IOP Conf. Series: Materials Science and Engineering **103** (2015) 012030 doi:10.1088/1757-899X/103/1/012030

Experimental study on improving cement quality with oxygen-enriched combustion technology

Y Q Liu[1,2], A M Zhang[3], S Qing[1], F S Li[1,4], S P Yang[1] and Z F Yang[1]

[1] State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Department of Metallurgical and Energy Engineering Faculty, Kunming University of Science and Technology, Kunming 650093, China
[2] Department of Media and Information Engineering Faculty, Yunnan Open University, Kunming 650000, China
[3] Kunming Sino-platinum Metals Catalyst Co. Ltd. Kunming 650093, China

E-mail: 609263134@qq.com

Abstract. With the intensification of the global energy crisis, the production cost of enterprises is continuously increasing because of the rising fuel prices and high requirements for environmental protection. As result, energy savings and environmental protection are vital considerations for a variety of enterprises. As a practical energy-saving technology, oxygen-enriched combustion has played a major role in energy saving and emissions reduction as its application in industrial furnaces has been popularized in recent years. This experiment was conducted in a cement rotary kiln with a capacity of 4000 t/d in a factory in China. Based on measured data in the oxygen-enriched combustion experiment, we determined the patterns of variation in the main parameters of the cement rotary kiln under oxygen-enriched production conditions. The results provide important theoretical and practical base for the cement building materials industry in energy saving and emissions reduction.

1. Introduction

Resources, energy and environmental problems have recently become bottleneck in the process of economic development. In particular, energy saving and emissions reduction are critical concerns of sustainable development. As one of the foremost energy-consuming and pollutant-emitting industries, cement production must adapt to save resources, mitigate the energy crisis and protect environment [1-4].

Oxygen-enriched combustion technology is one of the most promising approach to energy saving and environmental protection for cement kilns [5, 6]. Research results show that adopting oxygen-enriched combustion technology can not only save fuel, reduce emissions and lessen discharge of harmful gases, but also can improve the yield and quality of cement and extend the kiln's furnace life. Therefore, oxygen-enriched combustion technology has broad prospects for application in the cement rotary kiln [7-10].

2. Experiment

[4] Address for correspondence: F S Li, State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Department of Metallurgical and Energy Engineering Faculty, Kunming University of Science and Technology, Kunming 650093, China. E-mail: 326720228@qq.com.

This experiment was conducted in a cement rotary kiln with a capacity of 4000 t/d located in a factory in China. Enriched oxygen obtained from gasification and decompression of liquid oxygen was combined proportionally in a primary air muffler pre-filter after which is entered the primary air system. According to theoretical calculations and production practices, this test of local oxygen-enriched combustion led the oxygen enrichment rate to rise to 30%.

Figure 1 shows the test process flow diagram.

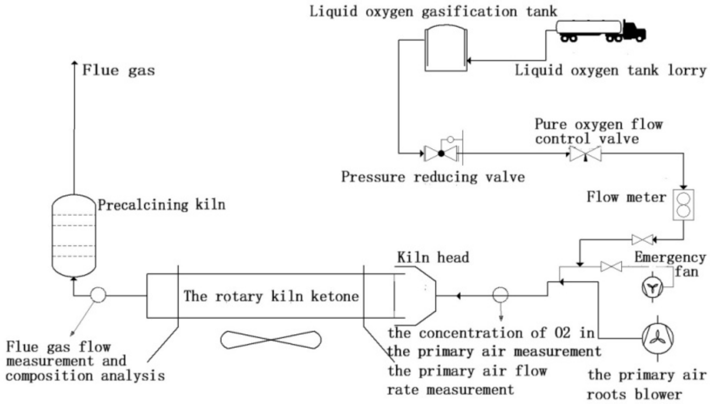

Figure 1. Test process flow diagram.

3. Test results and analysis

3.1. The influence of oxygen-enriched combustion on flame temperature inside the kiln

Cement rotary kilns reach extreme combustion temperature, but is smoke takes away a great deal of heat, leading to energy waste and wall damage. High flame temperature guarantees normal clinker burning, which is connected with fuel type, fuel supply, kiln body heat loss and other factors [11-14]. Table 1 shows the test data.

