International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 858

THE EFFECTS OF FLOW-BLOCKAGE ON THE PERFORMANCE OF ANODE BAKING FURNACES FOR ALUMINUM PRODUCTION

Abdul Raouf Tajik[1,2], Mouna Zaidani[1], Tariq Shamim[3], Rashid K. Abu Al-Rub[1,2*]
[1]Mechanical Engineering Department, Khalifa University, P.O. Box 127788, Abu Dhabi, UAE
[2]Aerospace Engineering Department, Khalifa University, P.O. Box 127788, Abu Dhabi, UAE
[3]Mechanical Engineering Department, College of Engineering and Engineering Technology, Northern Illinois University, IL 60115, USA
*Corresponding author: rashid.abualrub@ku.ac.ae

ABSTRACT

As time progresses, aging of the anode baking furnaces occurs, and packing coke (the powder) gets infiltrated into the flue-wall cavity, which gives rise to flow blockage. Using a fully coupled 3D multi-physics computational model, several modified flue-wall designs are proposed. In the current design of the flue-wall, the openings at the top of first and last baffle are meant for the flow bypass in case of flow blockage. However, these openings are considered to be accountable for non-uniform distribution of the flow and extra energy consumption. The effect of flow blockage for different designs is investigated. By closing the openings which, both the flow and temperature uniformity is enhanced substantially. It is also remarked that the modified flue-wall designs are safe to operate at the time of flow blockage. Moreover, considering the practicalities of modifying the flue-wall design, openings of different thickness are proposed by specifying the number of bricks to be removed. This modification is done by removing one brick (85 mm) as a reference case, and other scenarios are also considered by shifting the two openings to the top or the bottom. The methodology and results presented in the present research can be employed effectively by the aluminum industry in modifying the furnace geometrical and operational parameters to enhance baking uniformity for old furnaces.

Keywords: Anode baking furnace, flue-wall, flow blockage, aging, design modification, aluminum electrolysis.

1. INTRODUCTION

The baking of the carbon anodes is carried out in a very energy-intensive process in the ring furnaces often called anode baking furnace. The operational and physical parameters have a significant influence on anode baking furnace performance and anode quality. Anode baking furnace process models represent all the phenomena taking place in the furnace by using simple energy balance. However, these simple process models may not be able to assist in design modification [1-3]. CFD modeling provides a better alternative [4-12]. In anode baking furnaces, heating by flame jets are preferred over the induction heating techniques because of their high convective heat transfer, faster heating response time, but it suffers high baking non-homogeneity [13-16].

As shown in Fig 1, in the flue-wall, near the flame jets, there are openings that are meant for the flow bypass in case of flow blockage that happens for the old anode baking furnaces. However, based on the experience of anode baking operators at EGA, these openings near the flame jets cause excess fuel consumption since the jet momentum is distracted.

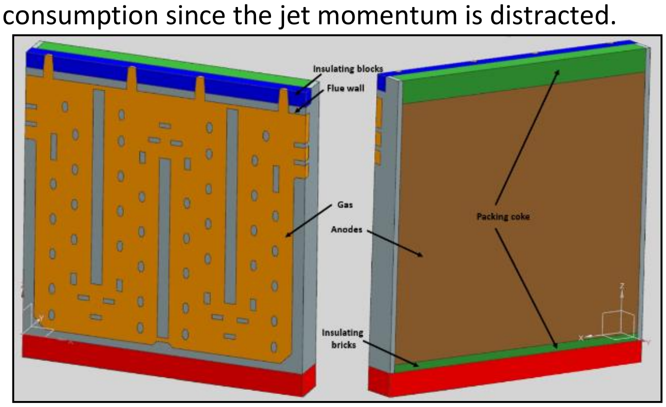

Fig 1 solid and gas computational domains, coupled at the interface

As shown in Fig 1, in the current design of the flue-wall, the openings at the top of first and last baffle are meant for the flow bypass in case of flow blockage (See Fig 2). However, these openings are considered to be accountable for non-uniform distribution of the flow and extra energy consumption. Thus, it is imperative to develop a fully coupled 3D multi-physics computational model which takes into account a large number of physical phenomena that play vital roles in the baking process and are affected by the flue-wall blockage.

