

## An Overview of Mathematical Modelling of Anode Baking Furnaces

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### Abstract

Carbon anodes are used in electrolytic cells in which aluminum is produced. They are consumed and replaced after about 20-25 days. One of the critical stages of anode production is baking in large furnaces. This is where the pitch in green anodes is baked and anodes attain their final properties. A good anode quality is important for a stable operation of the electrolysis cells. It also has an impact on energy and carbon consumption, and subsequently on environment.

Trials on these furnaces are costly; thus, there are few studies in which experimental data on such furnaces are available. Mathematical modelling has become a useful tool to analyze these furnaces, giving insight into the baking process. A variety of models have been published for anode baking furnaces, ranging from an approach based on overall heat and mass balances to three-dimensional models representing the geometry in detail and accounting for multiple phenomena occurring in the furnace.

In this article, an overview of the phenomena occurring in baking furnaces and their representation in various models, depending on the level of complexity considered, is presented. A number of examples will be given.

**Keywords:** Anode baking furnace, Carbon anodes, Aluminum production, Mathematical modelling

### 1. Introduction

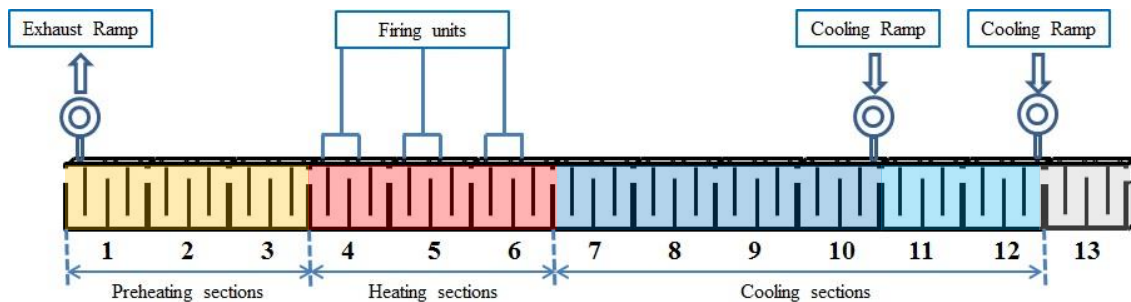
Carbon anodes are regularly consumed during the reduction of alumina by electrolysis in the Hall-Héroult process for the primary aluminum production. Their physical, electrical, chemical, mechanical, and thermal properties define their quality, which has a strong influence on cell stability, metal quality, energy and carbon consumptions, and environmental emissions. Anode quality depends on raw material properties and all the process parameters. The prebaked anodes go through a number of stages before their use in the electrolysis cells. Green anode production in the paste tower starts with the preparation of anode paste by mixing coal tar pitch (the binder) with the dry aggregate (calcined petroleum coke, recycled carbon materials: butts from the electrolysis and rejected baked and green anodes). Then, the paste is compacted in a press or a vibrocompactor to form green anodes. After cooling and storage, the anodes are baked in large furnaces. Baking fixes the anode properties. The last step is rodding. The anode assemblies are sent to the electrolytic cells for aluminum production. The costliest step of the anode manufacturing process is baking which is also the last determining step for the anode quality.

Two types of furnaces are generally used for baking anodes: horizontal and vertical. These furnaces consist of usually 34 to 70 sections arranged in two rows. Each fire cycle consists of up to 17 sections; thus, each furnace has a minimum of two fire cycles. The vertical furnaces (or closed-top furnaces) were more popular early on because of the better control of the furnace. The horizontal furnaces (or open-top furnaces) had low energy efficiency due to the lack of

appropriate control. With the improvements in furnace control, the horizontal furnaces became the technology of choice for the past number of decades due to lower construction and operational costs. The focus of this article is the modelling of the horizontal type anode baking furnaces.

Each section of the furnace consists of pits and flues. Pits are used to pack the anodes in multiple rows and columns depending on the size of the anodes and the pit dimensions. The remaining space is filled with packing coke. Each pit has a channel for gas flow on each side, and these channels are called flues. The pits and the flues are separated by refractory walls. The gases pass through the flue, heating or cooling the pit contents depending on the sections. The packing coke has multiple purposes: it maintains the physical integrity of the anodes; they minimize the infiltration of air and are consumed by combustion in the hot sections, acting as sacrificial material protecting the anodes; the coke bed provides a medium for heat and mass transfer (the granular media allow the passage of volatiles that evolve from the anodes from the pit to the flue where they are burned). The furnaces act like counter-current heat exchangers. The anodes remain stationary; however, the ramps are moved around to regulate the flow of gases. Anodes are first preheated and then heated to final anode temperature which varies from plant to plant. This is followed by the cooling till the anodes reach low temperatures. The flue contains baffles and tie bricks to provide a flow field that will result in a heat flow distribution as uniform as possible for the baking of anodes.

