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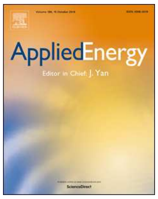

Investigating the flue-wall deformation effects on performance characteristics of an open-top aluminum anode baking furnace

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HIGHLIGHTS

- A 3D multi-physics modeling of the flue-wall deformation is performed.
- Effect of various deformation levels on anode temperature distribution is investigated.
- Comparison between un-deformed and deformed flue-walls is conducted.
- Flue-wall deformation significantly increases the maximum anode temperature.
- As flue-wall deflection increases, temperature non-homogeneity and size of over-baking zones increase.

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ABSTRACT

The carbon anode baking is typically the bottleneck in the production of anodes for the aluminum industry. The challenge is to produce high quality baked anodes while keeping the energy consumption, environmental emissions, and cost to a minimum. Anode baking homogeneity is an important consideration in the design and operation of the anode baking furnaces. The flue-walls, into which the firing takes place, are the heart of the furnace. The flue-walls must be well designed and well maintained in order to be able to regulate them properly. However, during the service life of a baking furnace, flue-walls deform which affect the baking uniformity and consequently result in over-consumption energy and reduction in carbon anode quality. Studying the effects of flue-wall deformation by plant tests is highly challenging and expensive. Hence, this study aims at investigating this phenomenon by developing a three-dimensional (3D) model which includes many physical phenomena and parameters that play vital roles in the baking process. It was observed that indeed the flue-wall deflection has a significant impact on heat transfer characteristics of the anode baking process and furnace energy consumption. In specific, the flue-wall deformation results in an increase in temperature gradients within the anode pack such that the differences between anode pack minimum, average and maximum temperatures lead to overbaking or underbaking of anodes. In fact, this non-uniform baking gives rise to the evolution of non-homogeneous carbon anodes material properties, which is the main reason for excess energy consumption and various instabilities in the aluminum reduction cell. The insights obtained in the present study can be employed in modifying the furnace geometrical and operational parameters with the deformed flue-walls.

1. Introduction

The anode baking is a very expensive step in the aluminum production. Fuel consumption and refractory maintenance contribute significantly towards the total cost of anode production. The anode baking is carried out in an anode ring furnace that is composed of a number of preheating, firing, and cooling sections. Anodes are placed between the flue-walls into a pit. The fire group equipment (the exhaust manifold, burner ramps and the cooling covers) moves and the anodes remain stationary. Fig. 1 shows a typical view of an open top furnace and a three-dimensional (3D) view of a section in the ring furnace. Usually, each furnace has two to four fire groups, where each fire group is composed of typically 10–16 sections: three to four anode preheating sections, three to four firing sections and four to nine cooling sections.

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Nomenclature

$\bar{I}$	identity matrix
C_P	specific heat (J/kg·°C)
D_h	hydraulic diameter inside the flue (m)
k	turbulent kinetic energy (m^2/s^2)
T	temperature (°C)
p	the static pressure inside the flue (Pa)
t	time (s)
ε	turbulent dissipation (m^2/s^3)
h	coefficient of heat transfer (W/m^2·°C)
Q_s	heat loss to the atmosphere from bottom and top of the pit (W/m^3)
C	constant
x, y, and z	coordinate axes (m)

Greek symbols

ρ	density (kg/m^3)
Δ	difference operator (·)
μ	dynamic viscosity (Pa·s)
μ_T	effective viscosity (Pa·s)
ω	emissivity (·)
σ	Stefan-Boltzmann constant = $5.67^* \times 10^{-8}$ (W/m^2·°C^4)
η	the absorptivity of the flue gas (·)
λ	thermal conductivity (W/m·°C)
α_T	thermal expansion coefficient (1/°C)

Subscripts/superscripts

∞	ambient (·)
C	convective
g	gas
R	radiative
S	solids (anode, packing coke and flue-wall)
T	transpose operator (·)
w	wall

Dimensionless numbers

Re	Reynolds Number (·)
Pr	Prandtl number (·)