Table 1. Relationship between oxygen concentration and clinker temperature.

Time	Oxygen concentration in primary air pipe /%	Flame temperature/℃	Temperature of the clinker /℃
D2 14:00	23.0	1,381	1,202
D2 18:00	24.0	1,322	1,312
D2 22:00	25.4	1,431	1,378
D3 02:00	24.7	1,523	1,349
D3 06:00	25.8	1,435	1,335
D3 10:00	25.2	1,420	1,353
D3 14:00	25.5	1,429	1,359

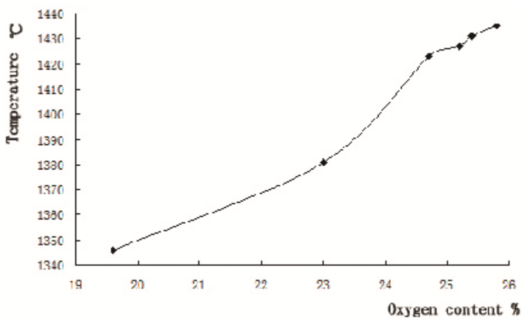

Figure 2. Relationship between oxygen concentration and the temperature of the clinker.

As oxygen content increases in the primary air system, oxygen molecules come into full contact with combustible and achieve complete combustion. Then the flame temperature increases, increasing heat transfer from the flame to the clinker, which in turn improves the clinker's kiln temperature and the heating effect. Figure 2 shows the relationship between oxygen concentration and clinker temperature.

3.2. Impact of oxygen-enriched combustion on energy consumption of clinker sintering

Table 2. The highest energy saving rate calculation table in the steady oxygen-enriched rate stage.

Items	Raw material t/h	coal in the kiln front end t/h	Tailings t/h	Conversion of clinker t/h	Total coal consumption t/h	Receive net calorific kCal/kg	Clinker sintering energy consumption kCal/ kg	Production of clinker per ton of coal t/t
23~25%The optimal value	310.4	9.82	21.37	188.12	31.19	3999.43	663.09	6.03
25~27%The optimal value	297.6	9.69	20.11	180.36	29.8	3999.43	660.79	6.05
Contrast value	304.6	10.22	22.32	184.61	32.54	4052.55	714.33	5.67
The improvement rate of index %						23~25%	7.17	6.31
						25~27%	7.49	4.16

The combustion temperature increases with the increase in oxygen content. At the same time, the feed coal quantity of the kiln head and kiln tail decreases. Pulverized coal fully burning in oxygen-enriched conditions improves the combustion temperature and enhances heat transfer in the furnace, which increases productivity. As oxygen content in the combustion air increase, the amount of pulverized coal required decrease, and the combustion-supporting air quantity significantly decrease. The decrease of feed coal and air volume leads to a decrease in smoke gas and carbon monoxide content. In turn, the heat loss of chemical flue gas greatly decreases, which improves the thermal efficiency and reduces energy consumption, as shown in table 2. Experiments show that an obvious coal saving effect results from adopting oxygen-enriched combustion.

3.3. The influence of enriched oxygen on the primary fan's air supply and energy savings

The amount of air needed per kilogram of coal burning under natural conditions exceeds that required by oxygen-enriched burning. Oxygen-enriched combustion also allows for reducing the primary air fan speed and the total air supply. The higher the oxygen content in the oxygen-enriched air, the lower the primary air fan speed and air supply required, which can be seen from table 3.

Table 3. The pure oxygen flow and primary air calculating table.

Primary air rate	Oxygen content in primary air %	Total amount of oxygen-enriched primary air Nm^3/h	Oxygen flow Nm^3/h	Primary air Nm^3/h
24.6%	21	12,200	0	12,200
	23	11,994	325.2	11,650
	25	11,035	566.5	10,500
	27	10,218	776.3	9,500

3.4. The influence of oxygen-enriched combustion on the quality of cement

The most important parameter affecting the quality of cement is the quality of clinker. Controlling clinker quality is the most important step in the process of cement calcinating. Parameters representing the quality of the clinker are free calcium oxide (F-CaO) content in cement and liter weight and strength.

