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Published in:
IFAC-PapersOnLine

DOI:
10.1016/j.ifacol.2018.09.416

Published: 23/08/2018

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Gomez Fuentes, J., & Jämsä-Jounela, S.-L. (2018). Control Strategy For A Multiple Hearth Furnace. *IFAC-PapersOnLine*, *51*(21), 189-194. https://doi.org/10.1016/j.ifacol.2018.09.416

Available online at www.sciencedirect.com
ScienceDirect
IFAC PapersOnLine 51-21 (2018) 189–194

Control Strategy For A Multiple Hearth Furnace

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Abstract: This paper presents and discusses a mineralogy-driven control strategy for a multiple hearth furnaces in kaolin production. The objective of the advanced control is to maximize capacity and to minimize energy consumption while preserving the desired product quality. The control is based on two main soft sensors: the mullite content indicator for capacity improvement and the spinel phase reaction rate indicator for energy use reduction. 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 significantly improved and the energy use is notably diminished.

Keywords: Calcination, Advanced control, Soft sensor, Control performance, Multiple hearth furnace, Energy consumption, Quality.

1. INTRODUCTION

Kaolin is a valuable clay mineral used in multiple industrial products such as rubber, paint, paper, and refractory items. Numerous applications of kaolin require calcination to improve clay mineral properties and to increase the added value to the material. Calciner furnaces such as rotary kilns and multiple hearth furnaces (MHF) are broadly utilised in industry for calcination of kaolin. However, maintaining efficient process operations is still hard in mineral processing [1]. The calciner control framework assumes a significant part in guaranteeing the uniform product quality while augmenting production capacity and enhancing the furnace energy savings. Even though the diverse applications of kaolin need specific requirements on its properties, the ore mineralogy is the main factor that affects final product quality. Specifically, various ore properties (such as particle size distribution, structure ordering, and some impurities) greatly affect the reaction rates and heat, thus altering the temperature profile in the furnace and the final product characteristics. Due to the difficulty to measure the product properties and solid temperature profile in the furnace, the current control strategies mostly attempt to regulate the gas temperature using conventional control such as proportional-integral-derivative (PID) controllers. These control strategies assist in attenuating the alterations in the solid phase temperature and calcination reaction rates throughout the furnace. However, the changes in the solid phase are not reduced completely due to frequent fluctuations in the ore type and mineralogy. Therefore, these strategies do not provide a uniform calcination of the product.

Furthermore, the impurities can directly affect the final product features without affecting the operating conditions in the furnace. In particular, iron impurities have a strong effect on the color of the product, while the iron content is too low to affect the energy balance and temperature profiles in the furnace. Hence, the different types of kaolin and the processing conditions need to be corresponded to demand in an optimal manner [2], [3].

The quality of the calcined product greatly depends on the temperature profile throughout the furnace; consequently, the stability of the desired temperature is critical to produce products with optimal quality. However, regulating the temperature in an industrial calciner is very challenging because of several reasons. Specifically, cross-coupling effects among the process variables, as well as amid the zones (hearths), increase the complications in maintaining the temperature profile.

Thus, in many cases, the desired gas temperature profile is not efficiently regulated by independent temperature control using conventional single-input single-output PI controllers. Therefore, diverse control methods such as multivariable controls, model predictive controls [4], and artificial intelligence with neural networks and fuzzy logic [5] have been applied to resolve this calciner control problem. To manage fluctuating ore mineralogy, this study develops an overall furnace control strategy, which focuses in maximizing the capacity and minimizing the use of energy while achieving the quality requirements of the product. The main component of the system is the database, which stores the feed-type characteristics (e.g., Fe_2O_3), the temperature profile setpoints of the controllers, and the feed rate of the furnace. A soft sensor to maximize the capacity of the process indirectly estimates the mullite content in the product, a value higher than the threshold provides an opportunity to increase the feed rate.

The stabilizing controllers regulate the gas temperature to compensate for changes in the calcination reactions in the solids. The feedforward controller regulates the temperature setpoint in the lower part of the furnace depending on the soft-sensor values of the exothermic reaction rates in the higher part of the furnace. Thus, the design of the proposed control strategy considers the effect of the ore mineralogy on the quality of the final product and the stabilizing control emphasizes the transition phase as the ore type and its mineralogy are changing.

