Journal of Engineering Science and Technology Review 3 (1) (2010) 85-88

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Developing an optimization model for CO_2 reduction in cement production process

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Received 17 November 2009; Revised 30 March 2010; Accepted 21 April 2010

Abstract

The Intergovernmental Panel on Climate Change (IPCC) has predicted global rise in temperature and carbon dioxide is a major greenhouse gas responsible for global warming. The cement industry contributes approximately five per cent of the total CO_2 emitted worldwide.

Ewekoro cement Plant, located in Ewekoro, Ogun State was used as a case study to evaluate the results of various modifications on cement plants operation that can impact on the plant CO_2 emissions. An economic model which objective is to highlight the best selection strategy to reduce CO_2 emissions with the least cost was developed using the industry data as part of this paper. The cement Plant achieved a significant result of 23.6 per cent reduction in CO_2 emissions per tonne of cement produced. The results were achieved mainly by applying a progressive approach prioritizing project implementation effort and feasibility.

Keywords: optimization, CO_2 emission, cement, greenhouse.

1. Introduction

The rapid deterioration of global environmental conditions indicated to society the increasing necessity to react to and debate environmental issues. One of the most important and debated issues is the enhanced greenhouse effect. The burning of fossil fuels releases more than six billion tonnes of carbon dioxide (CO_2) into the atmosphere each year.

The cement industry plays a significant role in this scenario. Concrete is the world's most important construction material, and for each tonne of Portland cement (an essential component of concrete) produced, approximately one tonne of CO_2 is emitted to the atmosphere. This scenario raises the necessity of practical solutions and improvements in the cement industry that could result in lower CO_2 emission [1].

According to the International Energy Authority World Energy Outlook 1995, worldwide cement production was responsible for seven per cent of the total CO_2 emitted around the world [2]. Environmental polices around the world are affecting different industrial sectors and will inevitably affect the cement industry. During the past 10 years, cement industries have been challenged to reduce and effectively control CO_2 emissions.

The possibility of making a profit with CO_2 emissions is also a parameter that may impact the competitiveness of cement groups. National targets vary from eight per cent reductions for the European Union and other countries, to six per cent for Canada and Japan.

2. Objectives of the paper

The objectives of this paper are to:

1 develop an optimization model for ewekoro cement industry.
2 investigate a better and efficient way of removing carbon(iv) oxide in cement production.
3 evaluate the impact on CO_2 mitigation by different projects implemented at Cement industry.

3. Materials and method

Cement manufacturing consists of raw meal grinding, blending, pre-calcining, clinker burning and cement grinding. In short, limestone and other materials containing calcium, silicon, aluminium and iron oxides are crushed and milled into a raw meal. This raw meal is blended and then heated in the pre-heating system (cyclones) to start the dissociation of calcium carbonate to oxide. The meal goes further into the kiln for heating and reaction between calcium oxide and other elements to form calcium silicates and aluminates at a temperature up to 1450°C: so-called clinker burning. The cyclone system is attached to the rotary kiln by a riser duct. Secondary fuel is fed to the riser duct, the main fuel mixture, coal/petcoke, fires the kiln. Reaction products leave the kiln as a nodular material called clinker. the typical clinker composition: $CaO= 65 \pm 3\%$, $SiO_2= 21 \pm 2\%$, $Al_2O_3= 5 \pm 1.5\%$, and $FeO_3 = 3 \pm 1\%$ [3].

The clinker will be interground with gypsum and other mate-

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rials to cement. Figure 1 shows a simplified flowsheet presenting the cement manufacturing process.

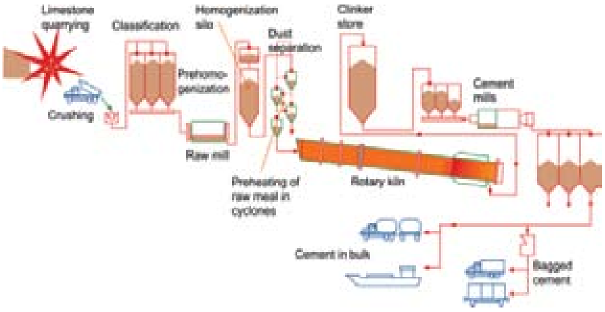

Figure 1. Cement manufacturing from the quarrying of limestone to the bagging of cement

3.1 Carbon Dioxide Emissions

The main sources of carbon dioxide in cement manufacturing are:

- Combustion of fossil fuel and;
- Limestone calcinations.

