k=1}^{n} y_{ijk}}_{Average\ effect\ of\ Input\ B};\ \underbrace{\bar{y}_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}}_{Average\ effect\ of\ Input\ AB};\ \underbrace{\bar{\bar{y}} = \frac{1}{abn}\sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{n} y_{ijk}}_{Average\ response\ for\ all\ levels\ (Grand\ Mean)}$$

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{n}(y_{ijk} - \bar{\bar{y}})^2 = bn\sum_{i=1}^{a}(\bar{y}_i - \bar{\bar{y}})^2 + an\sum_{j=1}^{b}(\bar{y}_j - \bar{\bar{y}})^2 + n\sum_{i=1}^{a}\sum_{j=1}^{b}(\bar{y}_{ij} - \bar{y}_i - \bar{y}_j - \bar{\bar{y}})^2 + \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{n}(y_{ijk} - \bar{y}_{ij})^2 \tag{7}$$

4. Results and Discussions

As shown in Figure 4, ABKA results are compared with the experimental measurements for two different furnaces having different operational parameters. Due to a confidential agreement with Emirates Global Aluminium (EGA) only the normalized average temperatures are illustrated. It can be observed that there are excellent agreements between the two results.

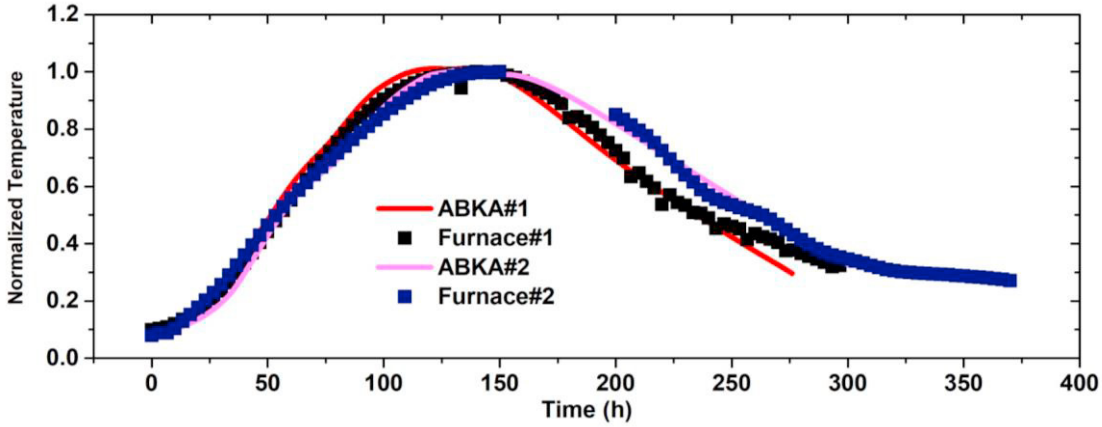
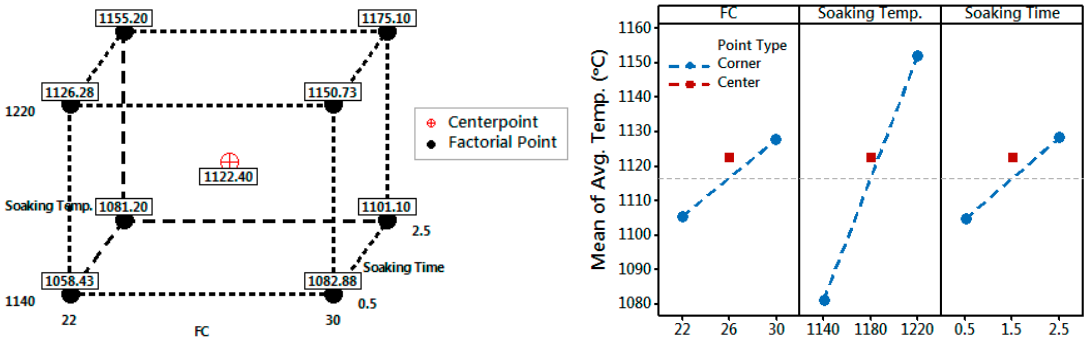


Figure 4. Comparison of anode average temperature with the experimental data at EGA (Furnace#1: FC = 23h, soaking temperature = 1170 ºC, soaking time = 38h; Furnace#2: FC = 25h, soaking temperature = 1150 ºC, soaking time = 34h).