10.1016/j.ifacol.2018.09.416

The remainder of this manuscript is organized as follows. Section 2 describes the process and Section 3 presents the overall control strategy. Section 4 presents the simulation results using the industrial data and ends with a discussion and analysis of the research. Finally, Section 5 concludes the manuscript.

2. PROCESS DESCRIPTION

This study considers a kaolin calciner, known as a multiple hearth furnace, which features a counter-current solid and gas flows. The furnace has eight hearths, and eight burners located in hearths 4 and 6, combusting natural gas and providing the necessary heat for the calcination reactions. The airflow supplied to the burners for the gas combustion, is calculated considering the stoichiometric ratio. The burners are disposed in a tangential alignment.

Kaolin is introduced to the first hearth located at the top of the furnace. In the calciner, the material is moved by the metal plates, called blades, which are attached to the rotating rabble arms, designed with the intention of transporting the material outwards on even-numbered hearths and inwards on odd-numbered hearths. The kaolin crossing the even numbered hearths travels outward to descend through the holes at the outside border of the hearth, while in the odd-numbered hearths kaolin falls to the next hearth through a single annulus located around the shaft carrying the rabble arms. Figure 1 illustrates the design of the calciner.

The solid temperature increases as the material moves down through the furnace and reaches the maximum in Hearth 6. Kaolinite reacts to metakaolin in hearths 3, 4 and 5 at a temperature between 400-700 °C. The metakaolin is discharged from hearth 5 at a temperature of 800 °C approximately, which continues to increase in hearth 6, where the reaction of metakaolin to the Al–Si spinel phase occurs [6]. Therefore, the main aim of the hearth 6 is to rise the temperature to expedite the absorption of aluminium into the silica phase. The temperature control in the hearth 6 is critical

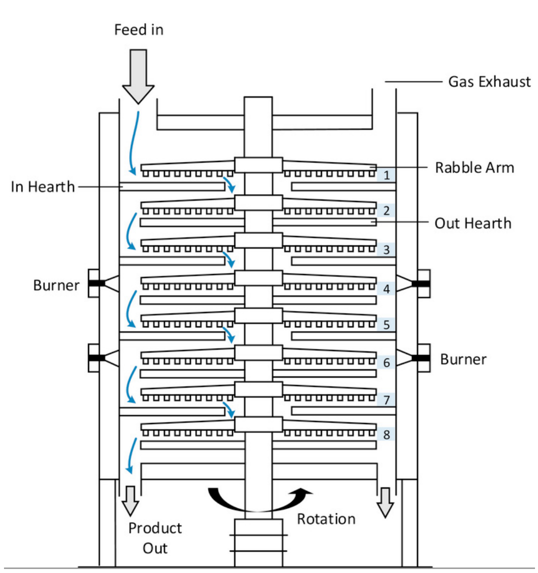

Figure 1. Cross-sectional picture of the Herreschoff calciner with direct fire burners.

to avoid overheating, which may result in the undesired formation of a material with a higher crystallinity degree, which may create some abrasion problems. The solid phase temperature begins to decrease in the hearths 7 and 8, and the product exits the hearth 8 through two discharge holes at a temperature of 750 °C.

Kaolin undergoes four physical-chemical transformations inside the calciner. First, the evaporation of the free moisture occurs at 100 °C.

$$H_2O(l) \rightarrow H_2O(g) \quad (1)$$

Second, kaolin is transformed to metakaolin through the dehydroxylation reaction, where the chemically bound water is removed at 450 – 700 °C.

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O \rightarrow Al_2O_3 \cdot 2SiO_2 + 2H_2O(g) \quad (2)$$

The third physical-chemical reaction involves the transmutation of metakaolin to the ‘spinel phase’ by exothermic re-crystallization at 925-1050 °C.

$$2(Al_2O_3 \cdot 2SiO_2) \rightarrow 2Al_2O_3 \cdot 3SiO_2 + SiO_2 \quad (3)$$

Finally, the nucleation of the spinel phase occurs and the material reacts into mullite at temperatures above 1050 °C.

$$3(2Al_2O_3 \cdot 3SiO_2) \rightarrow 2(3Al_2O_3 \cdot 2SiO_2) + 5SiO_2 \quad (4)$$

Mullite is a hard and abrasive material, and it can cause damage to process equipment [7]. The desired final product (within specification) has both a low metakaolin and mullite content.