Anodes are placed in the pits at room temperature and heated to around 1100-1200 °C at a given heating rate, and then they are cooled slowly. The entire cycle usually takes two to three weeks. Each cycle involves 13-17 sections, as shown in Figure 1. The ramps on the gas side are shifted after a 20-30-hour fire cycle. Figure 1 shows a typical cycle with 3 preheating, 3 heating, and 6 cooling sections. This may vary from one plant to another. Additional sections of the cycle are needed to remove baked anodes (the section after section 13), the preparation of anodes for baking (the section preceding section 1), and repairs.



**Figure 1. A typical fire cycle.**

These furnaces are fed oil or natural gas as fuel in the heating sections. In the preheating section, volatiles evolve from the anodes due to the baking of pitch. The volatiles are made up of tar (the heavier components), methane, and hydrogen. The heat released due to the combustion of volatiles provides nearly half of the energy need of the furnace. The packing coke also burns partially in the high-temperature regions. This is undesirable, but it cannot be avoided. The heating necessary for the anodes, refractories, and the packing coke is provided by these sources. Detailed information can be found on the design and construction of these furnaces in [1].

Even though it is possible to do some experimental work in the plant, carrying out detailed measurements is quite costly due to the furnace geometry and size. To study various design options and the impact of the operational parameters on the furnace performance, mathematical modelling could be highly useful. It helps gain insight into the furnace behavior by providing the

distributions of the flow, temperatures, chemical species, etc. in different parts of the furnace. Different modelling approaches used by various researchers can be found in reference [2].

The development of mathematical models closely follows the developments in computer technology. Early models appeared at the beginning of the 1980s using simple approaches [3-5]. The rapid technological developments in computing devices led to the developments in the numerical solution of differential equations and computing capacity (memory and speed). This allowed the elaboration of more complex models [6-9]. In mid-1990s, a 3D transient model was published [10]. Models of varying complexity have appeared since then [11-15]. In general, similar techniques are used in baking furnace modelling. For analyzing furnace operation and geometry, mathematical modelling has become a powerful tool. It is possible to represent the geometry with precision, to solve the governing equations based on advanced techniques and using a highly fine mesh. This allowed the analysis of the physical phenomena in more detail.

## 2. Mathematical Modelling

A large number of phenomena are occurring in the furnace. On the flue side:

- Flow with velocity and pressure distributions,
- Turbulence,
- Heat transfer including all three modes: conduction, convection, and radiation,
- Combustion of fuel and volatiles,
- Transfer of volatiles coming from the pit into the flue through the slits in the refractory,
- Air infiltration from various openings around the furnace,
- Heat losses from the top (to the air) and the bottom (to the foundation),
- Deformation of the flue wall.

On the pit side (including the refractory wall):

- Conduction heat transfer (in refractories, anodes, and packing coke which is a porous medium that requires the use of effective thermal conductivity),
- Mechanical, chemical, and structural changes in anodes (depending on the temperature distribution in the pit, the evolution of temperature, the initial green anode structure, etc.),
- Volatile evolution from the anodes (hydrogen, methane, and tar),
- Transfer of volatiles from anode surfaces to the refractory wall through the granular bed,
- Combustion of coke
- Air infiltration through packing coke (porous media)
- Heat losses from the top (to the air) and the bottom (to the foundation).

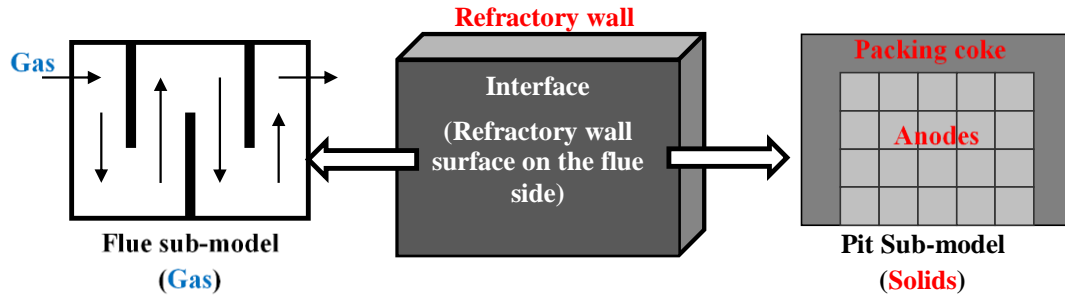
In addition, the furnace geometry needs to be considered, including:

- Flue side: gas entrance and exit, tie bricks (geometry and positions), baffles (positions),
- Pit side: anode dimensions, refractory wall thickness, volume for packing coke everywhere in the pit.