Approximately, half of the CO_2 emitted by the cement industry originates from the fuel and half from the calcinations that will convert raw materials into clinker.

3.2 Carbon Dioxide Emissions from Fuel Use

The cement companies use different sources of fuel. The most common are coal, petroleum coke, fuel oil and natural gas. Among the elements that make up the cement kiln, fuel carbon and hydrogen are the elements that contribute the most energy during the combustion process. Other elements, such as sulphur and nitrogen oxides, are also present in the combustion process and not only represent a small contribution to the energy process, but also represent a considerable environmental concern. Currently, the cement industry in North America and Europe bases their fuel choice on three basic points: cost, product quality and environmental impact. The fuel that best fills these three basic requirements will be the preferred choice. It is important to note that factors such as the cost of a new firing system, the amount of storage and local fuel availability will also play a key role in the decision process.

3.3 CO_2 Capture and Disposal

Different methods for the capture and disposal of CO_2 at the point of combustion have been researched and developed. Examples of possibilities are: chemical stripping, membrane system, cryogenic separation and physical absorption. The implementation cost of each one of these possibilities is highly uncertain; costs are directly related to technical performance, economic growth and fuel type. Moreover, the disposal solutions available today present a great level of doubt regarding the technical feasibility for a fullscale implementation.

The CO_2 concentration in a cement plant is higher than in a power generation process. Studies have shown that the cement production process has a high quantity of low quality heat. This extra heat could be used in the CO_2 capture process [4].

Chemical scrubbing has been considered as a capture process. Another possibility for the capture process in cement production is oxyfuel combustion, but the effect of higher CO_2 concentration in the flue gas on the clinker quality would need to be better assessed. In general the average cost to capture one tonne of CO_2 is estimated to be around USD 50 [5].

The different suggested solutions for disposal are: discharge into natural gas reservoirs or aquifers, discharge deep into the ocean or reuse the CO_2 in useful organic compounds. Reviewing all the solutions available today, the ocean scenario has the highest capacity to store CO_2, and absorbs the CO_2 quantities generated by the actual necessity of reduction. It is expected that in the next few years, CO_2 underground storage will be a technical and economical option for CO_2 disposal [6].

Currently, one of the main constraints is the integral long-term immobilisation preventing the CO_2 from migrating and leaking back into the atmosphere. This generates a demand for special "CO_2 cement" similar to the special oil well cement. Unfortunately such cement does not yet exist [7]. Following, is a brief discussion of the most common CO_2 capture methods.

3.4 Optimization Model

An optimization model for the cement industry is formulated in this paper. This model will reveal that the effort necessary to implement specific solutions represent a considerable increase on the regular operational cost of the cement plants. The results produced by the model will show that the actions similar to the ones taken by Ewekoro cement Plant described can produce results compatible to the theoretical findings.

The mathematical model consists of an objective function to be minimized and equality and inequality constraints. The objective of the model is to find the best strategy or mix of strategies to reduce CO_2 up to a certain target with minimum overall cost for cement production while meeting the demand.

The objective function to be minimized can be written as:

$$Z(\$ / yr) = \sum_{r} Cr\ Rr + \sum\sum_{If} C\ if\ Pif + \sum\sum_{If} R\ if\ X\ if + \sum\sum_{Ie} C\ ie\ Y\ ie + \sum\sum_{Ic} C\ ic\ Z\ ic$$

Where:

Z : annualized capital and operating cost of the cement plant (\$/yr)
Cr : cost of purchasing raw material r (\$/tonne)
Rr : purchased amount of raw material r (tonne/yr)
Cif : operating cost for a unit i with fuel f (\$/tonne)
Pif : amount produced from unit i using fuel f (tonne/yr)
Rif : retrofit cost for switching unit i to run with another fuel f (\$/yr)
Xif : binary variable representing switching or not.
Cie : cost of applying efficiency improvement technology (e) on unit i (\$/yr)
Yie : binary variable representing applying efficiency improvement technology (e) or not.
Cic : cost of applying CO_2 capture technology (c) on unit i (\$/yr)
Zic : binary variable representing applying CO2 capture technology (c) or not.

The first term in the objective function represents the cost associated with purchasing the raw material. The second term takes into account the operating cost for different units. The cost of switching to less carbon content fuel is shown in the third term. The fourth term represents the cost associated with applying efficiency improvement technologies. The remaining term adds the cost that result from applying CO_2 capture technology. A binary variable is defined for each CO_2 mitigation option under study.