3. SOFT SENSORS

3.1 Mullite Content

Online measurements of mullite content are not currently available in the MHF. Therefore, in this study, a soft-sensor based on energy balances was designed to estimate the amount of mullite in the product. The energy balances were calculated based on the heat transfer flow across the furnace. The equations defining the energy balances are as follows:

$$Q_{solid} = Q_{water} + Q_{kao} + Q_{dehyd} + Q_{meta} + Q_{spin} + Q_{prod} \quad (5)$$

$$Q_{mul} = Q_{comb} - Q_{loss} - Q_{gas} - Q_{air} - Q_{solid} \quad (6)$$

$$m_{mul} = \frac{Q_{mul}}{H_{mul}} \quad (7)$$

Q_{solid} is defined as presented in (5), Q_{water} is the energy to evaporate free water, Q_{kao} is the energy to heat kaolin to 450°C, Q_{dehyd} is the energy consumed as a result of the dehydroxylation reaction, Q_{meta} is the energy for heating metakaolin to 1000°C, and Q_{spin} is the energy released during the spinel phase formation reaction. Q_{prod} is the heat released in order to cool the final product to 700°C. Furthermore, Q_{comb} is the total energy generated by the combustion of methane from the burners, and Q_{loss} is the energy loss to the ambient through the furnace walls. In addition, the enthalpy of the net energy gained by the gas phase is denoted as Q_{gas}, the energy difference in the cooling air that flows through the central shaft is given as Q_{air}, the solid phase energy change is represented as Q_{solid}, and the total energy of mullite formation is defined as Q_{mul}. Finally, m_{mul} is the mass of mullite formed, and H_{mul} is the formation enthalpy of mullite, which is found in the literature.

3.1.1 Mullite content soft sensor validation

A soft sensor was developed to estimate the mullite content in the product using thermochemical equations and balances. A sampling campaign, during June 2017, provided the data to validate the estimation of the soft sensor. The data includes process measurements as well as X-Ray Diffraction (XRD) analyses results for the mullite content in the product, presented as weight percent (wt.%). The soft sensor uses the process data to estimate the mullite and then it is compared with the chemical analyses, as shown in Figure 2. The estimated mullite content shows good accuracy with respect to the XRD results. The number of the samples is however limited and the results are thus preliminary, further research is needed with a longer sampling campaign.

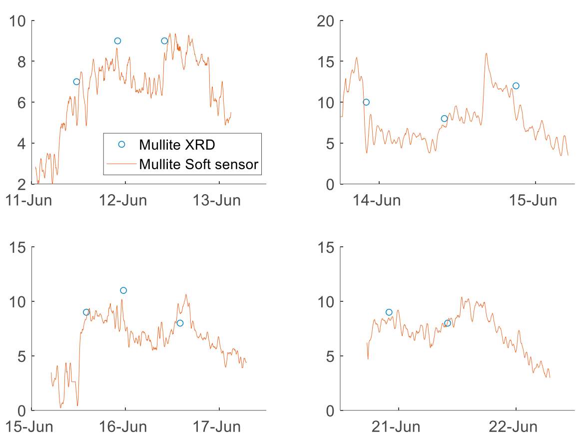

Figure 2. Mullite content, XRD vs the soft sensor estimation

3.2 Spinel Phase

To minimize energy use, a soft sensor that estimates the rate of the exothermic reaction occurring in hearth 4 is needed. Energy balances for the first four hearths are calculated according to the law of energy conservation. Combustion energy of methane from hearth 4 and cooling airflow from hearth 5 are considered as inputs. The air required for complete combustion is calculated with the stoichiometric ratio of the fuel gas and air. The energy leaves the furnace through solids, exhaust gases, and heat losses, which include the cooling air and heat exchange with the surroundings. The heat released from the spinel phase reaction occurring in hearth 4 is estimated with the following equation:

$$Q_{spin} = -Q_{s,in} + Q_{s,out} + Q_{evap} + Q_{dehyd} - (Q_{g,in} - Q_{g,out} + Q_{comb}) \quad (8)$$