Thus, a three factors, two-level full factorial design with a center point is considered, which requires a total of nine ABKA simulations, as shown in Figure 5 (a) that displays the cube plot (fitted means) (°C) and Figure 5 (b) the main effects plot for anode average temperature. It can be observed that the soaking time has the highest slope and thus greater impact on the response. The results are assessed in terms of five different responses. Table 3 shows the analysis of variance (ANOVA) for anode temperature and fuel consumption. In part (a) of the table, it can be observed that the soaking temperature has the highest F-value which indicates the significance of that factor, followed by the soaking time and fire-cycle time. Among 2-way interactions, the products of soaking time and soaking temperature, and FC and soaking time are significant. In part (b) of the table, considering fuel consumption as a response, soaking time and temperature are as significant. Among 2-way interactions, the product of soaking time and soaking temperature is only significant.

Table 2. Three factors, 2-level full factorial design table with the center point.

	Coded values for the three factors			**Un-Coded values for the three factors**			**Responses**				
Run	FC (hr.)	Soaking Temp. (°C)	Soaking Time (% of FC/100)	FC (hr.)	Soaking Temp. (°C)	Soaking Time (% of FC/100)	Avg. Temp. (°C)	Max Temp. (°C)	Min Temp. (°C)	Fuel (GJ/ton of anodes)	Productivity (h^{-1})
1	-1	1	1	22	1220	2.5	1154.4	1195.6	926.2	2.585	0.0455
2	-1	1	-1	22	1220	0.5	1126.4	1166.5	898.5	2.152	0.0455
3	-1	-1	1	22	1140	2.5	1082	1119.7	869.1	2.134	0.0455
4	-1	-1	-1	22	1140	0.5	1058.3	1094.8	846.4	1.593	0.0455
5	1	-1	1	30	1140	2.5	1100.3	1133.4	894.9	2.253	0.0333
6	1	1	1	30	1220	2.5	1175.9	1212	957.2	2.688	0.0333
7	1	-1	-1	30	1140	0.5	1083	1115.9	875.2	1.798	0.0333
8	1	1	-1	30	1220	0.5	1150.6	1186.7	927.9	2.198	0.0333
9	0	0	0	26	1180	1.5	1122.4	1159.7	905.1	2.158	0.0385



(a) **(b)**

Figure 5. (a) Cube Plot (fitted means) for Avg. Temp. (°C), b) Main Effects Plot for Avg. Temp. (°C).

Table 3. Analysis of Variance (ANOVA) table for (a) anode average temperature, (b) fuel consumption as the response.

(a)

Source	DF	SS	MS	F-Value	P-Value
Model	6	12217	2036	1552	0.001
Linear	3	12155	4051	3090	0.000
FC	1	983.5	983	750	0.001
Soaking Temp.	1	10060	10060	7672	0.000
Soaking Time	1	1111	1111	847	0.001
2-Way Interactions	2	29	14.6	11	0.082
FC*Soaking Time	1	10	10.4	7.8	0.107
Soaking Temp.*Soaking Time	1	18	18.9	14.4	0.063
Curvature	1	32	32.4	24.7	0.038
Error	2	2.6	1.3		
Total	8	12220			

(b)

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value
Model	4	0.91	0.229	255	0.000
Linear	3	0.91	0.304	339	0.000
FC	1	0.02	0.027	31	0.005
Soaking Temp.	1	0.42	0.425	474	0.000
Soaking Time	1	0.46	0.460	513	0.000
2-Way Interactions	1	0.0038	0.0038	4.2	0.108
FC*Soaking Temp.	1	0.0038	0.0038	4.2	0.108
Error	4	0.0035	0.00089		
Curvature	1	0.0002	0.00026	0.24	0.661
Lack-of-Fit	3	0.0033	0.0011	-	-
Total	8	0.92			

Figure 6 shows the normal plots of the standardized effects for the response as a) anode average temperature and b) fuel consumption. The red symbol indicates that the factor or their interactions are significant. Here, A is fire-cycle, B is the soaking temperature and C is the soaking time. As explained earlier, for the fuel consumption as a response

both soaking time and soaking temperature are equally significant which should be taken into the account for the process control.

