Energy 64 (2014) 615–625

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Effect of flue gas recirculation during oxy-fuel combustion in a rotary cement kiln

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ARTICLE INFO

Article history:
Received 17 May 2013
Received in revised form
16 September 2013
Accepted 18 September 2013
Available online 1 November 2013

Keywords:
CFD
Rotary kiln
Heat transfer
Oxy-fuel combustion
FGR

ABSTRACT

The effect of Flue Gas Recirculation (FGR) during Oxy-Fuel Combustion in a Rotary Cement Kiln was analyzed by using a CFD model applied to coal combustion process. The CFD model is based on 3D-balance equations for mass, species, energy and momentum. Turbulence and radiation model coupled to a chemical kinetic mechanism for pyrolysis processes, gas–solid and gas–gas reactions was included to predicts species and flame temperature distribution, as well as convective and radiation energy fluxes. The model was used to study coal combustion with air and with oxygen for FGR between 30 and 85% as controller parameter for temperature in the process. Flame length effect and heat transfer by convection and radiation to the clinkering process for several recirculation ratios was studied. Theoretical studies predicted a located increase of energy flux and a reduction in flame length with respect to the traditional system which is based on air combustion. The impact of FGR on the oxy-fuel combustion process and different energy scenarios in cement kilns to increase energy efficiency and clinker production were studied and evaluated. Simulation results were in close agreement with experimental data, where the maximum deviation was 7%.

1. Introduction

Clinker production is an area of considerable attention in the cement industry due to its high energy demand and greenhouse gas emissions [1–3]. The energy required for clinkering is generated by the combustion of coal in a rotary kiln. This energy is further transferred to the clinker via radiation and convection. Crystal shape, amount and composition influence the reactivity of the clinker, while energy consumption in the clinkering process is influenced by the temperature distributions and residence times inside the kiln, both of which can be positively modified using oxy-fuel combustion. This process can also increase the energy efficiency for clinker production process [3,4].

Previous studies have focused on the implementation of oxy-fuel combustion process in order to improve energy and environmental issues in the cement industry [1–6]. In the oxy-fuel combustion process, oxygen is fed to the kiln at a high concentration and further diluted with recirculated CO_2 from the flue gas to maintain an appropriate flame temperature. CO_2 is the main component of flue gases, but they also contain small amounts of nitrogen, carbon monoxide, water and other gases [1].

The oxy-fuel combustion process does not produce a significant amount of NO_x because nitrogen is fed at a low concentration into the oxidizing stream [2,3,7]. In addition, CO_2 may be easily captured and stored because of its high partial pressure in the flue gas. Therefore, the process allows for an easier separation than air-based combustion systems [3–6]. Thus, the oxy-fuel process is a good alternative for reducing CO_2 emissions in the cement industry and for reducing the energy demand [1].

Some authors and research institutes have worked with cement kilns driven by oxy-fuel combustion to assess this technology and improve CO_2 capture. Most of these studies focused on evaluating the components of the process using virtual and laboratory pilot plants [2–4,7]. Significant effort has been allocated for evaluating the impact of oxygen enrichment on kiln operation and reactivity during combustion of coal particles [8].

One-dimensional steady state modeling and numerical simulation were performed by Tomaz and Maciel Filho [9] over an air-fired rotary kiln, predicting temperature and concentration distributions in the kiln. The approach developed by Tomaz and Maciel Filho [9] allowed solid-bed volume reduction due to the volatilization, destructive distillation and pyrolysis of waste. An electric circuit

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http://dx.doi.org/10.1016/j.energy.2013.09.045

analogy was used to calculate the total heat transfer rate and temperature and concentration distribution.

Marin et al. [10] presented a simulation of a rotary kiln used to produce cement clinkers. They studied the impact of oxygen enrichment on kiln operation using multiple oxygen injection schemes. Two different coals were investigated: one with medium volatile content (27.6%) and one with low volatile content (10%). The models used for kiln simulation included devolatilization and char combustion; two-competing rate devolatilization models were employed as well as a surface reaction model for char combustion. Radiation was studied with a P1 radiation model, while a k-?model was used for turbulence. Their results showed that the oxygen-enriched operation increases the clinker production rate and overall efficiency, because heat transfer rates to the load are enhanced.

Kangwanpongpan et al. [11] simulated coal burner which has three entries to the kiln by using a CFD model. The model considered the OD radiation model (ordered discrete), where the weighted sum of gray body model was used for the gas. The main objective was to find a model that would describe the radiation emitted during the combustion of coal, especially in an environment with high concentrations of CO_2 and water. The models results were successfully compared respect to experimental results.

The International Energy Agency (IEA) has previously simulated the carbon capture and storage (CCS) process in cement plants [2]. In this work, three different cement plants (each 1 Mt/y) were studied including an oxy-fueled plant in order to evaluate the most efficient for the CCS process. The model is based on global mass and energy balances for each plant component, and the simulation results allows for the calculation of operational cost. Oxy-fuel plants produced favorable economic results when compared to traditional plants. However, this study did not take into account the kiln temperature and chemical reactions.

