



A heat and mass transfer study of carbon paste baking[☆]



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ABSTRACT

Ramming paste is a particular type of carbon paste which is used as lining for electric smelting furnaces and Hall-Héroult cells for the production of aluminium. The purpose of this lining is to form an impenetrable barrier, keeping the liquid within the furnace. If the lining has cracks or holes, then liquid can escape, which can lead to safety risks and financial losses, so the integrity of the lining is of great importance. In the present study, we develop a first principles mathematical model for the heat and mass transfer processes occurring during the baking of carbon paste. We then obtain numerical simulations using this model and compare the simulation results to experimental data, demonstrating that the model solutions do indeed describe and predict realistic behaviours of the carbon paste baking process. The simulations indicate a strong pressure buildup during the evaporation of water from fresh paste during the baking process, which is likely to lead to cracking of the paste as it hardens. Furthermore, we are able to show that more gradual heating during the baking process can lower the maximal pressures predicted by the model, which in turn may reduce the prevalence of cracks within the hardened paste.

1. Introduction

Baking and similar processes arise in diverse industrial applications, such as metallurgy, structural engineering [1], soil mechanics [2], and food manufacturing [3]. These processes may include a number of physical phenomena, including: heat convection and conduction, driven primarily by an external heat supply; chemical reactions including phase changes; mass transport through porous media; and deformation and hardening of porous media. In the present paper, we shall be interested in the baking of carbon paste.

Carbon pastes have several uses in industrial metallurgy, such as self baking paste in Søderberg- and composite electrodes. Ramming paste is a particular type of carbon paste which is used as lining for electric smelting furnaces and Hall-Héroult cells for the production of aluminium. The purpose of the lining is to form an impenetrable barrier, keeping the liquid within the furnace. If the lining has cracks or holes, then liquid can escape, which can lead to safety risks and financial losses. Lining made from poor quality ramming paste can mean a shorter lifespan before replacement, which is a costly process due to the expense of shutting down a furnace, the re-lining of the furnace, and lost production. The lifespan of ramming paste may vary from

5–10 years for high quality paste to less than 1 year for low quality paste. A key part of the installation of ramming paste as a furnace lining is baking, where the paste is heated, causing it to harden and become impermeable. Samples of ramming paste which have cracked during the baking process are shown in Fig. 1.

Traditional ramming pastes are mostly made of granular anthracite (a type of coal, with similar properties to graphite), held together with a binder made from coal tar pitch. Coal tar pitch is a substance containing polycyclic aromatic hydrocarbons (PAHs), which are carcinogens. Exposure to coal tar pitch has been linked with increased risk of cancer in the skin, lungs, bladder, kidney, and other organs [4]. The installation of ramming paste within a furnace can expose workers to PAHs, even with safety precautions in place. To this end, Elkem, a large Norwegian producer of basic materials, has been developing non-toxic (so-called ‘green’) binders for ramming paste made of organic compounds.

Given the harsh environments in which the baking of ramming paste occurs and the complexity of the processes involved, direct measurements can be difficult to obtain. In this situation, it is useful to have a mathematical model of the key physical processes, allowing for computational testing and predictions. This motivates us to develop such a

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Fig. 1. Samples of ramming paste which have cracked during baking.
Source: Elkem Carbon.

model.

This paper is organised as follows. In Section 2, we outline the experimental setup we are modelling and then derive the mathematical model. This model is non-dimensionalised and simplified, providing insight into which physical processes are most important. Numerical simulations are presented in Section 3, along with a discussion of fit to experimental data, qualitative model behaviour, and parameter sensitivity. Lastly, Section 4 provides a summary of the main results, as well as a list of suggestions for future work and improvements to the model.

2. Mathematical model of carbon paste baking

The process for the installation of ramming paste is: (i) line the furnace with paste, manually ramming (compressing) it into the correct shape; (ii) slowly heat the furnace to bake the paste; and (iii) lastly, as the paste heats, it solidifies to form an impenetrable layer (with the correct thermal and electrical properties). Typically, ramming paste consists of 80–85% granular anthracite (by mass) and 15–20% coal tar pitch. In Elkem's new ramming paste, the composition is approximately 85% granular anthracite, 5% free water and 10% organic compounds (which are dissolved in the water). CT scans of the new paste are shown in Fig. 2 – the large light grey pieces are anthracite, the dark grey areas are binder, and the black areas are voids.