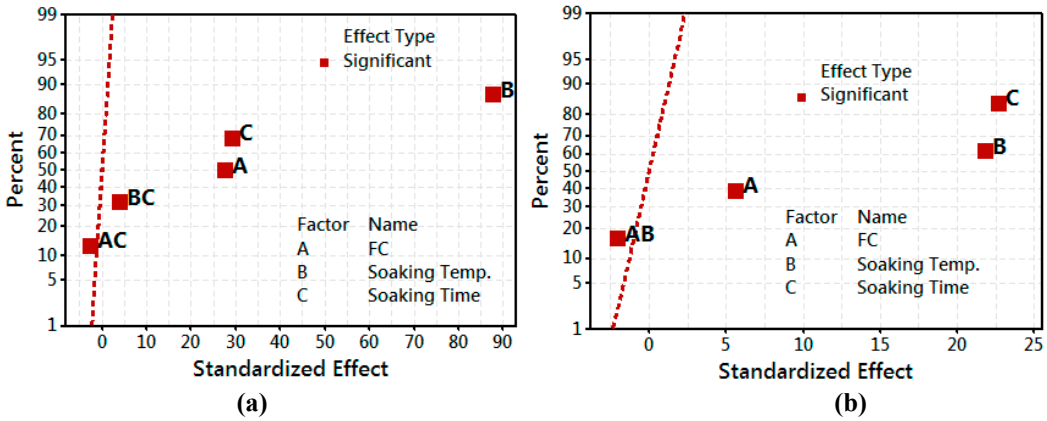


Figure 6. The normal plots of the standardized effects for the response as a) average anode temperature, b) Fuel consumption.

As shown in Figure 7, using overlaid contour plots, the acceptable operational area can be identified, the area where the predicted means of fuel consumption and average anode temperature are within (1.75-2.25 GJ/tons of anode) and (1075-1125°C) for different fire-cycle time. For the fire-cycle time of 22hrs, the soaking temperature and soaking time should be in the range of 1160 to 1215 °C and 1.8 to 2.5 of fire-cycle time (hrs), respectively. For higher fire-cycle times i.e., 26h and 30h, the range for the soaking time and soaking temperature moves to the left side (lower values).

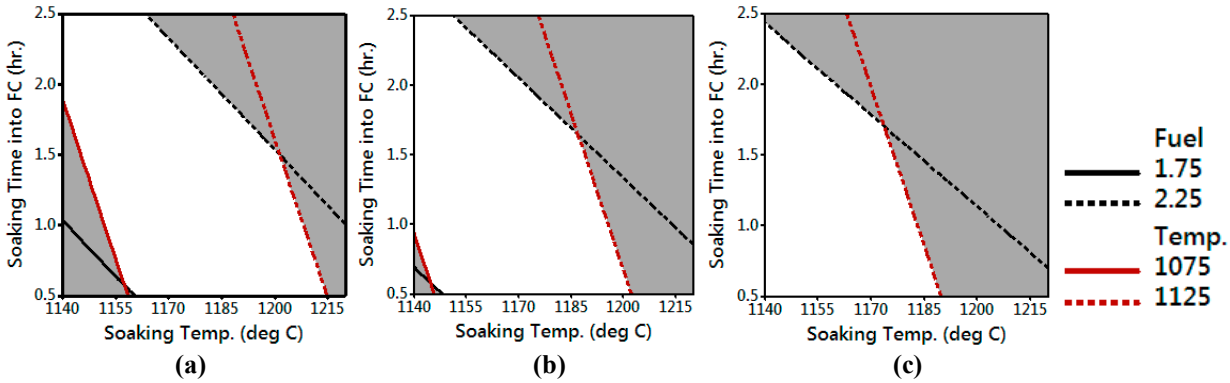


Figure 7. Overlaid contours to identify the area where the predicted means of fuel consumption and average anode temperature are within (1.75-2.25 GJ/tons of anode) and (1075-1125°C) for a) FC =22hrs, b) 26hrs and c) 30hrs.

In practice, instead of identifying an acceptable range, it is desirable to identify the exact combination of variable settings that jointly optimize the set of all five responses. In the multi-objective optimization process, it is aimed to maximize the anode minimum temperature, to minimize the anode maximum temperature, to maximize the productivity, to minimize the fuel consumption and to meet a value of 1080 °C for the anode average temperature. These values are combined to determine the composite, and overall desirability of the multi-response system. An optimal solution occurs where composite desirability obtains its maximum. As presented in Table 4, the three factors settings can be identified for three different scenarios. The individual and composite desirability assess how well a combination of variables satisfies the goals we have defined for the responses. Individual desirability (d) evaluates how the settings optimize a single response; composite desirability (D) evaluates how the settings optimize a set of responses overall. Desirability has a range of zero to one. One represents the ideal case; zero indicates that one or more responses are outside their acceptable limits. In Case-I, the furnace production is excluded from optimization. Hence, a fire-cycle of 30h, soaking temperature of 1140°C and soaking time of 0.5 of fire-cycle time are identified to