Abbreviations

CFD	Computational Fluid Dynamics
MP	Multi-Physics

Anodes are heated at a certain rate from room temperature to about 1100 °C and then cooled slowly. The process starts by placing green anodes in the pit at the ambient temperature. The anodes temperature will reach up to 600 °C by the end of preheating and up to 1100 °C in the fire sections. Finally, the baked anodes cool down in the cooling sections, heating the flue gas before it enters the fire sections. The entire baking process takes about 240–360 h. The green anodes are baked in furnace sections with a certain number of pits (max 8 pits/section). The incoming combustion air, pushed in by the first cooling ramp is preheated as it passes through flue sections of adjacent flues in the cooling zone. The pits are separated by the heated flue-walls. The heat generated by combustion is transferred through these flue-walls that are kept under negative pressure to retain and draw the fumes. The focus of the current study is on investigating the effect of deflected flue-walls on the temperature uniformity within carbon anodes through the complicated baking process. To the authors' best-knowledge, detailed investigation of the effect of flue-wall deflection, which increases with time and furnace operation, is absent from the published literature.

The anode quality has a significant impact on the aluminum production cost. Stringent anode quality and process control are required to improve the anode performance in the pots and hence reduce the smelter costs. The theoretical consumption is given by the stoichiometric equation according to the Faraday law is that to produce 1 ton of aluminum, 334 kg of carbon are needed, assuming a current efficiency of 100%. However, in practice due to excess consumption, carbon net consumption reaches more than 400 kg per ton of aluminum. Anode baking is an energy-intensive process and; therefore, continually reducing the specific energy consumption as far as possible is more important today than ever before. Great progress has been made in this respect in the last twenty years. Today, a modern anode baking furnace has an energy consumption of 1.8 GJ/ton of the baked anodes. In the mid-1990s the figure was about 2.5 GJ/ton, or over a third more. The furnace specific energy consumption must never be optimized at cost of the resulting anode quality, as the inferior anode performance in the pots will greatly outweigh the gains of the energy saved. Poor furnace design, operation and/or maintenance, resulting in a higher than optimum waste gas quantity may increase specific energy consumption by up to 1 GJ/tons of anodes. Due to the huge size of the baking furnace and its very large time constant (in the order of weeks), it is very challenging to conduct physical experiments. Plant trials on such furnaces are quite costly and may cause the loss of production. In general, it is difficult to make detailed measurements around the furnace due to limited accessibility or costs involved. The necessity in investigating the effect of different operational and geometrical parameters on anode baking furnace energy consumption has heightened the need for developing computational tools with varying levels of complexities. The active work on mathematical modeling of the anode baking furnaces started at the beginning of the 1980s with relatively simple approaches. With the developments in numerical modeling and computation capacity (memory and speed), more sophisticated models have appeared [1–3]. Some of these models aim at the furnace operation, they are one or two dimensional and simulate the dynamics of the process. These models could be resolved with fewer details based on simpler approaches, by eliminating such details as 3D velocity distribution or by neglecting gradients in certain directions and reducing the number of dimensions in the solution of equations. Later on, many models of varying complexity, but similar in nature to these early works have been published and are referred to as process models that assist in optimizing the furnace operation parameters for practical furnace optimization and control.

However, process models are highly simplified and may not be of great use in investigating anode baking furnaces design characteristics. Other more detailed models are called anode baking furnace design/CFD modeling. El Ghaoui et al. [4] developed a 3D numerical model for furnace design improvement and demonstrated the use of baffle-less flue-wall design in anode baking furnace. They have shown that baffle-less flue-wall results in a better baking homogeneity and at the same time a higher thermal efficiency. Johnson et al [5] presented a simplified baking furnace model for improving the flue-wall design by solving the conjugate heat transfer problem in the anode baking furnace. They have shown that the problem can be simplified by considering the processes in the flue as stationary and solve the transient thermal conductivity equation only in the pit. They confirmed that the temperature distribution in the pit filled with anodes is largely dependent on temperature distribution in flue gases and is defined by the result obtained after solving the problem of conjugate heat transfer from gas to the anodes in the pit via the flue-wall. Fan et al. [6] have studied the thermal stress and strain distributions of a wall-fired