Not all of these phenomena could be represented in detail in a mathematical model. The anode baking furnace operation is transient; thus, the model has to be based on a transient analysis. Pit and flue characteristics are different. Thus, a baking furnace model can be divided into gas and pit (refractory wall, packing coke, and anodes) sub-models. These sub-models can be developed separately and then coupled through an interface, usually found on the refractory surface on the flue side (see Figure 2). This modular approach makes the model development easier.

The models can be divided into two categories: design models and process models. The design models solve for partial differential equations, and the geometry is represented in detail. Velocity, temperature, pressure, chemical species mass fraction distributions can be obtained. Thus, the impact of various design changes on the furnace performance can be tested. The computation time

is normally in the order of a few hours at best. In the process models, a number of simplifications are made in representing certain phenomena and geometry. The model usually runs rapidly (a few minutes), but the information obtained is limited. They are used to verify the impact of operational parameters on the anode baking process. The choice of modelling approach depends on the expected results from the model.



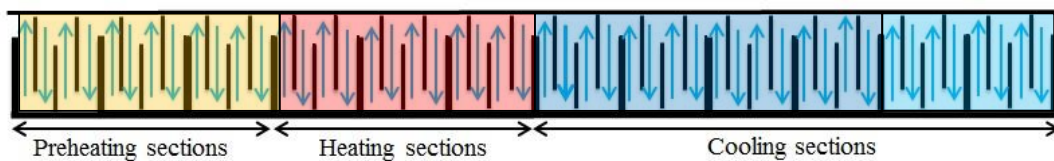
**Figure 2. Flue and pit sub-models and their coupling.**

The design and process models are discussed in the following sections. In most cases, half of the pit and half of the flue can be considered using the symmetry of the system. However, the entire geometry of the flue and/or pit may be necessary in some applications such as the flue deformation. Model validation is important. This is done based on data from measurement campaigns, which usually provide partial information.

## 2.1 Process Models

In the flue, the flow is usually simplified. Bui et al. [5], Ouellet et al. [8], Severo and Gusberti [15] considered a 1D flow in the horizontal direction and adopted a certain relationship between the furnace length and the baking time. Due to the presence of baffles, the actual flow is essentially vertical as seen in Figure 3. Oumarou et al. [16] used this configuration for the flow. This simplification allowed the calculation of the temperature distribution in the flue in 2D (variation in the vertical and horizontal directions). The pressure drop in the flue was calculated assuming a flow through a channel with a hydraulic radius. On each cell in the flue, overall mass, chemical species, and energy balances were carried out.

The treatment of transient conduction in the pit also varies from one work to another. Oumarou et al. [16] solved for the conduction heat transfer on vertical planes perpendicular to the refractory wall surface. A fine mesh was used on the vertical planes. The volatiles from the anodes were transferred directly to the flue. The combustion profile for volatiles and fuel were imposed. The details of this model can be found elsewhere [16]. This process model is more detailed than the previous ones reported in the literature due to more geometric details and better representation of various physical phenomena. Of course, this was possible due the availability of powerful computing and numerical simulation tools.



**Figure 3: Representation of flow in the process model [16].**

## 2.2 Design Models

In the design models, it is possible to solve for only flow under isothermal conditions. By including the heat and mass transfer equations, the temperature and chemical species mass fraction distributions could be determined. Usually the following differential equations are solved [17]:

- Continuity equation,
- Navier-Stokes equation (in 3D),
- The k- $\epsilon$  turbulence model equations (or an appropriate turbulence model),
- Heat transfer equation including conduction, convection and radiation, and
- Transport equations for the chemical species including combustion (of fuel and volatiles) [10, 12].

These equations are solved in 3D and transient form. The geometry is considered in detail.

In the pit, the transient 3D conduction heat transfer equation is solved. The geometry is represented in detail. The volatile evolution from the anodes is calculated using the kinetic equations determined experimentally [10]. The partial differential equations are solved using one of the available commercial codes such as ANSYS.

