Chapter 2

Oxygen Enrichment Technology—An Innovation for Improved Solid Fuel Combustion and Sustainable Environment

Ankur Mittal, Ashutosh Saxena, and Bibekananda Mohapatra

Abstract There is an absolute need to adopt innovative technologies to improve energy efficiency with minimum possible environment emission and conservation of natural resources. Oxygen-enriched combustion is one of the latest technologies that may improve combustion efficiency depending on the exhaust gas temperature and percentage of oxygen in the combustion air. Cement industry is responsible for approximately 8% of the global anthropogenic CO₂ emissions (IPCC, 2006) and the cement market is expected to grow with increased industrialization and urbanization. In typical cement manufacturing process, 60% of CO₂ emissions are due to the transformation of limestone to lime (the calcination process) and rest 40% is due to fuel combustion in pyro processing. The air is used as an oxidizing agent content in industrial combustion processes that has maximum nitrogen component (78–79%) by volume. The chemically inert nitrogen dilutes the reactive oxygen and carries away some of the energy in the hot combustion exhaust gas during the air-fuel combustion process. An increase in oxygen in the combustion air can reduce the energy loss in the exhaust gases and increase the fuel combustion efficiency. Oxygen enrichment is helpful in curbing gaseous emission. By increasing oxygen content in air, N₂ content is limited that leads to less NO_x in exhaust gases. In this condition exhaust gases are more CO₂ rich that are partially recirculate along with combustion air. In CO₂ rich exhaust gases, water vapour is removed through condensation process and remaining CO₂ is captured through CCS technology.

Keywords Oxygen enrichment • CO₂ emission • Combustion

A. Mittal (✉) · A. Saxena · B. Mohapatra
Centre for Mining, Environment, Plant Engineering, & Operation, National Council for Cement and Building Materials, Ballabgarh 121004, India
e-mail: ankurmittal82@gmail.com

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2.1 Use of Oxygen Enriched Air to Improve Combustion Processes

Combustion is a chemical process in which a substance reacts rapidly with oxygen and releases heat as product. The original substance is called the fuel and the source of oxygen is called the oxidizer (Mathieu 2006).

Oxygen is required for any combustion process and ambient air is the most common source of oxygen that contains about 79% Nitrogen by volume. N_2 is inert gas and does not contribute in heat released through combustion reaction (Oates 1998). The nitrogen contained in air actually inhibits fuel from reacting with oxygen. This results in a flame temperature below that attainable with pure oxygen (Schorcht et al. 2013). Oxygen enrichment which is known as increased O_2 % in combustion air. This improves the overall combustion process and the resulting heat transfer increases flame temperature and the amount of available heat (Eriksson 2015). Oxygen enrichment process enhances burning zone control and improves kiln stability in the industrial furnace or rotary kiln (Eriksson et al. 2014). We get more consistent kiln operation, better clinker quality, and increased production or alternative fuel substitution rate among all possible positive results (Liu et al. 2015). Oxygen is added to combustion air to increase specific fuel rates in kg fuel/kg air (supplemental enrichment) or reduce overall air volume (equivalent enrichment) (Sharma et al. 2017). Overall gas flow rates are reduced and thermal efficiency increases by substituting pure oxygen either for a portion or total combustion air (Gao et al. 2017). For an example 21 m^3/h of pure oxygen can replace 100 m^3/h of air, thereby reducing the total flue gas volume by 79 m^3/h . The benefits of oxygen enrichment can be achieved even at very low levels of enrichment (Hokfors 2014).

The volumetric reduction in exhaust gases is easily illustrated by comparing the combustion reactions of air/methane (2.1) and oxygen/methane (2.2). Similar reductions in combustion products occur for all fuels due to the elimination or reduction of nitrogen contained in air.

On the above, it can be easily understood that for the air/methane reaction, there are 10.5 volumes of combustion products, compared to only three volumes of combustion products for the oxygen/methane flame. The adiabatic flame temperature of the oxygen/methane flame is roughly 800 °C higher than the air/methane flame due to the elimination of nitrogen.

2.2 Calcination Process in Rotary Cement Kiln

Lime (calcium oxide, CaO) is produced by calcination of limestone, containing a high concentration of calcium carbonate (CaCO_3) better known as Limestone. Limestone is an abundant natural raw material where lime is used for environmental purposes like waste neutralization or flue gas desulphurization. Limestone is also widely used in many industrial processes like in formation of metallurgical Slags or for production of paper pigments. The method used is based on multi-component chemical equilibrium calculations to predict process conditions.

Lime is produced by calcination of calcium carbonates in industrial kilns. The mineral calcite containing the calcium carbonates is the main component in naturally abundant limestone. The limestone is quarried or mined, mechanically pre-treated and delivered to the lime plant. One of the most common kiln types is the rotary kiln. Calcination is an endothermic reaction requiring heat to evolve gaseous carbon dioxide from the calcite to form lime (Fig. 2.1).

The calcination starts between 800 and 900 °C and the operational solid temperature usually reaches 1000–1200 °C. The calcination temperature is dependent on the partial pressure of carbon dioxide in the kiln.

Fig. 2.1 Illustration of calcination/combustion process in kiln

2.3 Oxygen Injection Methods in Rotary Cement Kiln

The two main oxygen enrichment methods for the kiln burner are either by general enrichment or focused enrichment. General enrichment is a method of adding the oxygen to combustion air piping (typically primary air) to increase the percentage of oxygen above 21%. This method is simple to retrofit and is an inexpensive way to obtain some of the benefits of oxygen enrichment.

