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Thermal analysis of a tunnel kiln used to produce roof tiles

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HIGHLIGHTS

- Numerical simulation of tunnel kiln.
- Method of finite volumes.
- Global thermal analysis of the kiln.
- Numerical and experimental data results.

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ABSTRACT

This paper presents a thermal analysis of a tunnel kiln used for the production of roof tiles, fueled by firewood and shale oil. A tridimensional numerical model based on the finite volume method is presented and applied to model the thermal behavior of the kiln. The fuel combustion was treated as a one-step complete reaction. Surface to surface radiation between the kiln walls and load surfaces with non-participating media was considered. A prescribed flow of flue gas and air was used to surpass the obstacle of high computational cost due to the large dimensions of the numerical domain. Experimental measurements for an operating tunnel kiln were compared with numerical results and a good agreement was observed. Temperature profiles and heat fluxes for the walls and load are reported and discussed.

1. Introduction

Tunnel kilns used for the production of bricks and roof tiles in the ceramic industry are characterized by their length, which can reach up to 200 m [1]. Energy in this type of kiln is generally provided through the combustion of firewood, natural gas or oil. Another characteristic of this type of kiln is the high energy consumption. Firing curves for ceramic materials usually reach 1000 °C in the firing zone. Mancuhan and Kucukada [2] suggested an optimal specific consumption (fired material-based) in the range of 2.04 MJ–3.51 MJ per kilogram of product for brick production. Nicolau and Dadam [3] indicated a specific consumption of 3.47 MJ/kg of brick produced for a tunnel kiln operating in the south of Brazil. Specific consumption is here defined as the energy used to produce 1 kg of fired-ceramic.

Several studies can be found in the literature focusing on the application of numerical modeling to industrial kilns with operating temperatures of the order of 1000 °C. Possamai et al. [4] presented an experimental and numerical study on a ceramic frit production kiln. Nieckele et al. [5] described the numerical modeling of an aluminum melting furnace. Both research groups demonstrated the numerical complexity addressed when dealing with high temperature kilns, with the use of combustion, radiation and turbulence models. In both studies a 3-D model was solved. Combustion reactions were modeled with one to four-step mechanisms and radiation was considered spectrally independent.

Other studies have been carried out in the same field with similar techniques and objectives, such as Hachem et al. [6] and Abassi and Khoshmanesh [7]. Results revealed the heat flux distributions and the presence of hot spots inside the kiln. A major characteristic of these studies is the small dimensions of the numerical domain of the solution, mostly below 50 m^3. Abassi and Khoshmanesh studied the larger furnace, a glass melting furnace, with approximately 800 m^3 separated into three different numerical domains solved separately and coupled through boundary conditions.

When dealing with tunnel kilns used in the ceramic industry the large domain of the resolution is a significant obstacle. It can reach over 3000 m^3 and encompass complex physical phenomena associated with a high numerical cost. In view of this drawback, most authors studying tunnel kilns have applied 1-D numerical models or dynamic analysis [2,8–13]. Kaya et al. [12] presented a dynamic

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model of a tunnel kiln for brick production in order to optimize the heat recovery in the cooling zone. The results consisted of 1-D temperature profiles and the optimization of mass flux inlets. Kaya et al. [13] presented a second study on the same type of model and analysis for the optimization of mass fluxes in the firing zone. Once again, the results were one-dimensional. More recently, Nicolau and Dadam [3] reported an experimental and numerical analysis of a tunnel kiln for brick production. A simplified 3-D model was applied to obtain firing curves and analyze the mass fluxes.

A literature review reveals a lack of studies on more complex 3-D numerical models applied to tunnel kilns with results capable of identifying critical spots inside the kiln and the load. The work reported herein lies with this context, applying tridimensional modeling to a tunnel kiln for the production of roof tiles operating with firewood and shale oil. Combustion reactions were simplified into a one-step mechanism and the fluid flow inside the kiln was considered to be non-participative with surface to surface radiation. The Navier–Stokes equations were not solved numerically as the flow field inside the kiln was prescribed, to avoid the drawback of high computational cost. Experimental data obtained on an operating kiln were compared to numerical results. Results focus on the profiles for the temperature and heat flux inside the kiln.