The design model gives detailed information in 3D (velocity, temperature, and chemical species distributions, combustion and devolatilization patterns, etc.), but the computation time is long. In general, this type of model is used to simulate one section, which requires a computation time in hours. In a recent study, the entire cycle was simulated [18] by carrying out the simulation ‘section by section’ as indicated in Figure 4.

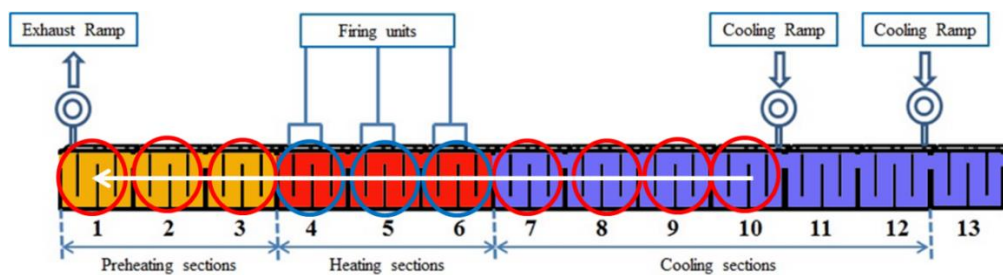


Figure 3. Simulation of the entire fire cycle by section-by-section simulation [18].

### 3. Examples

#### 3.1 Process Models

Figure 4 presents the temperature distributions obtained in the flue and in the pit on four planes in the second preheating section [18]. In the flue, gas enters hot and then cools down as the heat is transferred to the anodes. The temperature variation in the vertical direction can also be seen. On the four planes, the temperature profiles are shown in the pit (refractory wall is to the left and anodes are to the right of each image). The preheating of anodes (going from P1 to P4) could be seen clearly.

#### 3.2 Design Models

Velocity profiles predicted in the flue for two different types of brick are shown in Figure 5 [19]. The flow is isothermal. This type of analysis helps identify the flow structure and the zones where the velocities are small. In this case, the form of the brick does not seem to affect the flow distribution significantly. The position and the number of tie bricks could help improve the flow distribution. Other simulations would have to be carried out by modifying the geometry in the flue.

In Figure 6, the temperature profile in the entire section is given (anodes on the right and flue is on the left) within the heating zone (the middle section) [19]. Evidently, the gas temperatures in the flue are the highest. The sides are colder as it can be seen in the figure. The temperature profiles in the refractory and packing coke can also be observed. Anodes almost reached the maximum baking temperature, which occurs in the section where the first ramp of burners are located. Through this type of analysis, the impact of design changes on furnace performance could be evaluated.

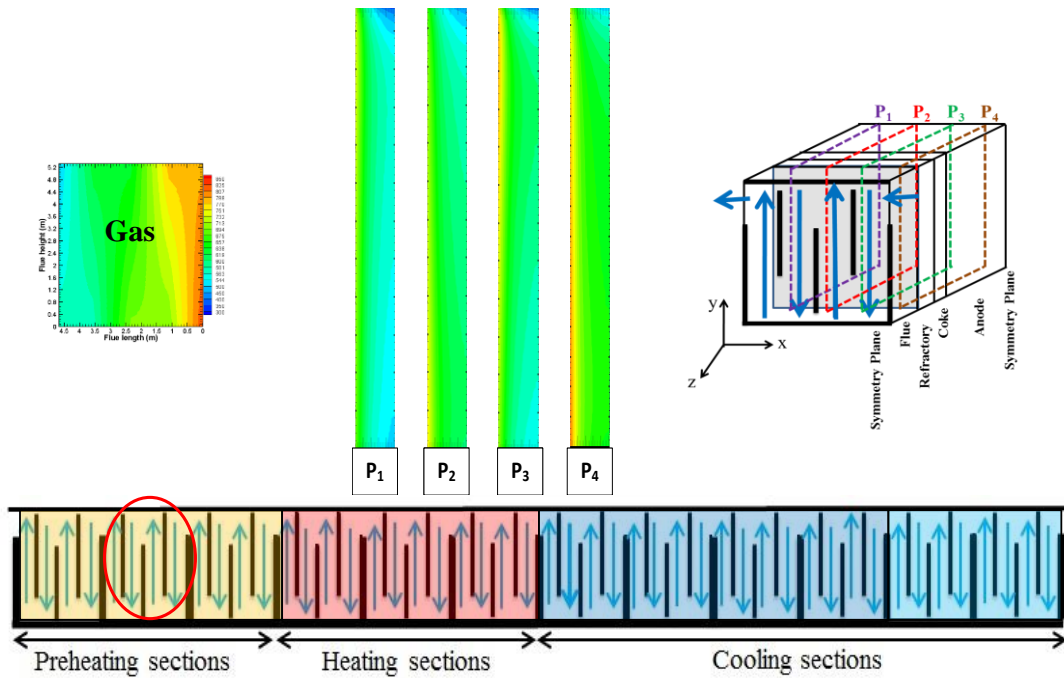


Figure 4. Temperature profiles in the second section of the preheating zone [18].

