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Dynamic modelling of a multiple hearth furnace for kaolin calcination with a sensitivity analysis with respect to reaction rates *

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Abstract: This paper is devoted to dynamic modeling of a multiple hearth kaolin calciner. The physical-chemical phenomena taking place in the six furnace parts, including the solid phase, gas phase, walls, cooling air, rabble arms and the central shaft, are described by the model. In particular, a mixing model is developed to describe the solid phase movement, dividing the solid bed in a hearth into volumes and considering the distribution of their contents after one full central shaft rotation. Step changes are introduced to the feed rate to study the responses of the gas phase temperature and solid bed component profiles in the multiple hearth furnace (MHF). In addition, the sensitivity analysis of the temperature profile with respect to the reaction kinetics is provided.

Keywords: Multiple hearth furnace (MHF), dynamic modelling, kaolin calcination, industrial application, parameter estimation.

1. INTRODUCTION

Multiple hearth furnaces (MHF) are widely used in industry for the calcination of clay minerals, such as kaolin, Thomas et.al. (2009). Various applications of kaolin, such as paper, rubber, paint and refractory items, require calcination to enhance its properties, see Murray (2005). However, maintaining efficient process operations is still hard in mineral processing, see Jämsä-Jounela (2001). Specifically, growing global competition in the mineral processing industry has increased the need for higher grade products. To improve the quality control in the kaolin calcination, more knowledge is needed especially on the temperature profile and on the physico-chemical phenomena taking place inside the solids. Mechanistic models are well known tools for gaining better understanding of processes and predicting their dynamic responses. The development of mechanistic models is supported by the numerous studies of the reactions related to kaolin calcination. As the basis for modelling work, the classification of kaolin grades and the fundamentals of kaolin calcination have been previously introduced in Murray (2005) and Murray and Kogel (2007). Furthermore, the kinetics of kaolin calcination reactions was actively studied by Ptacek et al. (2010) and (2011), whilst the influence of the heating rate on the properties of calcined kaolin is described by both Langer (1967) and Castelein et al. (2001). In order to gain additional knowledge on the solid phase movement, industrial experiments with tracer materials were used to study the residence time distribution in the MHF furnace used for calcination, Thomas (2009).

Despite the abundance of research examining the calcination reactions, only a limited number of mathematical models with necessary elements describing the physical-chemical phenomena have been reported in the literature. Martins et al. (2001) described a steady-state rotary kiln model for the petroleum coke calcination that predicts the temperature profiles for the bed, gas phase and the kiln wall in the axial direction. Additionally, the composition profiles for the gas and solid phase are also described by the model. In order to describe the solids flow in the axial direction, the model includes rheological characteristics of the system of particles. Meisingset and Balchen (1995) developed a steady-state model for a single hearth rotary coke calciner, including the mass and energy balance equations for the gas phase, coke bed, and the lining. Voglauer and Jörgl (2004) presented a dynamic model of a multiple hearth furnace describing the roast process recovering vanadium. Balance equations of mass, heat and components are described in both gas and solid layers in each hearth. Liu and Jiang (2004) have also developed a mechanistic model of a continuous plate dryer, involving the mass and energy conservation equations. A major part of the model is devoted to the solid mass transfer, including the equations to describe the height and the volume of each granular heap. Based on the derived equations, the model calculates the retention time in the dryer and estimates the effective covering ratio of the plates, affecting the heat exchange area and the dryer performance. More recently, Ginsberg and Modigell (2011) presented a rotary kiln model describing a titanium dioxide calcination process. The model assumes that the gas and solid phases are uniform in each kiln cross section. The model describes five reactions occurring in the solid phase and includes six heat transfer paths between the gas phase, the solids, the walls and also the ambient. The model succeeded to describe the dynamic behaviour of the

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furnace with quantitative accuracy, as confirmed by the validation using a 15-day period of plant operations.

This paper presents the dynamic model describing kaolin calcination in a MHF operated by a UK plant. Following Meisingset and Balchen (1995), the solid bed in a hearth is divided into volumes, which is required as the temperature difference through a solid bed in a hearth can be over 150 °C. A mixing model is developed to describe the solid phase movement in each hearth, considering the distribution of each volume contents between different volumes of the hearth after one full central shaft rotation. As the mined material properties frequently vary in mineral processing industry, the paper aims to study the sensitivity of the model with respect to the calcination reaction kinetics.

This paper comprises of the following. First, the kaolin calcination process in a MHF is described in Section 2, whilst Section 3 presents the model. In Section 4, the dynamic behaviour of the MHF model is analysed and finally, Section 5 concludes the paper.

2. DESCRIPTION OF THE MULTIPLE HEARTH FURNACE

The MHF modelled in this paper has eight hearths, as shown in Figure 1. The solid and gas flows are counter-current, meaning that the solids is fed to the top hearth and moves downwards, while the gas moves in the opposite direction. Four tangentially aligned burners are located in Hearths 4 and 6 to supply the energy needed for the calcination reactions. The fuel flow to the burners is varied to control the temperature in these hearths. The furnace walls are composed of several layers of bricks enclosed by a cylindrical steel shell.