Q_{spin} is the energy released during the spinel phase formation reaction in hearth 4, the enthalpies of the incoming and outgoing kaolin are denoted as $Q_{s,in}$ and $Q_{s,out}$, respectively; Q_{evap} is the energy of evaporated water; Q_{dehyd} is the energy consumed in the dehydroxylation reaction. Enthalpies of the inflowing and outflowing gases are denoted as $Q_{g,in}$ and $Q_{g,out}$ respectively; Q_{comb} is the energy produced by the combustion of methane from the burners in hearth 4.

Then, the conversion from metakaolin to spinel phase is obtained as follows:

$$R(t) = \frac{Q_{spin}(t)}{H_S F(t)} \quad (9)$$

Where, H_S is the product formation heat and F(t) is the current feed rate. The exothermic rate of reaction (R(t)) is estimated as the percentage of metakaolin transformed to the spinel phase in hearth 4.

4. ENHANCED CONTROL STRATEGY FOR THE MULTIPLE HEARTH FURNACE

This study proposes an overall control strategy, which aims to determine the best operating conditions to increase the production capacity and energy efficiency while maintaining the required product quality. The process control system comprises the optimizing, stabilizing, and basic levels, as shown in Figure 3.

The plant personnel consider the current ore mineralogy to determine the final product specifications. The look-up table contains and provides the setpoints for the gas temperatures in hearths 4 and 6 based on the current production capacity and iron content in the ore. The table is based on the classification of the feed type and process conditions utilizing the Self Organizing Map (SOM) technique [2], [3]. Furthermore, the temperature setpoints are regulated frequently (e.g., once a day) based on the laboratory measurements of the product characteristics, aiming to maintain the product quality within the specifications.

To achieve the maximum production rate, indicated by the mullite content soft sensor, the optimization problem is resolved to increase plant capacity, reduce energy use while preserving the quality of the product.

$$\begin{gathered} \max F \\ \min(F_4 + F_6) \end{gathered} \quad (10)$$

With respect to constrains:

$$\begin{gathered} F_{T4}(F_4, F_6, r, F) = T_4 \\ F_{T6}(F_4, F_6, r, F) = T_6 \\ m(F_4, F_6, T_1, F) \leq m^* \\ S(F_4, F_6, r, F) \leq S^* \\ T_6 \geq T_6^{min}(F, r) \\ T_4^{min} \leq T_4 \leq T_6^{max} \end{gathered}$$

Where F, F_4, and F_6 represent the feed rate and gas flows to hearths 4 and 6, respectively; T_1 ,T_4 and T_6 are the temperatures in hearths 1, 4 and 6, respectively; ***r*** is the current value of the reaction soft sensor; ***S*** and ***S**** are the soluble aluminium content and its threshold (if applicable). Finally, ***m*** and ***m**** are the mullite content and its threshold. The stabilizing level aims to reduce the variations in the calcination reaction