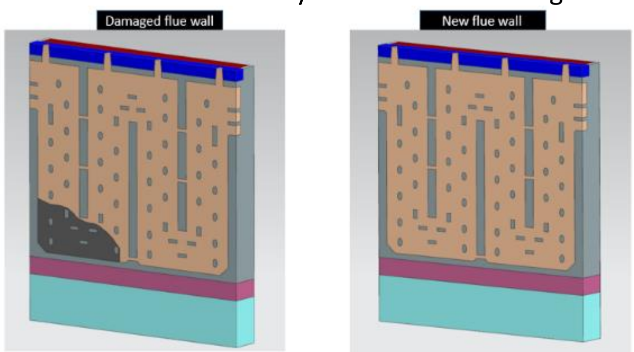

Fig 2 Blockage in the flue-wall due to coke infiltration

In the present study, the effect of flow blockage for different designs is investigated. Moreover, considering the practicalities of modifying the flue-wall design, openings of different thickness are proposed by specifying the number of bricks to be removed. This modification is done by removing one brick (85 mm) as a reference case, and other scenarios are also considered by shifting the two openings to the top or the bottom.

2. MODEL SPECIFICATIONS

Followings are the main governing equations that are solved in the present study. The equation for conservation of mass, or continuity equation, can be written as follows:

$$\nabla.(\bar{\rho}\tilde{\vec{v}})=0 \quad (1)$$

Conservation of momentum in an inertial (non-accelerating) reference frame is described by:

$$\nabla(\tilde{\vec{v}}.\nabla\tilde{\vec{v}})=-\nabla p+\nabla.(\bar{\bar{\tau}})+\bar{\rho}\vec{g}+\vec{F} \quad (2)$$

The stress tensor $\bar{\bar{\tau}}$ is given by:

$$\bar{\bar{\tau}}=\mu\left[\left(\nabla\tilde{\vec{v}}+\nabla\tilde{\vec{v}}^{T}\right)-\frac{2}{3}\nabla.\tilde{\vec{v}}I\right]$$

For the conservation equations closure, the realizable $k-\varepsilon$ model is employed. Followings are the equations for turbulent kinetic energy (k) and its dissipation rate (ε):

$$\bar{\rho}\left(\tilde{\vec{v}}.\nabla\right)\tilde{k}=\nabla.\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla\tilde{k}\right]+G_k+G_b-\bar{\rho}\tilde{\varepsilon}-Y_M \quad (3)$$

$$\bar{\rho}\left(\tilde{\vec{v}}.\nabla\right)\tilde{\varepsilon}=\nabla.\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\tilde{\varepsilon}\right]+\rho C_1 S\tilde{\varepsilon} -\rho C_2\frac{\tilde{\varepsilon}^2}{\tilde{k}+\sqrt{v\tilde{\varepsilon}}}+C_{1\varepsilon}\frac{\tilde{\varepsilon}}{\tilde{k}}C_{3\varepsilon}G_b \quad (4)$$

The energy equation can be expressed as follows:

$$\nabla\cdot(\tilde{\vec{v}}(\bar{\rho}\tilde{E}+\bar{P}))=\nabla\cdot\left(k_{eff}\nabla\tilde{T}-\sum_{j=1}^{N}h_j\vec{J}_j\right)+S_h \quad (5)$$

where the mixture enthalpy is computed as $h=\sum_j\tilde{Y}_j\left[h_{f,j}^0+\int_{Tref}^{T}c_{p,j}dT\right]$, $\tilde{Y}_j$ is the mass fraction of jth species, and $\tilde{E}=h-\frac{p}{\bar{\rho}}+\frac{\tilde{\vec{v}}^2}{2}$.

In an absorbing, emitting, and scattering medium, the radiative transfer is mathematically modeled by the radiative transfer equation which describes the rate of change of the spectral radiation intensity, I_λ, of a radiation beam traveling in the medium at the point r that propagates along a direction S and can be written as:

$$\frac{dI_{ri}(\vec{r},\vec{s})}{ds}=an^2\frac{\sigma T^4}{\pi}-(a+\sigma_s)I_{ri}(\vec{r},\vec{s}) +\frac{\sigma_s}{4\pi}\int_0^{4\pi}I_{ri}(\vec{r},\vec{s}')\phi(\vec{s},\vec{s}')d\Omega' \quad (6)$$

A mesh sensitivity study is performed, and it can be seen that after increasing the number of elements from 30,000 to 410,000 the difference in anode average temperature is found to be less than 1% for gird size above 150,000 elements. Hence, for the present study, the selected mesh is constituted of 179,669 grid elements. In practice, the generated grid is done at “fine’’ level (in terms of COMSOL internal grid definitions) such that the average element quality being on the order of 0.7. Finite element-based software COMSOL 5.1 Multi-physics model is used. To solve governing equations, segregated solvers are used to calculating the fluid flow (velocity and pressure) and heat transfer (temperature) variables. Generalized minimal residual (GMRES) iterative method solver is used to calculate the parameters with a tolerance of 10^{-6} and a factor in error estimate of 20. As a preconditioner, Geometric Multigrid solver is used with PARDISO (Parallel Sparse Direct Linear Solver) fine solver.