3.4.1. Free calcium oxide (F-CaO). Due to materials' composition and structure, raw materials ratio, fineness and uniformity, clinker calcination temperature and time and the clinker cooling system, a small amount of CaO can not be combined with acidic oxides like i.e.SiO_2, Al_2O_3, Fe_2O_3 to form free oxides (F-CaO) during the process of cement clinker calcination. Hydration of F-CaO in cement occurs slowly, leading to poor stability in the cement; therefore, it is necessary to control the content of F-CaO in cement clinker. F-CaO content directly affects the stability and other properties of the cement. It is difficult to control during the production of cement and exerts great influence on cement quality, which serves as an important index by which to judge the quality of clinker.

The lower the content of F-CaO in the clinker, the better the cement quality. Generally, production requirements of F-CaO fall at 1.5% or less. As the content of F-CaO increases, clinker strength significantly decreases, while its stability and qualified rate drop dramatically. When ventilation and oxygen are deficient in the kiln, pulverized coal combustion in the kiln head remains incomplete, and the continuously reducing atmosphere reduces the temperature in the kiln. If the kiln burning temperature is low, the liquid phase quantity of the clinker is insufficient or the liquid phase reaction is incomplete, high F-CaO content results [15-17].

F-CaO content in the cement clinker is different when calcinated under normal production conditions versus oxygen-enriched combustion. When the oxygen in kiln head is sufficient and the pulverized coal burns fully, F-CaO content displays different degrees of decline in oxygen-enriched combustion compared with normal production conditions at the same time point. As oxygen concentration increases, F-CaO in clinker gradually decreases, indicating that the quality of cement clinker is much better under conditions of oxygen-enriched combustion.

Figure 3 shows the relationship between oxygen concentration in air and F-CaO content in cement clinker. Under conditions of oxygen-enriched combustion, the average content of F-CaO in cement linker is 1.15%, or 0.197% lower than the average F-CaO content under normal conditions, which is 1.347%. Therefore, the cement clinker quality improves with oxygen-enriched combustion. The flame temperature increases as oxygen content in the air increases, which follows oxygen-enriched combustion in the rotary kiln; this improves the temperature of the whole kiln, resulting in greatly increased thermal efficiency and decreased F-CaO content.

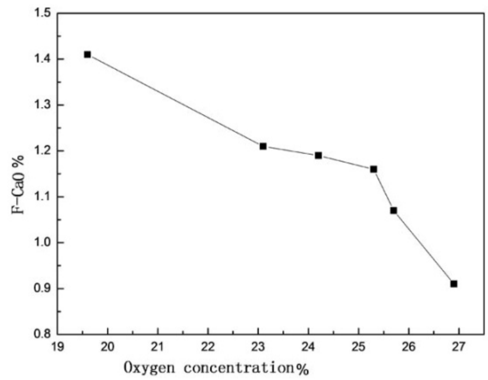

Figure 3. Relationship between oxygen concentration and F-Cao content.

3.4.2. Clinker liter weight. Clinker liter weight is the quality of a liter of clinker expressed in g/L; it is one of the parameters that determine clinker quality and kiln temperature. A material's particle size and uniformity, allows us to conclude whether the firing temperature is normal. Low liter weight indicates less clinker burning; on the contrary, the clinker burnt. At normal furnace temperatures, clinker has high yield, uniform particle size, compact appearance, smooth surface, small spherical approximation, and higher liter weight. If the burning temperature is too high or the material remains in firing too long, the clinker burns too much, leaving the liter weight too high and reducing the clinker quality. As the chemical reaction of material in the kiln remains incomplete, most of the clinker particles are small with a fine powder and low liter weight indicating that the temperature in the kiln is low. Therefore, liter weight should be controlled within a certain range [18, 19]. The liter weight of rotary kiln clinker is generally exceeds 1,240 g /L. Figure 4 shows clinker liter weights in normal production and oxygen-enriched combustion.