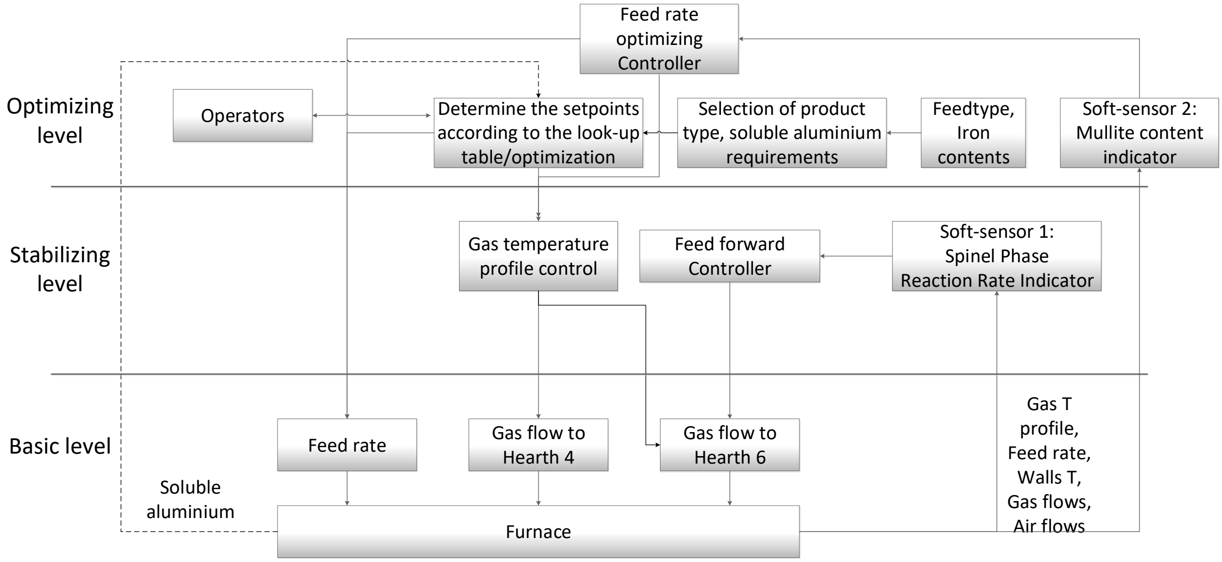

Figure 3. Control scheme of the furnace

that occur in the solid phase of the process. In other words, the gas temperature setpoints must be regulated based on the calcination progress in the solid phase. Thus, if the exothermic reaction occurs actively in hearth 4 or starts when the material reaches hearth 6, the temperature setpoints must be decreased to save fuel and to avoid over-calcination. To assess the calcination progress, the soft sensor estimates the exothermic reaction rate in hearth 4 and the feedforward control adjusts the temperature in hearth 6. The basic level controls the temperature with a mean temperature control scheme. The mean temperature control aims to homogenize the gas phase temperature in hearth 4 by operating on the average temperature of the gas phase instead of manipulating each burner individually.

5. RESULTS

5.1 Testing environment

The testing environment for modelling and control of the MHF was implemented in MATLAB®. The setup consisted of the dynamic model of the MHF [8] and controllers: optimizing controllers, stabilizing control, and basic temperature control. These included two soft sensors: a spinel phase reaction rate indicator for energy use reduction and a mullite content indicator for capacity improvement.

5.2 Simulation of basic temperature control

A mean temperature control scheme was developed and tested for the hearth 4 case [9]. The mean control achieves stability of the mean temperature by manipulating the total gas flow; a simulation is depicted in Figure 4. The mean temperature during the first half of the simulation is near 1000 °C, while during the second half, the mean temperature is fixed to 960 °C. The temperature follows the setpoint very closely in both setpoint operations. The charts at the top illustrate the development of the gas temperatures of all burners during the simulation. Finally, the bottom chart displays one of the manipulated gas flow to achieve the desired control.

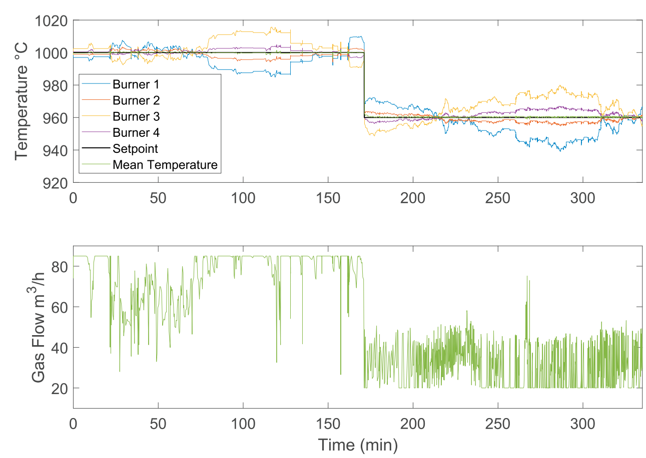

Figure 4. Simulation results of the temperature setpoint change for the hearth 4 mean temperature control.