3. RESULTS AND DISCUSSIONS

The computational model has been validated versus experimental data based on comparing the anode temperature distribution [4].

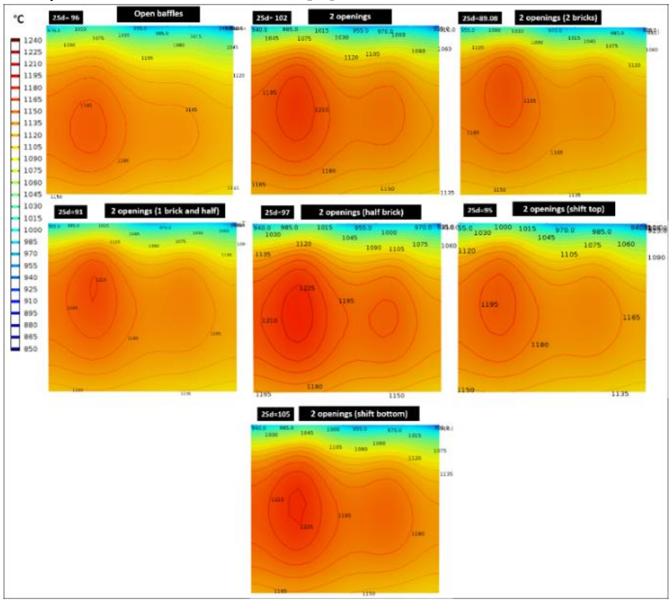

Fig 3 Anode temperature at the mid-plane for new flue wall for different designs

Fig 3 shows the temperature contours for different designs without the flow blockage (the middle of the flue) for five different flue wall designs: open baffles, close baffle (upstream and downstream) and close baffles (with one or two openings) at the center.

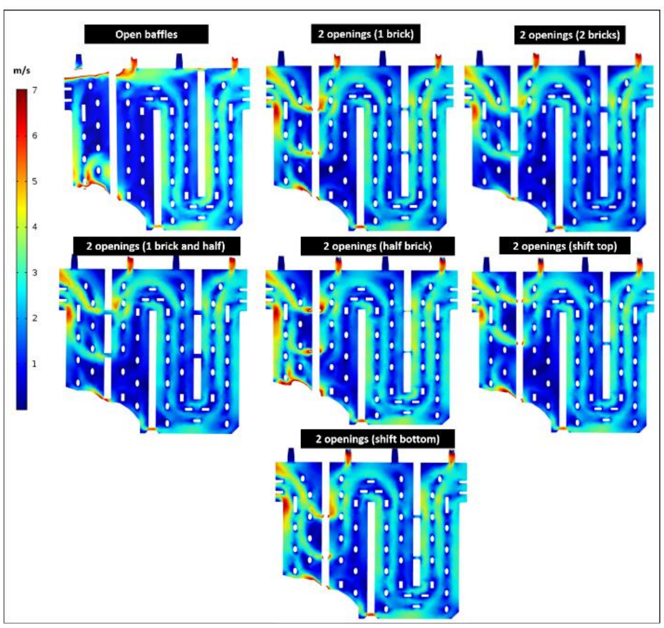

Fig 4 Velocity contours for flow-blockage in different flue-wall designs

Fig 4 presents the flow pattern on the symmetry plane in the flue domain (the middle of the flue) for five different flue wall designs: open baffles, close baffle (upstream and downstream) and close baffles (with one or two openings) at the center. It can be observed that the flow distribution is significantly affected by the flow blockage. It can also be remarked that the modified flue-wall designs are safe to operate at the time of flow blockage. Fig 5 shows the temperature contours for different designs with flow blockage.

