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Model predictive control of a rotary cement kiln

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ABSTRACT

A first principles model of a cement kiln is used to control and optimize the burning of clinker in the cement production process. The model considers heat transfer between a gas and a feed state via convection and radiation. Furthermore, it contains effects such as chemical reactions, feed transport, energy losses and energy input. A model predictive controller is used to stabilize a temperature profile along the rotary kiln, guarantee good combustion conditions and maximize production. Moving horizon estimation was used for online estimation of selected model parameters and unmeasured states. Results from the pilot site are presented.

1. Introduction

In a cement plant the clinker production is of major importance as the quality of the cement greatly depends on the quality of the clinker. The clinker production process can be roughly split into four sequential subprocesses: preheating, calcining, sintering (or burning, formation of clinker minerals) and cooling. However, many different plant configurations with different types of rotary kilns, preheater cyclone configurations, with or without precalciner, with or without tertiary air duct, etc. are known. Typically, the configuration depends strongly on the available raw material, the available fuels and the plant evolution driven by the progress of the cement production technologies. A number of examples of possible configurations can be found in Peray (1986).

The approach described in this work provides a generic method to model and control any type of cement clinker production line. This is important as the engineering and commissioning of controllers in an industrial setting are costly. Therefore, it is proposed to divide the models into generic compartments where each compartment can be tuned to match the characteristics of specific parts of the process.

Early results in controlling the clinker production are presented in Otomo, Nakagawa, and Akaike (1972), where statistical methods were applied to control the process. In Witsel, Barbieux, Renotte, and Remy (2005), simulation results of a multi-loop control scheme are presented. The model used to design the controller was previously presented in Spang III (1972), which is based on partial differential equations and includes heat transfer by convection and radiation, mass transport and reactions of water evaporation, calcination and clinker minerals formation. In Witsel et al. (2005) two PI controllers are designed to control a two input two output system. The PI controllers were parameterized based on a linear model identified by step responses from the model by Spang III (1972). It specifically excludes control of the oxygen level, which is important to guarantee combustion of the fuels. In Dumont and Belanger (1978a, 1978b), the successful control of a titanium dioxide kiln is presented. Even though the process relies on a rotary kiln too, the chemical reaction is significantly different (no exothermic component). Kim and Srivastava (1990), Koumboulis and Kouvakas (2003) and Mills, Lee, and McIntosh (1991) present simulation and application results for an industrial calciner, respectively. Again the chemical reaction is significantly different as calcination is purely an endothermic reaction. Additionally to temperature control the latter also controls CO–O_2 levels for combustion efficiency reasons.

All these works do not consider usage of alternative fuels. Today alternative fuels consisting of bone/carcass meal, whole tires, sewage sludge, house hold waste or solvents are of major importance to produce cement economically. The downside is that alternative fuels not only have a high variability in calorific value and combustion characteristics, they may also change the sintering process of the clinker. In Stadler, Wolf, and Gallestey (2007) a precalciner in the cement clinker production was controlled using a first principles model and model predictive control. This contribution explains how the models developed for that simpler application have been extended and adapted to address optimal control of a rotary kiln in the presence of alternative fuels.

Several aspects of this work are strongly influenced by the industrial setting. Typically, the lifetime of a cement plant is

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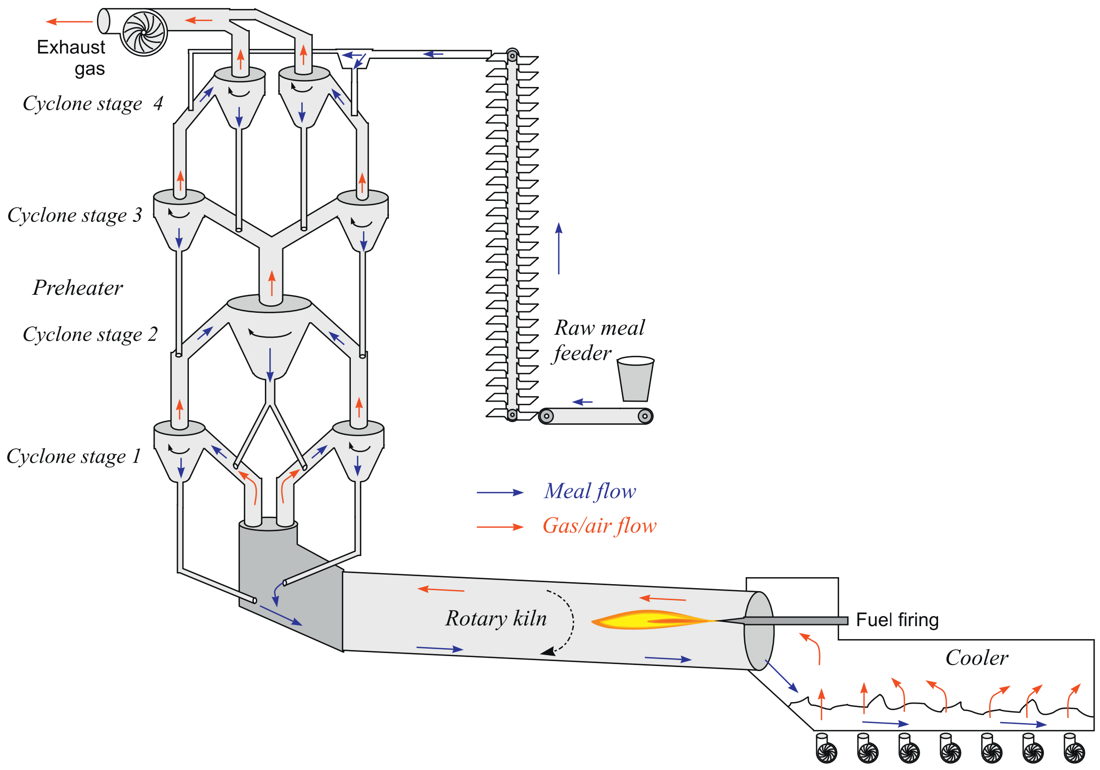