be optimum. Fuel consumption in this case is as low as 1.78 GJ/tons of anodes which is desirable. The gradient between minimum temperature and the average is ΔT_{min}=207°C, and the maximum temperature and the average temperature is ΔT_{max}=33°C. However, choosing a higher fire-cycle time slows down furnace production (total time = 360h). In Case-II, it is aimed to maximize the furnace productivity. The optimal setting of the three factors are as, fire-cycle time of 22h (total time = 264h), 1176 °C for the soaking temperature and 0.5 of fire-cycle time for the soaking time. The total time reduces by almost 100h. However, the fuel consumption increases to 1.85 GJ/tons of anodes. Moreover, as a result of a shorter fire-cycle time, the gradients are ΔT_{min}=220°C, ΔT_{max}=39°C which indicates a higher non-uniformity, which results in the non-homogenous evolution of carbon anodes properties. Hence, in Case-III, instead of minimizing the fuel consumption, in a view to minimizing the baking non-uniformity, it is intended to consume 2.0 GJ of energy per ton of anodes, which is higher fuel consumption than the previous two cases. The optimal setting of the three factors are as, fire-cycle time of 24h (total time = 288h), 1142 °C for the soaking temperature and 1.85 of fire-cycle time for the soaking time. the gradients are ΔT_{min}=212°C, ΔT_{max}=36°C which are lower than Case-II.

Table 4. Multi-objective response optimization for three different cases I) Excluding the furnace productivity as a response, II) Including the furnace productivity as a response (minimizing the fuel consumption), and III) Including the furnace productivity (target fuel consumption of 2.0GJ/ton of anode).

Sl. No.	Response	Case-I	Case-II	Case-III
1	Productivity	-	Maximum	Maximum
2	Fuel (GJ/ton of anodes)	Minimum	Minimum	Target
3	Min Temp. (°C)	Maximum	Maximum	Maximum
4	Max Temp. (°C)	Minimum	Minimum	Minimum
5	Avg. Temp. (°C)	Target	Target	Target

Solutions

Case	FC	Soaking Temp.	Soaking Time	Fuel (GJ/ton of anodes)	Min Temp. (°C)	Max Temp. (°C)	Avg. Temp. (°C)	Productivity	Composite Desirability (D)
I	30	1140	0.5	1.78	874	1114	1081	0.033	0.64
II	22	1176	0.5	1.85	870	1129	1090	0.045	0.63
III	24	1142	1.85	2.0	870	1118	1082	0.042	0.65

5. Conclusions

The present study employs a high-fidelity in-house developed computational tool named ABKA (anode baking kiln analysis) to conduct a three-factors, 2-level full factorial design, with a center point run, to investigate the effects of various operational parameters of an anode backing furnace for the aluminum production. The parameters studied included fire-cycle, soaking temperature, and soaking time on furnace production rate, fuel consumption, and anode maximum, minimum and average temperatures. Using ANOVA (analysis of variance), the effect and significance level of each factor and their interactions are effectively estimated. It is observed that soaking temperature has the highest impact on the final anode temperature distribution. Considering the furnace fuel consumption as the response, it is perceived that the soaking time and soaking temperature jointly have the same significance level. Finally, employing a response surface methodology, conducting multi-objective optimization, the optimal settings of the soaking time and soaking temperature for different production rates (fire-cycle) are calculated. If furnace production is excluded from optimization, longer fire-cycle time with lower soaking time and soaking temperature are identified to be optimum which results in a lower fuel consumption and higher baking uniformity. However, it slows down furnace production. In another case study, it is aimed to maximize furnace productivity. The total time

is reduced by almost 100h. However, fuel consumption and baking non-uniformity increased. Hence, in the last case, instead of minimizing the fuel consumption, in a view to minimizing the baking non-uniformity, it is intended to spend a certain amount of energy per ton of anodes, which is higher fuel consumption than the previous two cases. Thus, in this last case, baking uniformity and furnace production rate improved.