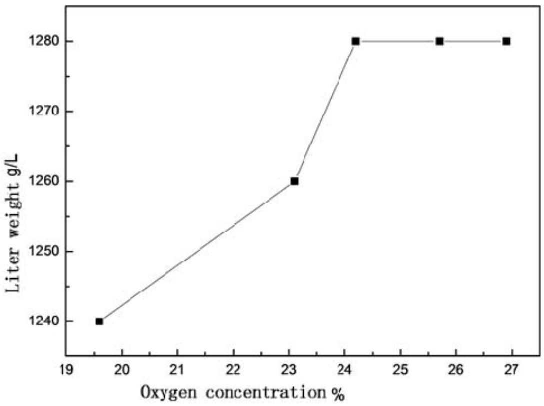

Figure 4. Relationship between liter weight and the oxygen concentration.

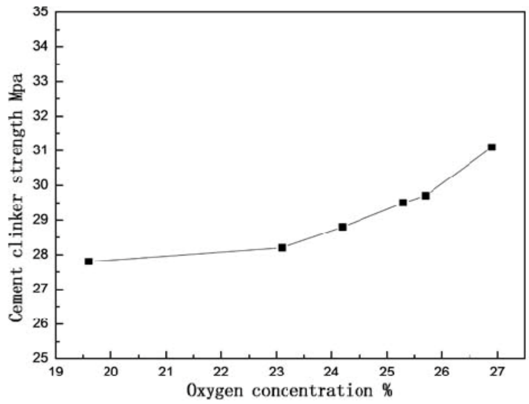

Figure 5. Relationship between oxygen concentration and cement clinker strength.

As the test data show, little difference exists between the average liter weight of 1,249 g/Lin the oxygen-enriched experiment compared with the average liter weight of 1,248 g/L in the normal production period. Both reached the requirement. Figure 4 shows the relationship between liter weight and the oxygen concentration in the oxygen-enriched air.

According to liter weight data measured under the conditions of oxygen enriched combustion, the average clinker liter weight is 1,267 g/L, which is 1.52% higher than the value under normal production conditions 1,248 g/L. Therefore, oxygen-enriched combustion can improve the quality of cement clinker.

3.4.3. Clinker strength index. Cement clinker strength is an important index by which to evaluate cement quality, and it forms the basis for determining cement strength grade. Cement clinker strength refers to the ability of a cement mortar-hardened specimen to withstand external damage, as expressed in Mpa. It is one of the most important physical and mechanical properties of cement.

According to the test results, average cement clinker strength under the conditions of the oxygen-enriched combustion is 29.46, which is 5.97% higher than the value under normal conditions 27.8. Cement clinker strength increases as oxygen concentration increase. Oxygen-enriched combustion in a rotary kiln increases the flame temperature, causing full calcination of the clinker, which improves its strength. Figure 5 shows the relationship between oxygen concentration and cement clinker strength.

3.5. The influence of oxygen-enriched combustion on fuel gas emissions

Oxygen-enriched combustion reduces the required amount of air, and the exhaust heat drops. Usually only one fifth of the total oxygen is in combustion; the rest of the air, rather than providing fuel, absorvs a great deal of heat from burning and emits fuel gas. This results in large energy wastes. The use of oxygen-enriched combustion reduces the amount of air needed for combustion, reaches complete combustion, reduces emissions and meets the requirements of environmental protection [20, 21]. Experimental results show that energy consumption of clinker sintering decreases by about 3.7 kgce of standard coal in the primary air oxygen-enriched test. If the daily output is about 4,000 kg of clinker and the reduction of CO_2 emissions per kilogram of standard coal is 2.493 kg, the daily CO_2 emission reduction will be 36.9 tons. Accounting for 320 working days, CO_2 emissions can decrease by 11,086 tons per year, yielding both environmental and social benefits.

4. Conclusions

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, thus increasing the flame radiation heat ability of a material and improving the whole system's thermal efficiency. It can also reduce waste gas and dust and harmful gas emissions, which is beneficial to energy conservation and emissions reduction. Finally, 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.

- Without any increase in fuel, oxygen-enriched combustion can improve furnaces flame temperatures by 100-300℃, yielding a remarkable energy-saving effect. According to the results, flame temperature can rise 200-300℃ when oxygen content increases by 4-5%. Higher flame temperatures promote increases in the whole furnace temperature, and the furnace-heated material is easier to heat, increasing the thermal efficiency.
- Oxygen enrichment improves the combustion of pulverized coal, so that the the kiln burns more fully, the combustion rate of coal improves, the kiln temperature improves, F-CaO content in cement clinker decreases, stability and strength increase, better quality clinker results and the cement quality improves.
- Because the oxygen content in combustion air exceeds 20%, combustion occurs more fully, the amount of air needed reduces, less smoke production results and dust pollution and environmental pollution decrease greatly.
- The successful application of oxygen-enriched combustion technology in the rotary kiln cement production industry will bring huge economic and social benefits, and it has broad application prospects.