Zeman and Lackner [6] studied the possibility of implementing oxy-fuel combustion in a cement plant for clinker production. All additional components required to implement oxy-fuel process were studied, such as FGR, an air separation unit (ASU), the clinker transformation process, gas pre-heaters and separation, storage and compression units. They found that the efficiency of the oxy-fuel process is increased due to flue gas energy recovery, and the CO_2 emission is lower relative to the air combustion process. However, energy consumption was increased when using the oxy-fuel process due to the presence of additional CCS units.

The European Cement Research Academy (ECRA) studied the oxy-fuel process in a cement kiln [4]. Their goals were to find the technology's restrictions and requirements, as well as its impact on energy balances, clinker quality, plant operation and flue gas components. They reported that oxy-fuel combustion is a promising process with respect to CCS.

Other authors have worked on modeling and simulating the oxy-fuel process. Chui et al. [5], developed two modes of oxy-coal combustion: O_2 enriched air and recycled flue gas. Their objective was to study the CO_2 production available to capturing it or to using it in other applications. Both operation modes were experimentally tested in a 0.3 MW pilot-scale combustor with variations in oxidizing gas composition and two kinds of burners. Energy transfer, pollution and combustion were evaluated with the model and then experimentally validated. Good agreement was obtained between experimental data and the theoretical model when temperatures, CO, O_2 and NO concentration were compared.

Anderson et al. [12] studied the radiative energy flux in oxy-fuel and air combustion processes in a vertical kiln by using mathematical model. The molar fraction of oxygen was changed from 25% to 29%. The model was validated in a 100 kW vertical kiln with excellent agreement. The authors concluded that FGR is an important parameter for controlling kiln operating conditions, such as temperature and radiation energy flux.

Nikolopoulos et al. [13] also studied the oxy-fuel and air combustion processes by mathematical model. A three-dimensional CFD model was developed in a vertical kiln to evaluate three different cases; the first case corresponds to normal air operation, while the other two represent operation under either partial oxy-fuel (enriched air) or full oxy-fuel conditions. Gas temperature distribution, flue gas species distribution, gas velocities and energy transfer were evaluated. The high temperatures found in the oxy-fuel case suggest that the process efficiency can be increased.

A CFD model was developed by Al-Abbas et al. [14] for the oxy-fuel and air combustion processes. The model was developed to predict the flame length based on axial temperatures in the kiln, gas velocities, species concentrations of the flue gases and coal particle consumption during combustion. Model validation was performed in a 100 kW laboratory-scale kiln, being modeled in this paper. Numerical results showed that the flame temperature distribution and O_2 concentration in the oxy-fuel combustion case are similar to those in air-fired case with an oxygen volume fraction of 25%. When the oxygen concentration is either 27% or 29%, flame temperatures increase, even though the flame structure is shorter and more confined to the region of the burner exit plane because of a higher oxygen consumption rate.

Another CFD study was developed by Al-Abbas and Naser [15] who evaluated three different reaction mechanisms for the coal combustion process with both air and oxygen. The authors also evaluated the production/destruction of NO_x during the combustion process. The best results seem to be consistent with the mechanism of three reactions prediction regarding the kiln temperatures, species and radiation heat transfer in the furnace walls. The study showed that there is a reduction in the amount of NO_x in the oxy-fuel combustion cases because there is not thermal NO_x in these scenarios. Concentration of NO_x in case of 29% of oxygen was incremented, probably it due to the higher O_2 concentration in the oxidizing gas, enhancing the conversion of nitrogen-fuel to NO_x.

Al-Abbas et al. [16] performed a CFD simulation of air-combustion air and oxy-combustion using propane. They evaluated one-step and a four-step reaction mechanism (two irreversible and two reversible reactions). A turbulence model (EBU) with empirical coefficient was used. The results obtained by the CFD model were compared with experimental results, showing agreement with global temperature and species formation when the four-step mechanism is used.

This work presents a complete 3D model for air and oxygen coal combustion in a rotary kiln. The model considers two phases: gas was modeled in the Eulerian frame [17] and particles in the Lagrangian frame [18,19]. In this work, the Discrete Ordinates (DO) radiation model [20,21] is used despite its higher computational cost. The DO radiation model is one of the most complete models for radiation flow calculations because it considers effects from both a discrete phase and walls. Boundary and initial conditions for the simulated cases are obtained from global mass and energy balances done in the kiln. The CFD model can be used for predicting velocity fields, gas temperature and composition distribution in the kiln. The model also predicts the residence time inside the kiln, solid volume fraction and velocity of the disperse phase.

The main objective of this work is to find the effect in temperature and energy flux when the FGR is changed in a kiln when is operated with oxy-fuel combustion. Results were compared with the conventional process with air. Eight different levels of FGR were studied in the oxy-fuel combustion process. Computational models developed in our study not only satisfactorily predicted the behavior of industrial cement kilns, but also provided useful information for reducing energy consumption.