3.5 Constraints

The constraints for demand satisfaction, fuel selection and CO_2 emissions reduction are given in details as follows:

3.6 Demand satisfaction

This constraint simply says that total cement produced should be greater than or equal to the demand.

$$\sum\sum_{if} P_{if} \geq \mathit{demand}$$

3.7 Fuel selection

Each unit i has to run with only one fuel f. For that reason, a binary variable is introduced to represent the type of fuel used in a given unit.

$$\sum_{f} X_{if} = 1$$

3.8 Emission constraint

The CO_2 emitted from all units must satisfy a CO_2 reduction target. Different technologies, e, to improve the efficiency are implemented in the mathematical model. It is assumed that the effect of these technologies is additive. The emission is also affected by applying CO_2 capture technology.

$$\sum\sum_{if} CO_{2\,if}\,(1-\sum_{e} e_{ie}\, Y_{ie})\,(1-\Sigma\varepsilon_{ic}\, Z_{ic})\, P_{if} \leq (1-\%CO_2)\; CO_2$$

Where:

CO_2 if : CO_2 emissions from unit i using fuel f (tonne per tonne cement produced)

eie : percent gain in efficiency associated with applying technology e on unit i

Yie : binary variable for applying efficiency improvement technology e or not

εic : percent CO_2 capture

Zic : binary variable for applying CO_2 capture technology c or not

% CO_2 : reduction target

CO_2 : Current CO_2 emissions (tonne/yr)

The CO_2 emissions are calculated by multiplying emission factor for a given fuel with fuel consumption. Selection of CO_2 capture process to be installed [8].

This constraint let the model select only one capture process for each unit i

$$\sum_{c} Y_{ic} \leq 1$$

Non-negativity constraints

The amount produced must be greater than zero

$$P_{if} \geq 0$$

3.9 Solution Technique

The pollution control model (P) is a Mixed Integer Linear Program (MILP). It differs from Linear Programs (LP) in that its variables are restricted to have values of either 0 or 1. Mixed integer programming problems are combinatorial optimization problem that are difficult to solve. This difficulty is due to the exponential growth of solution space with a linear increase in the number of variables in the model. For instance, for a problem with twenty binary variables, the number of possible linear programs (LP) that one has to consider in an exhaustive enumeration approach is more than 1,000,000. If the number of variables is 30, then the numbers of LPs that have to be considered would be more than one billion. Hence, even for a small number of binary variables in the model, an exhaustive approach that enumerates over all possible combinations of assignments of control technologies to pollution sources, check if each combination satisfy the pollution reduction requirements, and then selects the best combination in terms of total cost would be completely intractable.

The most widely used method for MILP problems is the Branch-and-Bound (B&B) technique, [9]. This technique is based on the idea of divide and conquer. Since the original "large" problem is too difficult to be solved directly, it is divided (branched) into smaller and smaller sub-problems until these sub-problems can be conquered. The branching is done by partitioning the entire set of feasible solutions into smaller and smaller subsets. The conquering (fathoming) is done partially by bounding how good the best solution in the subset can be and then discarding the subset if its bound indicates that it cannot possibly contain an optimal solution for the original problem. The B&B algorithm starts with a feasible solution to the mixed integer linear program. This solution is usually obtained from a heuristic procedure and represents a bound on the optimal solution of the problem. Then, at each iteration of the algorithm three basic steps are performed: branching, bounding, and fathoming.

The branching step fixes the value of one of the variables at zero for one subset and at one for the other subset. For each sub-problem, a relaxation is solved. The solution to the relaxation gives a bound on how good the best feasible solution of the sub-problem can be. A relaxation is obtained by deleting (relaxing) some of the constraints in the model. The most popular relaxation for binary linear programs is to relax the binary restriction on the variables of the model.

4. Results and Discussion

The developed model was illustrated using Ewekoro Cement factory as a case study. The problem of reducing CO_2 emissions from combustion sources within a cement plant is considered three different mitigation options. The first option is applying efficiency improvement technology to reduce CO_2 emissions. The efficiency improvement technologies to reduce CO_2 emissions shown in Table 1. The second option for reducing CO_2 emissions is by switching, in which the unit will be switched to operate with less carbon content fuel such as natural gas. The third option is applying CO_2 capture technologies.