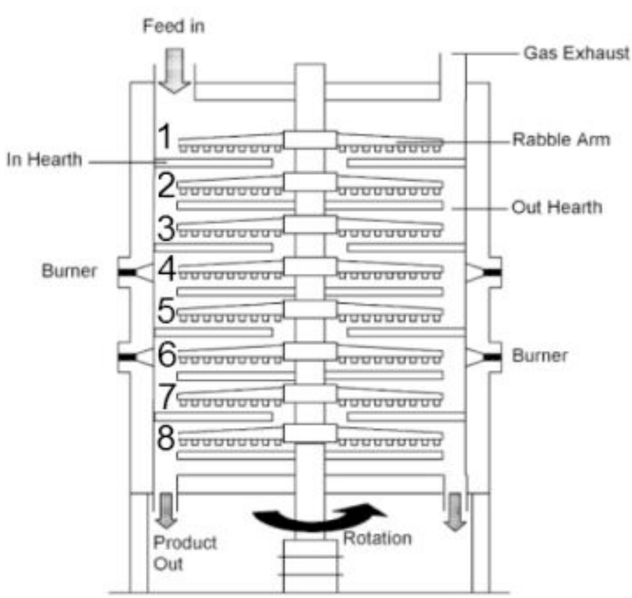

Fig. 1. Cross-sectional picture of the multiple hearth furnace.

The solids are fed into the top hearth through a single drop whole at the periphery of the hearth. In each hearth, the solids are moved spirally by four rabble arms located on the rotating central shaft. Each arm carries three to five rabble blades, stirring the material towards the centre of the hearth in the odd numbered hearths, where it drops down to the next hearth through a single annulus surrounding the shaft. The material on the even numbered hearths is moved outwards and drops to the following hearth through the special holes at the periphery of the hearth. The solids are transported through all hearths in this way, and the calcined product leaves from the last hearth through two exit holes, as shown in Figure 1.

Kaolin undergoes four physical-chemical transformations in the furnace, Ptacek et.al. (2010). The differential scanning calorimetry (DSC) and thermo gravimetric (TGA) curves describing the kaolin calcination are given in Figure 2. First, the evaporation of the free moisture occurs (T≤100 °C).

$$H_2O(l) \rightarrow H_2O(g) \tag{1}$$

Next, kaolin undergoes a dehydroxylation reaction at 450 – 700 °C, in which the chemically bound water is removed and amorphous metakaolin is formed.

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O \rightarrow Al_2O_3 \cdot 2SiO_2 + 2H_2O(g) \tag{2}$$

The third reaction is the exothermic re-crystallization resulting in the transformation of metakaolin to the 'spinel phase' at 925-1050 °C.

$$2(Al_2O_3 \cdot 2SiO_2) \rightarrow 2Al_2O_3 \cdot 3SiO_2 + SiO_2(amorphous) \tag{3}$$

The last process is the nucleation of the spinel phase producing mullite at temperatures above 1050 °C.

$$3(2Al_2O_3 \cdot 3SiO_2) \rightarrow 2(3Al_2O_3 \cdot 2SiO_2) + 5SiO_2 \tag{4}$$

Mullite is hard and abrasive, and therefore, it can harm the furnace equipment, Thomas (2010). The process control has to maintain the conditions in the furnace resulting in both a low mullite and metakaolin content.

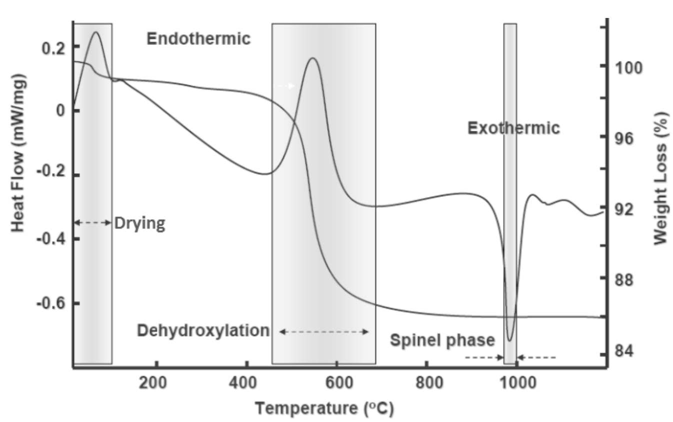

Fig. 2. DSC and TG curves of kaolin

3. DYNAMIC MODEL OF A MULTIPLE HEARTH FURNACE

In this modelling work, the MHF is divided to six parts: the solid bed, gas phase, walls, central shaft, rabble arms, and the cooling air. The model of the furnace includes the kinetics of the reactions occurring in the solid phase, and contains the mass and energy conservation equations for each of six parts. In addition, the equations for calculating the parameters