5.3 Simulation of feedforward control

The soft sensor calculates the value of the reaction rate as a conversion percentage from metakaolin to spinel phase calculated for the first part of the furnace (hearths 1 to 4), and then the data is sent to the feedforward control.

Under typical process conditions, the spinel phase is formed in hearth 6. Thus, a shift in the reaction location would appear when the soft sensor values are higher than 40%. When this occurs, the feedforward control is activated and the control is kept active for 240 minutes. This control interval was obtained from the maximum duration of the exothermic reaction.

Figure 5 presents a comparison of the current control strategy with the developed feedforward control. The variables displayed in the figure are as follows: reaction rate, total gas flow, the gas temperature of hearth 6 (T6), and the gas temperature 6 setpoint. At 150 minutes, the effect of the disturbance on the reaction rate may be clearly observed as the value of the conversion percentage rises, which increases from

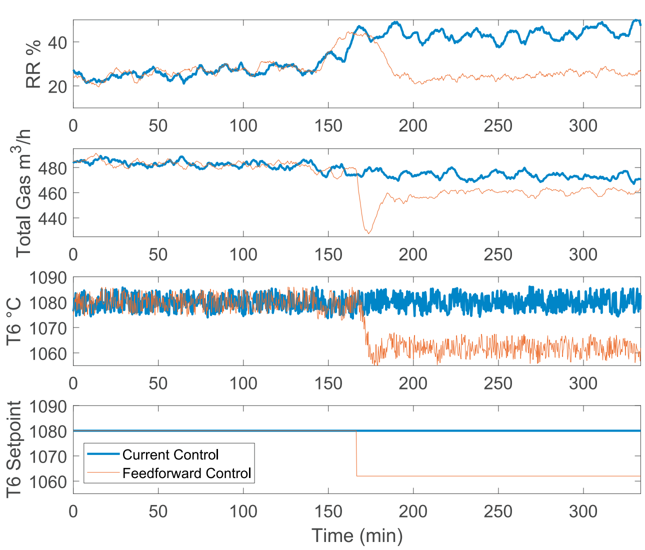

Figure 5. Comparison of the plant current control strategy (blue) vs. the feedforward control (orange)

approximately 25 % to 40 %. This increase continues until the end of the simulation. A decrease in conversion is shown after the feedforward control activates and the value returns to approximately 20 %. As a comparison, the current control did not present any changes from its setpoint of 1080 °C, unable to respond to the disturbance in reaction rate. The feedforward control changes the temperature setpoint at simulation time 170 minutes in response to the increase in conversion above 40 %, thus decreasing the temperature to 1062 °C. This change in setpoint was obtained with a similar approach as that for the reaction rate energy balance, with regard of the desired product quality. In the simulation results with the current temperature control, the gas consumption shows a decrease of 1.6 % after the disturbance affected the process, while the feedforward control presents possible energy savings of 3.6 %.

5.4 Simulation of feed rate optimization

For evaluation, the strategy proposed in Section 3 was included in the simulation environment. Initially, the furnace performs at the selected operating conditions until it reaches steady-state conditions. The initial values for the feed rate optimization are as follows: the feed rate is 100%, the temperature in hearth 6 is 1100 °C, and the mullite content is 16 %. The mullite soft-sensor results are filtered with a moving average method, the time window being 30 min. The objective is to maintain the mullite content at approximately 4 %. The control interval is 6 h calculated on the time required for the furnace to reach the steady state, and the maximum feed rate variation is limited to 5 %. Utilizing the filtered values, the control strategy defines the optimal setpoint for the feed rate and the gas phase temperature in hearth 6.

In this simulation study, Figure 6 illustrates that the control strategy raised the feed rate from the initial value of 83.33 % to 95.83 %, and the hearth 6 temperature setpoint was decreased by 43 °C. The charts show a small difference between the soft-sensor estimate and the model results. However, the difference was considered relatively low and explained due to the simplicity of the soft-sensor calculations.