2. Kiln and experimental analysis

A tunnel kiln operating in a continuous process for the production of roof tiles was analyzed. A schematic diagram of the kiln showing the main dimensions is shown in Fig. 1, indicating the main components. The kiln is divided into three zones: heating (37.0 m length), firing (25.1 m length) and cooling (49.1 m length). Six firewood furnaces are located on each side of the burning zone. Six more shale oil burners are located on the roof of the same zone. An extractor is located at the beginning of the heating zone for the extraction of flue gas. Another extractor is positioned at the beginning of the cooling zone for the extraction of ambient air, which is injected at the end of this zone through 6 lateral fans for the slow cooling of the load. An air curtain at the beginning of the same zone supplies ambient air for fast cooling directly on top of the load pile.

The kiln was idealized as a hexagonal prism with 3 m height, 5.6 m width and 111.2 m length. The walls and roof are comprised of two external thermal insulation layers of brick and one internal refractory brick layer, totalizing 0.7 and 0.5 m of wall and roof thickness respectively. The load is comprised of roof tiles and brackets arranged in the shape of a hexagonal prism, with dimensions of 1.2 × 2.6 m, over a rectangular lorry measuring 0.3 m in height and 2.6 m in length. The load was considered continuous over the entire kiln length seen as one block. The load configuration and dimensions are shown in Fig. 2.

The experimental approach was aimed at obtaining the variables required to determine the energy and mass balances in the kiln. Table 1 shows the measured variables. For the flow measurement, Pitot's tubes of 350, 1000 and 2000 mm length and 4, 10 and 15 mm diameter, respectively, were used. The only exception was the measurement of the flow of the shale oil combustion air, which was performed with a vane anemometer (Testo, model 521-2). To measure the flow and external surface temperatures a type-K thermocouple probe (OMEGA KMQSS-020U-12) coupled to a digital thermometer (OMEGA HH-21) was used. The temperatures of the external surfaces were also measured, with an infrared thermometer (Raytek, model RAYMX4PB).

3. Numerical model

The following physical phenomena were modeled: (i) one-step combustion reaction of firewood and shale oil in the burning zone, (ii) thermal exchanges by convection and radiation inside and outside the kiln, (iii) flue gas and air advection inside the kiln and (iv) thermal conduction through the load, lorry and kiln walls and roof. Chemical reactions in the load were neglected.

The finite volume method [14] was applied to solve the differential equations. The following hypotheses were adopted: all fluid domains (a) follow the ideal gas law; (b) are incompressible with respect to the pressure; (c) and do not emit or absorb thermal radiation. The flue gas is (d) composed only of CO_2, H_2O, N_2 and O_2. All solid domains are considered (f) homogeneous and continuous and (g) to have constant properties. This last hypothesis is based on the fact that the properties of the solid domains vary little within the working temperature range. All thermal properties required are shown in Table 2.

For the conservation equations only the energy equation was solved, given by

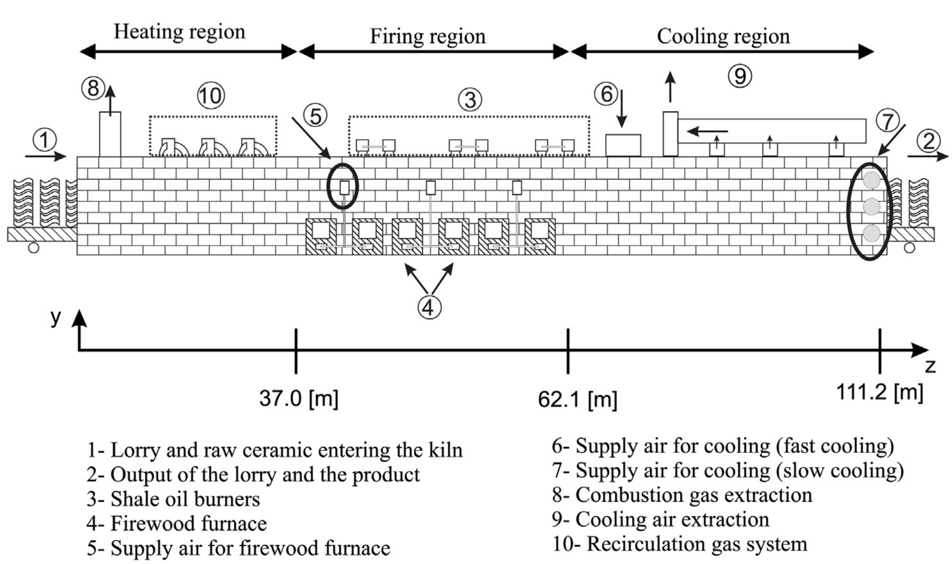

Fig. 1. Schematic diagram of kiln.