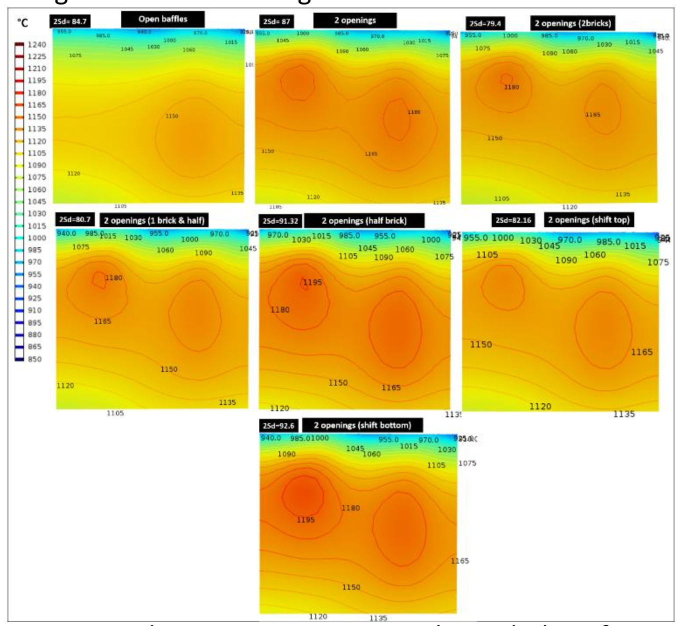

Fig 5 Anode map temperature at the mid-plane for a damaged flue wall for different designs

It can be clearly seen that using the proposed design in the current research, an acceptable level of uniformity of and temperature can be obtained at the of flow blockage with the safe operation of the furnace.

4. CONCLUSIONS

In the present study, a fully coupled 3D multi-physics computational model is developed which takes into account a large number of physical phenomena that play vital roles in the baking process and are affected by the flue-wall deformation mode. The openings at the top of first and last baffle are meant for the flow bypass in case of flow blockage. This will remove the possibility of flue-wall explosions at the time of flue-wall blockage. However, these openings are considered to be accountable for the loss of momentum of the flame jets in the vertical direction, and consequently, the non-uniform distribution of the flow and extra energy consumption. The effect of flow blockage for different designs is investigated. By closing the openings, both the flow and temperature uniformity is enhanced substantially. It is also remarked that the modified flue-wall designs are safe to operate at the time of flow blockage. Moreover, considering the practicalities of modifying the flue-wall design, openings of different thickness are proposed by specifying the number of bricks to be removed. The methodology and results presented in the present research can be employed effectively by the aluminum industry in modifying the furnace geometrical and operational parameters to enhance baking uniformity after a flue-wall is deformed.

ACKNOWLEDGMENTS

The authors acknowledge the financial support provided by the Emirates Global Aluminium (EGA) in UAE under the direction of Dr. Mohamed O. Mahmoud. Also, the authors acknowledge the support and help of the carbon anode team at EGA.

REFERENCES

[1] Tajik AR, Shamim T, Ghoniem AF, Abu Al-Rub RK. Multi-objective Optimization of Aluminum Anode Baking Process Employing a Response Surface Methodology. Energy Procedia. 2019 March 15; 158: 5541-5550.

[2] 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).

[3] Severo DS, Gusberti V, Pinto EC. Advanced 3D modeling for anode baking furnaces. Light metals. 2005; 2005:697-702.

[4] Zaidani M, Tajik AR, Qureshi ZA, Shamim T, Abu Al-Rub RK. Investigating the Flue-wall Deformation Effects on Performance Characteristics of an Open-Top Aluminum Anode Baking Furnace. Applied Energy. 2018 Dec 1; 231:1033-1049.

[5] 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.

[6] Tajik AR, Shamim T, Ghoniem AF, Abu Al-Rub RK. Multi-objective Optimization of Aluminum Anode Baking Process Employing a Response Surface Methodology. Energy Procedia. 2019 March 15; 158: 5541-5550.

[7] Zaidani M, Abu Al-Rub RK, Tajik AR, Shamim T. Computational Modeling of the Effect of Flue-Wall Deformation on the Carbon Anode Quality for Aluminum Production. In. Proceedings of the ASME's Heat Transfer Summer Conference, Paper No. HT2017-5063, pp. V001T02A010; 11 pages, 2017.

[8] 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; 230:207-219.

[9] 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.

[10] 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.

[11] 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.

[12] Tajik AR, Shamim T, Ghoniem AF, Abu Al-Rub RK. CFD Modelling of NOx and Soot Formation in Aluminum Anode Baking Furnace. In. ASME's International Mechanical Engineering Congress and Exposition (IMECE), 2018. Paper No. IMECE2018-88390, pp. V08AT10A016; 8 pages.

[13] 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.

[14] 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.

[15] 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.

[16] 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.