Second method is focused enrichment of the kiln burner. This is accomplished by adding lance(s), rather within the burner or adjacent to the burner for injecting oxygen into the flame. This method of enrichment provides the most effective use of oxygen for increasing production or alternative fuel utilization. This is related with modifying the flame heat release profile. Special attention must be given to burner flame shape to maximize performance and to avoid degradation of the protective coating on the kiln refractory. Often various techniques can be used to allow the producer to adjust the flame length and heat release pattern to optimize the overall performance, economics and emissions. Proper lance design along with the evaluation of burner primary airflow is essential to ensure successful implementation.

CFD has proven to be a valuable tool when evaluating the proper method of oxygen enrichment for predicting situations that may occur when using oxyfuel combustion technology in a rotary cement kiln. Computational Fluid Dynamics (CFD) methodology can be used to investigate the temperature distribution, burn out rate of coal, flame shape, release of NO_x etc. The result indicates significant temperature increase in the rotary kiln. Coal particles combust more rapidly near the burner and final degree of burnout also increases (Fig. 2.2).

It may be clearly noticed from figures that the highest temperature zone around the core of the flame has been increased while the temperature at the walls of the kiln has remained similar to the conventional air combustion flame case. This can translate into increased production, increased alternative fuel usage and reduced emissions.

Fig. 2.2 Flame profile with and without oxygen enrichment

2.4 Result Analysis and Research Gap

Most cement plants adopt ambient air for combustion purpose that is catered through induced draft fans. Nowadays plants are pondering over exploring oxygen enrichment at their facility for sake of increasing productivity as well as improving fuel combustion efficiency. The approach for predicting the required oxygen usage to affect desired changes in kiln production and firing rate relies on the concept of heat availability. For a given amount of fuel and a constant excess oxygen level, addition of oxygen will increase the percentage of high grade heat. This is useful because clinker production is limited by the high-grade heat while excess low grade heat simply goes up the stack. Some results in rotary kiln with varying oxygen % are presented below (Tables 2.1 and 2.2).

Despite of encouraging results as above, some concerns are there for providing a early and significant thought like:

1. Cost of air separation technology must be economically feasible with a lucrative low pay back period.
2. The lack of extensive experiments and for extended periods of time is still a concern for easy adoption of this technology.
3. Higher flame temperatures with oxygen enrichment can cause overheating in the burning zone leading to a depletion of kiln coating and excess refractory wear.

2.5 Summary

Oxygen-enriched combustion technology can improve the fuel combustion conditions of cement production, increase flame temperature, shorten the time needed for combustion and achieve complete combustion enabling cement plants to increase the flame radiation heat ability of a material and improving the whole system's thermal

Table 2.1 Influence on flame temperature inside the kiln

Oxygen concentration in primary air (%)	Flame temperature (°C)	Clinker temperature (°C)
23.0	1381	1202
24.0	1322	1312
25.4	1431	1378
25.8	1435	1335

Table 2.2 Influence on energy consumption of clinker sintering

Oxygen concentration in primary air (%)	Total coal consumption (t/h)	Clinker sintering energy consumption (kcal/kg clinker)
23.0–25.0	31.2	663.1
25.1–27.0	29.8	660.8

efficiency. It can also reduce waste gas and dust and harmful gas emissions, which is beneficial to energy conservation and emissions reduction. It can improve the production efficiency and quality of cement. Therefore, applying oxygen-enriched combustion technology in cement production can yield economic, social and environmental benefits.

- Oxygen-enriched combustion can improve furnaces flame temperatures by 100–300 °C without any increase in fuel. This step is resulted into remarkable energy-saving effect.
- Flame temperature can rise by 200–300 °C when oxygen content increases by 4–5%.
- Oxygen enriched combustion increases in the whole furnace temperature and the furnace-heated material is easier to heat that increases thermal efficiency.
- Oxygen enrichment improves the combustion of pulverized coal, so that the kiln burns more fully. The kiln temperature improves with improvement in coal combustion rate.
- Free lime (F CaO) content in cement clinker decreases, stability and strength increase, better quality clinker results and the cement quality improves with improved combustion in the rotary kiln.
- Combustion is completed with less amount of air due to excess oxygen content in combustion air.
- There is less smoke production with reduction in dust pollution and environmental pollution. The successful application of oxygen-enriched combustion technology in the rotary kiln cement production industry will bring huge economic and social benefit aspects.

The oxy-fuel combustion process involves burning of pulverized coal in an oxygen enriched atmosphere that consists of pure O₂ that is mixed with recycled flue gas. This process differs from the conventional fuel combustion process where ambient air serves as the only oxidant. This entails specific conditions regarding thermo-physical properties, which affect both combustion characteristics and heat transfer.

Apart from efficient fuel combustion, oxyfuel combustion technology equally provides an opportunity to simplify carbon dioxide (CO₂) capture in coal fired cement plants. The capital cost, energy consumption, and operational challenges of oxygen separation are a primary challenge of cost-competitive oxy-combustion systems. Oxy-combustion system performance can be improved by two means:

- By lowering the cost of oxygen supplied to the system and
- By increasing the overall system efficiency.

The R&D within the advanced combustion systems program is aimed at strategies to improve oxy-combustion system efficiency and reduce capital cost, offsetting the challenges of oxygen production.

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