Table 1. Technologies for Efficiency Improvements.

Technology	CO_2 Emission Reduction (%)
High efficiency motors and drives	4
Efficient grinding technologies	8.3
Adjustable Speed Drives	5.5
Conversion from wet to dry process	50

The Three CO_2 mitigation options considered are:

(i) Applying efficiency improvement technologies to reduce CO_2 emissions shown in Table 1.
(ii) Switching to less carbon content fuel such as from coal to natural gas
(iii) Applying "end of pipe solution" CO_2 capture technologies. The chemical absorption process is the only considered option in this research.

The model is formulated using General Algebraic Modeling System.

The CO_2 mitigation options are incorporated into the model to select the least cost option to reduce CO_2 emissions to a specified target. Different CO_2 reduction target are specified. Table 2 shows the results for different CO_2 reduction targets. For 1% reduction target, for example, the optimizer chooses to apply the technology of high efficient motors and drives. The cost of production increases by about 2%. A second improvement technology is applied at a reduction target of 5%. No fuel switching is applied up to 10% where efficiency improvements technologies is applied with an increase of about 7.3% in the cost. For a 20% reduction target, fuel switching, from coal to natural gas, is selected to be applied with only one technology for efficiency improvement. This technology is installation of high efficient motors and drives. The cost increases by about 17.4%.

Table 2. Results for Different CO2 Reduction Target.

CO_2 reduction(%)	Cost (million $/yr)	CO_2 Emission Reduction (%)
0	25	0
1	25.60	2.4
5	25.72	2.9
10	26.80	7.3
20	29.35	17.4
30	33.31	33.2
50	38.85	55.4

The table above shows that the increase in the production cost for each CO_2 reduction target. The line starts to be sharply increases at reduction target ranging from 20 to 50%. This is expected since the capture cost is much higher than other mitigation options.

5. Conclusion

It is clear that the cement industry is a key player in the sustainable development of different regions. Different alternatives discussed in this paper can contribute to a significant progress in reducing emissions and energy waste.

Optimization model was developed in order to meet demand at a given CO2 reduction target. Three mitigation options were considered. The model chose the best strategy or mix of strategies in order to meet a certain CO2 reduction target with the least cost providing that the demand and other requirements were met.

Applying different efficiency improvement technologies is a good option especially at reduction target up to 12%. Beyond that reduction target, fuel switching should be applied to achieve a reduction target such as 25%. At reduction target higher than 25%, carbon capture technology should be applied and efficiency improvement technologies are no more a good mitigation option. The cost of production increases dramatically when the reduction target is beyond 25%. This is expected since carbon capture technology is the most expansive selected technology. Switching from wet to dry process was never chosen because of this technology is a natural option for cement plants to reduce cost and increase competitiveness. Actually wet system is not an option for the newer cement plants.

References

1. Duda, W. H. 1977. "Cement data-book. International process engineering in the cement industry", 2nd ed., Berlin, Germany. 311-317.
2. Malhotra J. E. 1999. Portland Cement Industry: Plant Information Summary", Portland Cement Association, 8-10.
3. Batty, G. R. 2005. Cement raw materials, their effect on fuel consumption, Rock Products, Chicago, 80(10): 60-64.
4. Saxena, J. P. 1999. The reduction of greenhouse gas emissions from the cement industry International Journal of Green Energy. 3(1): 56-59.
5. Nazmul S. M., Croiset, E., Douglas, P. L. 2006. Techno-Economic study of CO_2 capture from an existing cement plant using MEA scrubbing, International Journal of Green Energy. 7(3): 1-24.
6. Alie, C., Backham. L., Croiset, E., Douglas, P.L. 2005. Simulation of CO_2 capture using MEA scrubbing: a flowsheet decomposition method, Energy Conversion and Management Journal. Canada. 7(46): 475-487
7. Ehrenberg, A. 2002. CO_2 emissions and energy demand of granulated blast furnace slag, Proceedings of the 3rd European Slag Conference, EUROSLAG publication, 7(2): 151-166.
8. Gartner, E. 2004. Industrially Interesting Approaches to "Low-CO_2" Cements, Cement and Concrete Research, 149-154.
9. Choate, T. W. 2003. Energy and Emission Reduction Opportunities for the Cement Industry. Industrial Technologies Program, U.S Department of Energy, Energy Efficiency and Renewable Energy. 3(5): 24-29.