Fig. 1. Preheater kiln for the cement clinker production with four cyclone stages in the preheater tower, the rotary kiln and the cooler.

measured in decades and thus changes to the process structure are common. This means that also a kiln controller implementation needs to be easily adaptable to capture these changes. Moreover, for economic reasons it is a necessity that the controller can be easily adapted to serve different plants. The controller presented in this work was implemented on *cpmPlus Expert Optimizer* a commercial advanced process control and optimization platform developed by ABB.[1] The model is based on the mixed logic and dynamic (MLD) modeling approach (Bemporad & Morari, 1999) which is implemented in a graphical modeling environment. The graphical interface allows the model to be constructed from easily understandable and configurable submodels. Within the same modeling environment cost functions can be attached to formulate the optimization problem and to tune the controller performance all by dragging generic modeling elements from the library and dropping them on the model space (Stadler, Gallestey, Poland, & Cairns, 2009). The moving horizon estimation problem and the model predictive control problem are then generated automatically from this graphical representation.

The compartmental approach presented here meets these requirements because the whole estimation and control problem can be set-up by generic and predefined building blocks. Therefore, the complexity of the model and of the mathematical formulation can be hidden from the users. Additionally, the process depicts significant variability due to for example to diminishing of refractory lining of the kiln and changing chemistry of raw materials and fuels. The model needs to capture changes in the process dynamics sufficiently well to ensure that the controller operates over long periods without need of maintenance or re-tuning.

The paper is constructed as follows. In Section 3 the process and the basic equations of the model are presented. In Section 4 the formulation of the estimation and the control problem are given. Finally, in Section 5 results from the pilot site installation are described.

2. Process description

An overview of the cement production process can be found in Peray (1986) or Sahasrabudhe, Sistu, Sardar, and Gopinath (2006). In Fig. 1 the layout of a preheater kiln is shown. The preheater tower consists of several suspension cyclone stages where the feed and the exhaust gas from the combustion process further down the process exchange heat. The feed flows down the kiln and the gas is drawn upwards by a ventilator at the exhaust. The chemical composition of the raw feed needs to be controlled tightly to ensure good quality clinker; the main components are $CaCO_3$ (80%), SiO_2 (13%), AlO_3 (3%), Fe_2O_3 (2%) and MgO (1.6%). The feed temperature at the lowest cyclone stage reaches 800 °C or more. At this point calcination ($CaCO_3 + \text{heat} \rightarrow CaO + CO_2$) already has started (Peray, 1986).

Usually, at this stage in modern kilns a precalciner is introduced. Essentially, a precalciner is an additional combustion chamber, which is able to drive the dominant endothermic process of calcination. The more CO_2 from the raw material is released, the less work needs to be performed on the feed in the kiln, which increases the efficiency of the process greatly. The pilot plant presented in this work does not have a precalciner. This means that the calcination process needs to be driven by the heat in the exhaust gas from the main burner at the other end of the kiln. Decoupling of the dominant chemical reactions (calcination and sintering) is therefore not possible, which makes it intrinsically a more difficult process to control. The hot feed then enters the rotary kiln where its temperature is further increased. Between 1400 and 1500 °C, in the last third of the kiln, sintering of the clinker takes place. This is partially an exothermic reaction where the clinker compounds are formed (Peray, 1986). The clinker then drops onto the cooler which rapidly cools the clinker

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[1] http://www.abb.com/cpm