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Control strategy for a multiple hearth furnace in kaolin production

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ABSTRACT

In the face of strong competition, the kaolin calcination industry is aiming at higher profitability through increased productivity and reduction of costs. Specifically, the industry is facing market demands to maintain product quality with the depletion of high-quality ore. Therefore, considerable research is being conducted to enhance existing processes and their operation and control. In this paper, the concept of a mineralogy-driven control strategy for multiple hearth furnaces for kaolin production is presented and discussed. The aim of the advanced control concept is to increase capacity and to reduce energy consumption while maintaining the desired product quality. The control is based on two main soft sensors: the spinel phase reaction rate indicator for energy use reduction and the mullite content indicator for capacity improvement. In this simulation study, the control strategy is tested and compared with an industrial controller based on a proportional–integral scheme as a benchmark. The results show that the capacity of the process is considerably improved and energy use is remarkably reduced.

1. Introduction

Kaolin is an important industrial clay mineral used in multiple products such as paper, rubber, paint, and refractory items. Various applications of kaolin require calcination to enhance clay mineral properties and to provide added value to the material. Calciner furnaces such as rotary kilns and multiple hearth furnaces (MHF) are widely used in industry for the calcination of kaolin. The calciner control system plays a major role in ensuring uniform product quality while maximizing furnace capacity and improving furnace energy efficiency for optimal operation.

Although the different applications place specific requirements on the properties of kaolin, the degree and ease with which kaolin properties can be customized during refining varies with mineralogy. More specifically, the effect of ore mineralogy on product quality is twofold. First, various ore properties (such as particle size distribution, structure ordering, and some impurities) strongly affect the reaction rates and heat, thereby shifting the temperature profile in the furnace and the final product properties. Because it is difficult to measure the product characteristics and solid temperature profile in the furnace, the existing control strategies mostly attempt to maintain constant gas temperature using traditional control implementations such as proportional–integral–derivative (PID) controllers. These strategies help to attenuate the variations in the solid phase temperature and calcination reaction rates through the furnace. However, the variations in the solid phase are not eliminated completely because of the fluctuating ore types and mineralogy. Therefore, these strategies do not allow uniform product calcination.

The second effect of ore mineralogy on product quality concerns impurities that can directly affect the final product characteristics without influencing the operating conditions in the calciner. In particular, impurities containing iron are known to have a strong effect on product color, whereas the iron content is too low to disturb the energy balance and temperature profiles in the furnace. Hence, the in-situ distribution of different types of kaolin and their processing conditions need to be matched to demand in an optimal manner (Jaemsae-Jounela, Laine, Ruokonen, et al., 1998; Laine, Lappalainen, & Jämsä-Jounela, 1995).

Because the quality of the calcined product heavily depends on the temperature profile along the furnace, the stable desired temperature is acute for producing optimal quality products. However, controlling the temperature in an industrial calciner is very challenging because of various factors. Specifically, cross-coupling effects among the variables as well as between zones (hearths) increase the difficulties in maintaining the temperature profile. Thus, in many cases, the desired gas temperature profile cannot be efficiently maintained by controlling temperature

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independently using conventional single-input single-output PI control. Therefore, different control methods such as multivariable control, model predictive control (Stadler, Poland, & Gallestey, 2011), and artificial intelligence with neural networks and fuzzy logic (Järvensivu, Saari, & Jämsä-Jounela, 2001) have been applied to overcome this problem in the calciner control.

Galvez and de Araujo (1996) designed a controller for a large industrial electrical tubular oven, which was divided into six heating zones with temperature measurements on each zone. The multivariable controller was built by combining the pre-compensator and PI controllers. The high level of interaction observed between the zones was compensated by the implementation of the decouplers. Sauermann, Stenzel, Keesmann, and Bonduelle (2001) also described using decoupling methods to maintain the desired and stable temperature profile in a four-zone furnace. Similar to the method previously described, each zone was equipped with an individual power supply, resulting in the individual control of temperature. A mechanistic model was developed by the researchers that considered all thermal coupling effects between the zones. It was found that the state (temperature) at one zone was not only affected by the power source of that zone but also by the temperature of other zones. Hence, the decoupling controllers were implemented to compensate the thermal coupling effects between the neighboring zones, including the non-neighboring zones. This resulted in improved temperature stability.

Ramírez, Haber, Pea, and Rodrguez (2004) designed and tested a multiple-input multiple-output fuzzy controller with multiple rule bases to control the postcombustion process in a multiple hearth furnace. The authors used a mamdani-type inference system for the fuzzy logic controller (Viljamaa & Koivo, 1995). The fuzzy controller considers five variables: the control errors of temperatures in Hearths 4 and 6, the change of these errors, and the specific fuel consumption. Several disturbances were introduced to the furnace for testing, and the controller regulated the temperature of the Hearths 4 and 6 in the desired range in all cases. Gouveia et al. also developed a controller for a multiple hearth furnace in a Nickel reduction process (Gouveia, Lewis, Restrepo, Rodrigues, & Gedraite, 2009). The authors used multivariable model-predictive techniques to design the controller, where the control actions are calculated to compensate for the strong interactions and time delays that characterize this type of furnaces. The results showed a reduction in the variability of the furnace conditions and an increase in energy efficiency and recovery of nickel.

