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Research article

Numerical analysis of an entire ceramic kiln under actual operating conditions for the energy efficiency improvement

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ABSTRACT

The paper focuses on the analysis of an industrial ceramic kiln in order to improve the energy efficiency and thus the fuel consumption and the corresponding carbon dioxide emissions. A lumped and distributed parameter model of the entire system is constructed to simulate the performance of the kiln under actual operating conditions. The model is able to predict accurately the temperature distribution along the different modules of the kiln and the operation of the many natural gas burners employed to provide the required thermal power. Furthermore, the temperature of the tiles is also simulated so that the quality of the final product can be addressed by the modelling. Numerical results are validated against experimental measurements carried out on a real ceramic kiln during regular production operations.

The developed numerical model demonstrates to be an efficient tool for the investigation of different design solutions for the kiln's components. In addition, a number of control strategies for the system working conditions can be simulated and compared in order to define the best trade off in terms of fuel consumption and product quality.

In particular, the paper analyzes the effect of a new burner type characterized by internal heat recovery capability aimed at improving the energy efficiency of the ceramic kiln.

The fuel saving and the relating reduction of carbon dioxide emissions resulted in the order of 10% when compared to the standard burner.

1. Introduction

The ceramic industry is well known to be characterized by energy intense processes. In particular, the kiln for the firing of the tiles is the main process that employs a large amount of energy. Recent regulations for the energy consumption require a more accurate design of the kiln in order to limit the fuel or electricity use (Gabaldon-Estevan et al., 2016). Furthermore, the environmental concerns drive the design towards cleaner systems and more stringent limits about the pollutant emissions. Bovea et al. (2010) proposed improvements to the firing and pressing processes by means of a LCA approach. Peng et al. (2012) identified the firing and drying processes as the main responsible for the CO_2 emissions in the ceramic industry since mainly fossil fuels are adopted for powering them.

Different approaches have been adopted for the optimization of the kilns' performance. In particular, a theoretical formulation for the prediction of the kiln operating characteristics has been proposed by Kaya et al. (2009) under regime conditions and many simplifications to the physical phenomena had to be made in order to close the mathematical model. An optimization procedure was adopted to minimize the fuel cost while improving the fuel consumption; the optimized working conditions led to a energy consumption per unit brick 2.7% lower than the standard operation. Similar approach is adopted also in Mezquita et al. (2014) in which the focus was the assessment of the heat transfer between the hot air flow and the kiln walls. In this approach, global energy balance was used for different sections of the kiln assuming steady state conditions and mean values of the considered quantities. They estimated an energy saving up to 17% by recovering the heat from the exhaust gases. Halasz and Toth (1988) found the energy optimal

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operation conditions of a tunnel kiln using a one-dimensional simple method and it resulted in a 5–8% savings in the used energy.

The numerical simulation becomes a valuable tool in investigating the performance of complex physical systems including different physical phenomena. In Nicolau and Dadam (2009) a numerical model has been proposed and implemented into a Fortran routine for evaluating the temperature distribution within the walls, gas and tiles along the kiln under steady state assumption. Xiaohui et al. (2016) numerical simulation was used to optimize a biological wastewater treatment process, while Rui et al. (2015) proposed a numerical approach for the prediction of the pollutant emissions in municipal solid waste incineration.

Indeed, the processes typical for a ceramic kiln are strongly time dependent and in particular the assessment of different control strategies involves the analysis of the transient phase. Lumped and distributed numerical analysis has been extensively adopted for the simulation of complex systems under time dependent operating conditions. In Mercati et al. (2012) a novel concept for the hydrogen production has been investigated by modelling the entire proposed plant and different operations have been compared in order to define the best energy efficiency configuration. Similarly, in Franzoni et al. (2011) the numerical analysis of the entire cogeneration systems based on aluminum-water combustion was used to determine the best turbine operating point under different working conditions. The modelling approach has also been employed for the validation of integrated waste-to-energy systems with low environmental impact and the advantages compared to traditional technologies have been outlined (Milani et al., 2014). Despite the dimensional approximation, the 0D/1D models proved also to be able to account for complex physics involving heat transfer phenomena while including the layout of the full system (Bottazzi et al., 2012).