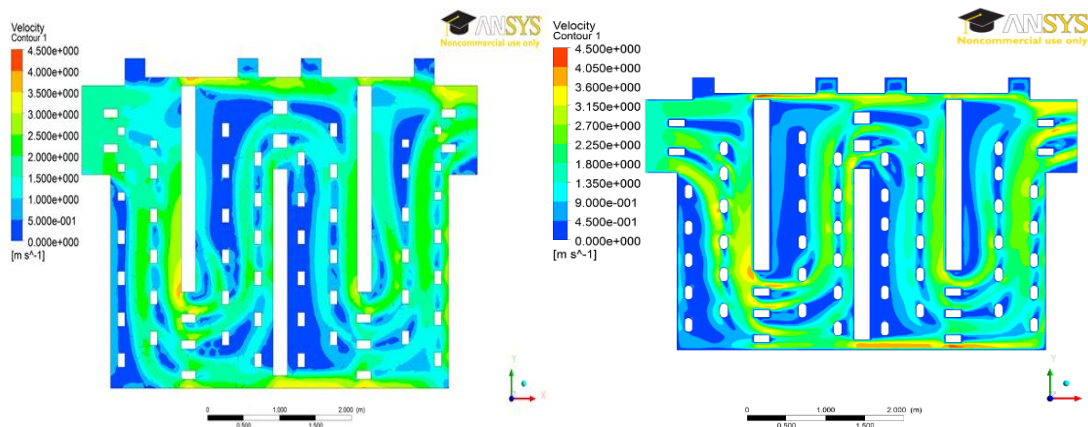
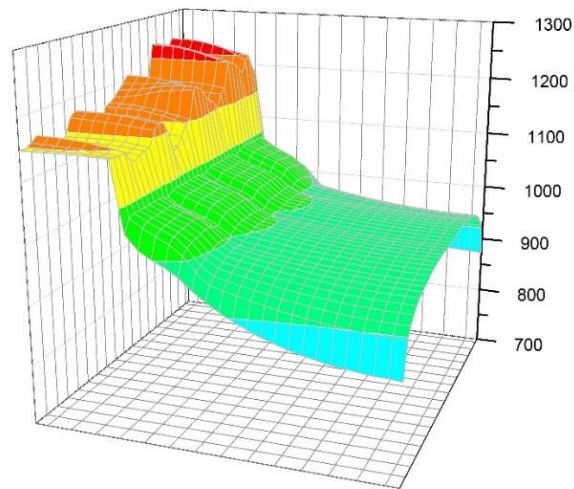


Figure 5. Flow in the flue for two different types of tie brick, rectangular on the left and elliptical on the right [19].



**Figure 6. Temperature profile (in °C) in the entire section in the heating zone [19].**

#### 4. Challenges

There are studies on various aspects of the baking process such as the comparison of combustion models [20], the effect of the kinetic parameters on model predictions [21], the chemical and mechanical changes occurring during baking [22, 23], experimental data on the effect of anode positions in the pit on anode cracking [23], etc. Such studies are quite useful for further modelling work, indicating the type of approach to be used and the important parameters to be considered.

The simulation of an entire cycle using a 3D model is still quite cumbersome, which requires a computation time in days. The simultaneous physical, chemical, thermal, and mechanical changes the anode goes through during baking are usually not included in the model due to inherent problems with respect to mesh, appropriate representation of relevant properties, computation time, and computer memory. The cross-over is rarely considered, which has a significant impact in the redistribution of gas flow. There are still a significant number of challenges in anode baking furnace modelling.

#### 5. Conclusions

An overview of various modelling approaches is discussed in this article. The models generally can be divided into two categories, design and process models. More detailed information is obtained from the design models. For that reason, the design parameters could be evaluated based on these models at the expense of computation time. The process models provide information usually for the operational aspects. Thus, various operational parameters and their impact on the furnace performance can be assessed using such models.

Even with the considerable developments in the computational field (numerical methods and computational equipment), the simulation of entire furnace including all the phenomena occurring during baking is not yet possible. Thus, the mathematical modelling anode baking furnaces is still very much a state-of-the-art business.

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