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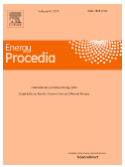
References

[1] Hindasageri V, Kuntikana P, Tajik AR, Vedula RP, Prabhu SV. Axis switching in impinging premixed methane-air flame jets. Applied Thermal Engineering. 2016; 107:144-53.
[2] Tajik AR, Kuntikana P, Prabhu SV, Hindasageri V. Effect of the preheated mixture on heat transfer characteristics of impinging methane-air premixed flame jet. International Journal of Heat and Mass Transfer. 2015; 86:550-62.
[3] Kadam AR, Tajik AR, Hindasageri V. Heat transfer distribution of impinging flame and air jets–a comparative study. Applied Thermal Engineering. 2016; 92:42-9.
[4] Tajik AR, Hindasageri V. A numerical investigation on heat transfer and emissions characteristics of impinging radial jet reattachment combustion (RJRC) flame. Applied Thermal Engineering. 2015; 89:534-44.
[5] Zaidani M, Al-Rub RA, Tajik AR, Shamim T. Effects of Flue Wall Deformation on Aluminum Anode Baking Homogeneity and Temperature Distribution, The International Committee for Study of Bauxite, Alumina & Aluminum – ICSOBA2016.
[6] Zaidani M, Al-Rub RA, Tajik AR, Shamim T. Investigation of the Flue-wall Aging Effects on the Anode Baking Furnace Performance. In ICTEA: International Conference on Thermal Engineering 2017 Mar 15 (Vol. 2017).
[7] Tajik AR, Shamim T, Zaidani M, Al-Rub RK. The effects of flue-wall design modifications on combustion and flow characteristics of an aluminum anode baking furnace-CFD modeling. Applied Energy. 2018 Nov 15; 230:207-19.
[8] Tajik AR, Shamim T, Al-Rub RK, Zaidani M. Two-Dimensional CFD Simulations of a Flue-wall in the Anode Baking Furnace for Aluminum Production. Energy Procedia. 2017 May 31; 105:5134-9.
[9] Tajik AR, Al-Rub RK, Zaidani M, Shamim T. Numerical Investigation of Turbulent Diffusion Flame in the Aluminum Anode Baking Furnace Employing Presumed PDF. Energy Procedia. 2017 Dec 31; 142:4157-62.
[10] Zaidani M, Al-Rub RA, Tajik AR, Shamim T. 3D Multiphysics model of the effect of flue-wall deformation on the anode baking homogeneity in horizontal flue carbon furnace. Energy Procedia. 2017 Dec 31; 142:3982-9.
[11] Zaidani M, Al-Rub RA, Tajik AR, Shamim T. Computational Modeling of the Effect of Flue-Wall Deformation on the Carbon Anode Quality for Aluminum Production. In ASME 2017 Heat Transfer Summer Conference 2017 Jul 9.
[12] Zaidani M, Al-Rub RK, Tajik AR, Qureshi ZA, Shamim T. The Influence of Flue Wall Deformation on Anode Baking Homogeneity for the Aluminum Production Life, The International Committee for Study of Bauxite, Alumina & Aluminum – ICSOBA2017.
[13] Severo DS, Gusberti V. USER-FRIENDLY SOFTWARE FOR SIMULATION OF ANODE BAKING FURNACES. Proceeding of 10th Australisian. 2011.
[14] Tajik AR, Shamim T, Al-Rub RK, Zaidani M. Process Modelling of a Horizontal Anode Baking Furnace for Aluminum Production, The International Committee for Study of Bauxite, Alumina & Aluminum – ICSOBA2016.
[15] Oumarou N, Kocaefe D, Kocaefe Y. An advanced dynamic process model for industrial horizontal anode baking furnace. Applied Mathematical Modelling. 2018 Jan 1; 53:384-99.
[16] Tajik AR, Shamim T, Al-Rub RK, Zaidani M. Performance Analysis of a Horizontal Anode Baking Furnace for Aluminum Production. In ICTEA: International Conference on Thermal Engineering 2017 Mar 15 (Vol. 2017).
[17] Tajik AR, Al-Rub RK, Zaidani M, Qureshi ZA, Shamim T. Effects of Fire-cycle Time on Heat Transfer Characteristics and Energy Consumption in Anode Baking Furnace, The International Committee for Study of Bauxite, Alumina & Aluminum – ICSOBA2017.
[18] Oumarou N, Kocaefe D, Kocaefe Y, Morais B. Transient process model of open anode baking furnace. Applied Thermal Engineering. 2016 Aug 25; 107:1253-60.
[19] Qureshi ZA, Al-Rub RK, Zaidani M, Tajik AR, Shamim T. An Introduction to Phase-Field based Model for Predicting the Baking Level of Carbon Anodes, The International Committee for Study of Bauxite, Alumina & Aluminum – ICSOBA2017.



Biography

The first author is a Ph.D. candidate at Khalifa University, UAE. Abdul Raouf is perusing his doctoral degree in a collaborative program with Massachusetts Institute of Technology, USA. His main area of research is computational modeling of the reactive flows. Currently he is working on combustion, emissions and heat transfer characteristics of an open-top aluminum anode baking furnace.