In brief, the aforementioned studies focused on the gas phase temperature profile control, which requires several sensors and actuating elements (heaters) to be distributed through a furnace. Nevertheless, little attention is given in the literature to the solid phase temperature and its control strategy.

To cope with varying ore mineralogy, this study presents an overall furnace control strategy concept, which aims to maximize capacity and to minimize the use of energy while meeting the quality requirements of the products. The main module of the system is the database, which contains the feed-type characteristics (e.g., Fe_2O_3), the setpoint values to the temperature profile controllers, and the feed rate of the furnace. The mullite content in the product is indirectly estimated by the soft sensor to maximize process capacity, a value higher than the threshold provides an opportunity to increase the feed rate. The stabilizing controllers manipulate the gas temperature to attenuate or compensate for variations in the calcination reactions in the solids. The feedforward controller adjusts the temperature setpoint in the last part of the furnace based on the soft-sensor values of the exothermic reaction rates in the first part of the furnace. Thus, the design of the proposed control strategy considers the effect of ore properties on the quality of the final product and the stabilizing control emphasizes the transition phase as the ore type and its mineralogy are changing.

The remainder of this manuscript is organized as follows. Section 2 describes the process and Section 3 provides the mechanistic model of the MHF. Section 4 describes the dynamic behavior of the process and analyzes the effect of ore mineralogy on the properties of the final product. The overall control strategy is also described. Section 5 presents the simulation results using the industrial data and ends with a discussion and analysis of the research. Finally, Section 6 concludes the manuscript.

2. Process description and control strategy

Calcination is the process of heating a substance in order to remove water from the structure of that substance. This process is one of the most important means of enhancing the properties and value of kaolin. As a result of calcination, the kaolin improves its physical properties such as its brightness, allowing it to be used in a wide variety of products, such as paper, rubber, paint and refractory items.

The MHF considered in this study has countercurrent solid and gas flows and consists of eight hearths. The thermal energy required for calcination is provided to the furnace through four methane burners located on hearths 4 and 6. The temperature in these locations is controlled by manipulating the fuel gas flow, which determines the quantity of combustion air. The furnace walls are built with bricks and circumscribed by a cylindrical steel shell with a refractory lining. Fig. 1 illustrates the cross-sectional view of the furnace. The material flow through the furnace is stirred spirally and transported across the hearths by a centrally located vertical rotating shaft carrying arms with rabble blades. Four arms are used on each hearth and each arm holds three to five rabble blades. The material is dispensed into the top hearth through a single inlet from the weigh feed hopper to the periphery of the hearth. Inside the odd-numbered hearths, the material is conducted by the rabble blades towards the center of the hearth and then descends to the hearth beneath from the center through a single annulus around the shaft. By contrast, the material in the even-numbered hearths is transported outwards before descending through the drop holes at the border of the hearth to the subsequent hearth. The transportation is repeated until the base hearth is reached, from which the calcined product is evacuated through the two exit holes.

Kaolin consists primarily of the mineral kaolinite, which has the formula $Al_2Si_2O_5(OH)_4$. During calcination, kaolin undergoes four physical–chemical processes as presented in Ptáček, Šoukal, Opravil, Havlica, and Brandštetr (2011). First, the evaporation of free moisture occurs ($T \leq 100\ ^\circ C$).

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

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

$$\underset{\text{Kaolinite}}{Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O} \rightarrow \underset{\text{Metakaolin}}{Al_2O_3 \cdot 2SiO_2} + 2H_2O(g) \tag{2}$$

The third physical–chemical process involves a reaction leading to the transformation of metakaolin to the "spinel phase" by exothermic recrystallization at 925 °C to 1050 °C.

$$2(Al_2O_3 \cdot 2SiO_2) \rightarrow \underset{\text{Silicon-spinel}}{2Al_2O_3 \cdot 3SiO_2} + SiO_2(\text{amorphous}) \tag{3}$$

In the fourth and final process, the nucleation of the spinel phase occurs and the material transforms into mullite at a temperature above 1050 °C

$$2Al_2O_3 \cdot 3SiO_2 \rightarrow \underset{\text{1:1 mullite-type phase}}{(2Al_2O_3 \cdot SiO_2)} + SiO_2. \tag{4}$$

Mullite formation intensifies when the temperature increases to above 1400 °C

$$3(Al_2O_3 \cdot 2SiO_2) \rightarrow \underset{\text{3:2 mullite}}{3Al_2O_3 \cdot 2SiO_2} + SiO_2 \tag{5}$$

Mullite is hard and abrasive and, as a result, can cause damage to process equipment. The desired final consistent product, which is within the specification limits, has both a low mullite and metakaolin content. The