Acknowledgments

This work was supported by National Natural Science Foundation of China under Contract (No. 51064015), to which the authors are greatly obliged.

References

[1] Wang Z P and Zeng X W 2009 Theoretical calculation of energy-saving eficiency and the key issues in technology of combustion in rich oxygen atmosphere *Glass* **36** 36
[2] Wang H and Wen Z 2006 Research on the application of oxygen-enrichment combustion technology to rotary lime kilns and its economic prediction *Modern Chemical Industry* **26 (S2)** 21-6
[3] Lin F, Ross M and Wang S 1995 Energy efficency of China's cement industry *Energy* **7** 669-81
[4] Li H Y and Wang H 2003 Performance compare analyses of high temperature air combustion and oxyboosted combustion technology *Industrial Heating* **32** 9-12
[5] Anon 1993 Developments and prospects of the Chinese cement industry *World Cement* **24** 1-18
[6] Li J and Xie J L 1997 Theory discussion of the application of oxygen-enriched combustion in cement rotary kiln production *Journal of Wuhan University of Technology* **19** 47-9
[7] Zhu G J, Liang Z Y, Wu M Q, Deng N Y and Zhang S Q 2005 Effects analyses of coal oxygen-rich combustion to energy saving and environment *Industrial Heating* **34** 34-7
[8] Claude P 2000 Cements of yesterday and today, Concrete of tomorrow *Cement and Concrete Research* **30** 1349-59
[9] Chen R 2005 Dissipation rate at extinction and the effects of oxygen-enriched combustion *Combustion and Flame* **142** 62-71
[10] Bejarano P A, Levendis Y A 2007 combustion of coal chars in oxygen-enriched atmospheres *Combustion Science and Technology* **179** 7-9
[11] Murphy J J, Shaddix C R 2006 Combustion kinetics of coal chars in oxygen-enriched

environments *Combustion and Flame* **144** 710-29

[12] Yang S P, Qing S, Yang N, Zhang A M, Liao B and Liu T S 2015 Study on combustion and kinetics of pulverised coal in mixed O_2/CO_2 atmosphere *Materials Research Innovations* **19** 1263-7

[13] Su J L, Pan L and Zu C M 2008 Research status and development of oxygen-enriched combustion technology *Industrial Boiler* **3** 1-4

[14] Zhu G J, Liang Z Y, Wu M Q ,Deng N Y and Zhang S Q 2005 Effects analyses of coal oxygen-rich combustion to energy saving and environment *Industrial Heating* **4** 11-3

[15] Yang N, Qing S, Wang H, Zhang A M, Li W T and Wang J Y 2014 Study on the effect of heating rate on combustion and kinetics of pulverized coal in mixed O/CO atmosphere *Coal Conversion* **37** 50-4

[16] Liu Q C and Chen S R 2004 Overview of the main factors afffecting the enviroment in the oxygen-enriched combustion *Energy Conservation & Environmental Protection* **9** 21-8

[17] Han C Y, Xu M H and Zhou H C 2001 *Pulverized Coal Combustion* (Beijing: Science Press) pp 67-9

[18] Zhu G J, Liang Z Y and Wu M Q 2004 Analysis of the influence of oxygen-enriched combustion of coal on energy saving and environment *Industrial Heating* **34** 11-3

[19] Zheng L, Kang Z J, Zhang L and Zhao Q X 2004 The thoery and application of oxygen-enhanced combustion *Industrial Boiler* **3** 10-4

[20] Zheng X F, Feng Y X and Jia M S 2006 The oxygen-enriched combustion energy-saving features and its impact on the environment *Energy Conservation* **7** 26-8

[21] He Q A and Gao C L 2004 The technical features of the cement rotary kiln using inferior coal in plateau area *Development Guide to Building Materials* **3** 55-9