Lumped parameter numerical approach has been already employed for the simulation of the entire ceramic kiln; nevertheless, steady state assumption was always adopted. De Paulo Nicolau and Dadam (2009) developed an algorithm for the thermal analysis of the tunnel kiln and a coarse 3D simulation was also employed for evaluating the temperature distribution in the cooling zone. Similarly, Mujumdar and Ranade (2006) studied the temperature distribution along the axis of cement rotary kiln under steady state conditions.

In this paper, the simulation of an industrial ceramic kiln has been carried out by means of a lumped and distributed parameter approach under fully transient conditions. Thus, the thermos-fluid dynamics characteristics of the kiln were predicted along the axis of the system and their time histories were recorded. Therefore, the numerical model can be employed for testing different control strategies of the burners as well as different residence time of the tile in each section of the kiln (i.e. tiles' velocity). Particular care was devoted in modelling the many burners employed in the real kiln and the heat transfer processes between the different elements that encompass the system and affect the final temperature of the tiles and therefore the quality of the product. The results of the numerical model are validated against experimental measurements carried out on a real ceramic kiln during regular production operations. The agreement between the calculations and the measured values demonstrated to be very satisfactory; hence, the lumped and distributed numerical model can be employed for evaluating different kiln configurations and alternatives.

In particular, the effects of a new burner type characterized by internal heat recovery capability has been investigated and the improvement in terms of energy efficiency of the ceramic kiln addressed. The fuel saving and the relating reduction of carbon dioxide emissions resulted in the order of 10% when compared to the standard burner.

2. Analyzed ceramic kiln

The ceramic kiln simulated in this paper is real production facility located in the ceramic district in Emilia Romagna – Italy. It is characterized by a production rate of approximately 5000 kg/h of tiles and it is designed for a continuous working load of about 8700 h per year.

The entire ceramic kiln includes 43 modules with a length of 2.1 m each and it can be subdivided into the following 5 sections: pre-heating, firing, fast cooling, slow-cooling and outlet section, see Fig. 1.

This study focuses mainly on the first three sections since they demonstrated to be the critical ones for the quality of the tiles and the energy consumption. In particular, an accurate temperature control is mandatory for achieving the desired product quality and avoiding material defects.

In the pre-heating section, no burners are employed and the heating is due to the hot air flow from the burners zone. As far as the energy consumption is concerned, the most important zone is the firing section where the burners are installed. The burners are fuelled by natural gas and the fuel rate is controlled for each group of 8 burners as depicted in Fig. 2. One group of burners belongs to two modules and there are two groups of burners for each module, one above the roller plane and the second below respectively. The different control of the burners above and below the rollers is critical in achieving different temperatures in these chambers.

At the end of the firing section, a fireproof wall is positioned in order to separate the cooling zone to the firing zone; main task of this wall is to partition the flow between the firing and fast-cooling sections. Its height is adjusted in order to always direct the flow from the cooling to the firing section and regulate the temperature at the interface of these two regions.

An important characteristic of the analyzed kiln is the opposite direction of the hot air flow and the tile motion. A mentioned before, the air is inducted from the cooling zone by means of a fan located at the beginning of the kiln before the flue gas stack. Therefore, the pressure in the cooling zone is higher than the one in the firing section, which is usually characterized by values below the atmospheric pressure.

As a consequence, the leakages in the walls of the modules allow the cold ambient air to enter the kiln chambers influencing the temperature of the hot air flow and thus the energy consumption of the entire system. The remaining portion of air in the fast-cooling section exits the kiln through the slow-cooling section and the

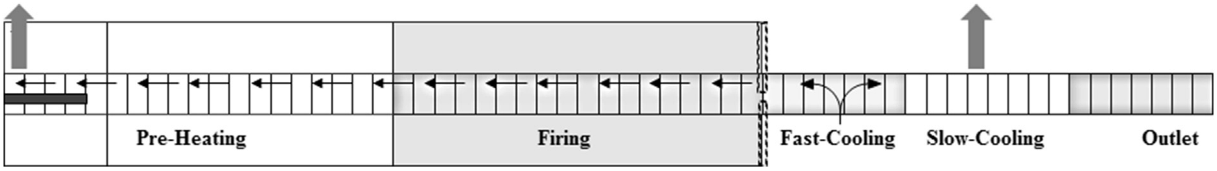

Fig. 1. Schematic of the entire ceramic kiln.

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