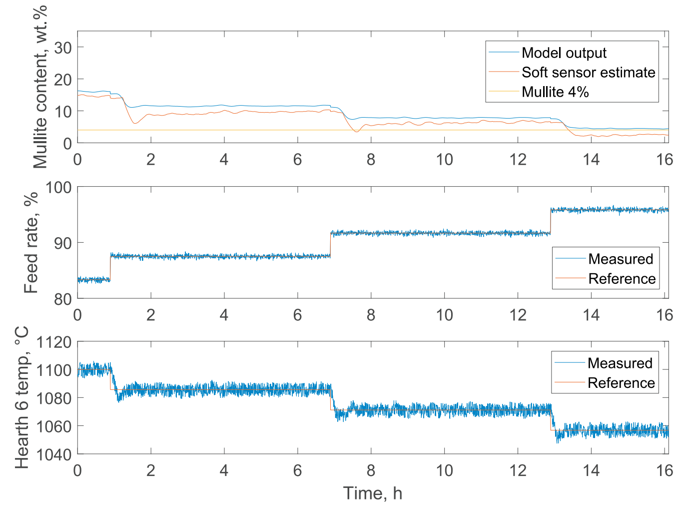

Figure 6. Simulation of capacity optimization.

5. CONCLUSIONS

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 research, a new control strategy for the MHF was proposed. The main principle of the calciner control system is to guarantee the uniform quality of the product while optimizing the furnace capacity and minimizing the energy use. The industrial PI control strategy served as a benchmark to evaluate the performance of the proposed control. The furnace is controlled on three layers: the basic level is responsible for the temperature control of the furnace; the stabilizing level regulates the temperature profile and guarantees the disturbance rejection due to feed impurities; and the optimizing level aims to maximize the capacity of the calciner.

The performance and effectiveness of the proposed scheme were demonstrated through simulations using actual industrial data. Through the case studies, the control strategy can adapt to critical disturbances to the furnace (e.g., change of the feed type or impurities in the feed), such that the overall system continues to achieve its goal. In addition, the process performances are automatically optimized.

In a future study, the authors will investigate the effectiveness of this control approach across a wider variety of feed (ore) types to the calciner. Moreover, the authors will extend the formulation to consider product quality through new instrumentation and more advanced control methods such as model predictive control.

ACKNOWLEDGMENTS

The authors express gratitude to Imerys, S.A. for providing the industrial data used in this study. The research conducting to these results has obtained funding from the European Union Seventh Framework Programme (FP7/2013-2016) under grant agreement No. 310645. The authors also thank the Academy of Finland for the financial support received under grant agreement No. 296432.

References

[1] S. Jämsä-Jounela, "Current status and future trends in the automation of mineral and metal processing," *Control Eng. Pract.,* vol. 9, *(9),* pp. 1021-1035, 2001.

[2] S. Laine, H. Lappalainen and S. Jämsä-Jounela, "On-line determination of ore type using cluster analysis and neural networks," *Minerals Eng,* vol. 8, *(6),* pp. 637-648, 1995.

[3] S. Jämsä-Jounela, S. Laine and E. Ruokonen, "Ore type based expert systems in mineral processing plants," *Particle & Particle Systems Characterization,* vol. 15, *(4),* pp. 200-207, 1998.

[4] K. S. Stadler, J. Poland and E. Gallestey, "Model predictive control of a rotary cement kiln," *Control Eng. Pract.,* vol. 19, *(1),* pp. 1-9, 2011.

[5] M. Järvensivu, K. Saari and S. Jämsä-Jounela, "Intelligent control system of an industrial lime kiln process," *Control Eng. Pract.,* vol. 9, *(6),* pp. 589-606, 2001.

[6] P. Ptáček *et al*, "The non-isothermal kinetic analysis of the thermal decomposition of kaolinite by thermogravimetric analysis," *Powder Technol,* vol. 204, *(2-3),* pp. 222–227, 2010.

[7] R. E. Thomas, *High Temperature Processing of Kaolinitic Materials,* 2010.

[8] A. Eskelinen *et al*, "Dynamic modeling of a multiple hearth furnace for kaolin calcination," *AIChE J.,* vol. 61, *(11),* pp. 3683–3698, 2015.

[9] J. V. Gomez Fuentes, "Simulation Environment for Advanced Control Development of a Multiple Hearth Furnace." , 2016-05-17.