Elkem has observed that paste using these new green binders exhibit a fast rate of mass loss during the baking process. This is shown in Fig. 2, which plots the mass (as a proportion of original mass) of an experimental sample against baking temperature (which can be thought of as a proxy for time), using both coal tar pitch and green binders.

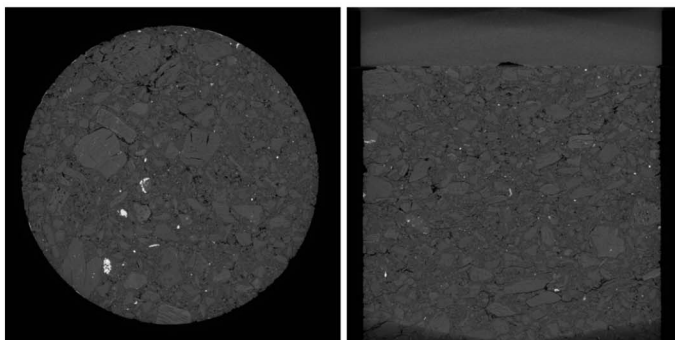


Fig. 2. (left and middle): CT scans of baked ramming paste, using the new organic binder.

Source: Elkem Carbon. (right) Mass loss profiles for coal tar pitch (black line) and green binders. The dashed lines represent the rates of change of mass.

Although both types of pastes lose a similar amount of mass over the entire baking process, the loss with the green binder is faster than for the coal tar pitch binder. As this rate is the highest around 100°C, Elkem believes this is primarily due to the evaporation of water. They also believe that this evaporation is causing pressure to build up within the paste, leading to cracking. Experiments have confirmed that baking the new paste more slowly reduces the amount of cracking, consistent with this hypothesis.

In the experimental setup, a small cylindrical sample (diameter and height 5 cm) is heated from all sides from room temperature to approximately 400°C over several hours. The external pressure is kept at atmospheric pressure, and the sample is free to expand or contract in all directions.

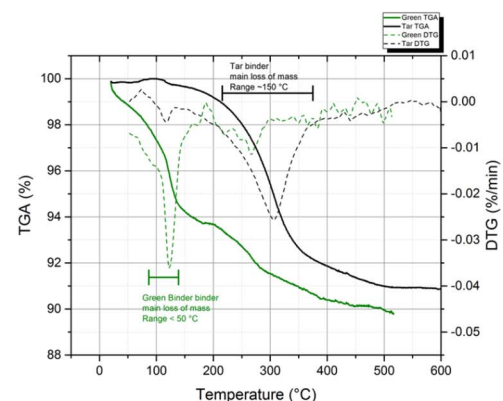
To build a mathematical model of ramming paste based on this experimental setup, we will treat the paste as a porous medium, where the voids are filled with water vapour (gas g). The solid skeleton will be a mixture of anthracite (a) and binder (b). We will make the following assumptions. The binder is only comprised of free water (i.e. we will treat the organic compounds as part of the anthracite); the only reaction is the evaporation of water; the anthracite and binder move together; we are at local thermal equilibrium (i.e. no heat transfer between components in the same representative volume); the solid skeleton is isotropic; no solid deformations such as hardening or thermal expansion occur; the effects of mechanical energy and work are negligible compared to heat energy and latent heat of evaporation; and water vapour is an ideal gas.

There are several processes we wish to model, including heat transfer through the paste, evaporation of water, and flow of water vapour through the paste (a porous material).

2.1. Conservation of mass

The model used here for flow and mechanical effects in a porous medium is based on the general framework from [5–8], although we assume no solid deformations for the sake of simplicity. In this medium, consider a representative volume V (assumed to be significantly larger than the microstructure size). This volume is taken up by volumes of each constituent, $V = V_a + V_b + V_g$, and has mass $m = m_a + m_b + m_g$. We normalise and consider the volume fractions of each constituent, $\phi_k := V_k/V$ ($k \in \{a, b, g\}$), so $\phi_a + \phi_b + \phi_g = 1$. These materials have an *intrinsic* density $\rho_k := m_k/V_k$ ($k \in \{a, b, g\}$) and, within the porous medium, an *apparent* density $m_k/V = \phi_k \rho_k$. If each material is moving with velocity \mathbf{v}_k , and is created at a rate I_k per unit volume (of the whole medium), conservation of mass within the volume V reads

$$\frac{\partial m_k}{\partial t} + \nabla \cdot (m_k \mathbf{v}_k) = V I_k, \quad k \in \{a, b, g\}. \quad (1)$$



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