Oxygen economics

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The technical benefits of oxygen-enhanced combustion in many industries have been well documented. Throughout the world, cement and lime plants have been able to increase alternative fuel substitution, raise clinker and lime production and improve thermal efficiency through the implementation of oxygen enrichment.

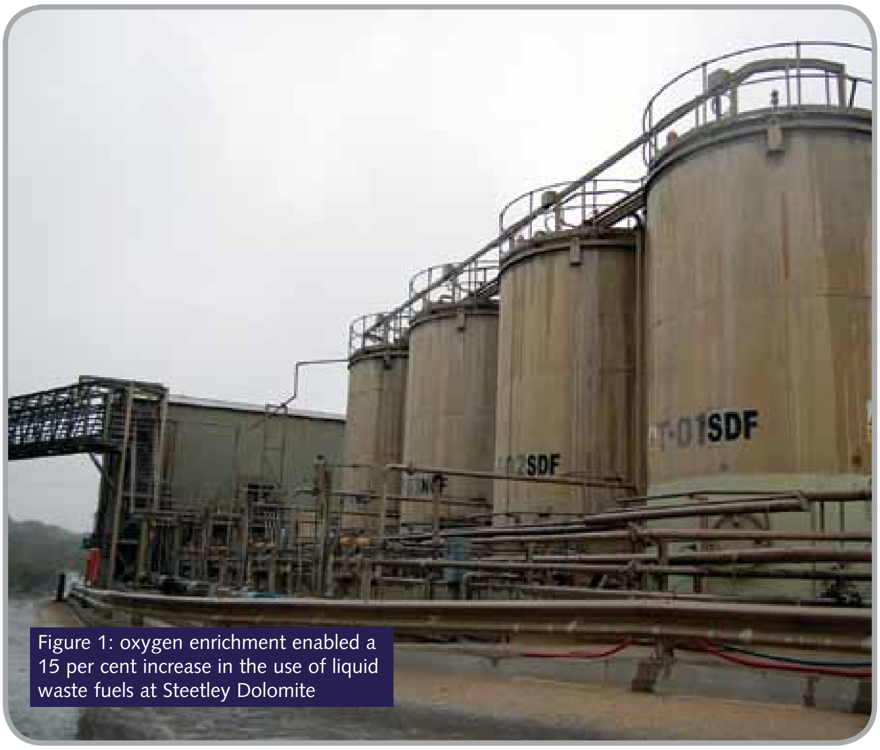

Figure 1: oxygen enrichment enabled a 15 per cent increase in the use of liquid waste fuels at Steetley Dolomite

The economics of oxygen-enhanced combustion are typically site specific and quantifying benefits requires a detailed understanding of operating conditions, cost stack and plant constraints. Additionally, the variety of fuels available today and their impact on pyroprocesses further complicates the matter. Through Air Products' experience with many different plants and fuel mixes, the company has been able to develop an economic model for comparing operating scenarios and optimising benefits when employing oxygen. Air Products employed this model to analyse and project the financial impact of oxygen-enhanced combustion for several cement plant operating scenarios routinely encountered. The analyses do not address capital equipment options since there are many different choices available and it is difficult to compare the actual performance of each technology. Furthermore, many other considerations impact equipment upgrade decisions, which are outside of the scope of this study.

Economic model

The economic model Air Products developed calculates the financial benefit of varying substitution rates of different fuel types with the option of oxygen enrichment. The model performs a heat balance for the production line taking into consideration the qualities of each fuel and current kiln performance. Different substitution scenarios are evaluated, accounting for projected changes in thermal efficiencies and production rates. Oxygen enrichment is then evaluated to either enable greater substitution rates of alternative fuels or to improve production rates. The model can fully evaluate various operating options available and project which one provides the greatest calculated economic benefit. The model also has the capability of performing detailed sensitivity analyses around the key variables so that the impact of future changes in the cost of fuels or product value is understood.

There are many variables, both technical and financial, that are required to utilize the model and evaluate the economic benefits of oxygen-enhanced combustion. By improving combustion, oxygen enrichment has a positive impact on production rates, thermal efficiencies, product quality, emissions, etc. Therefore, the key inputs to the model include product value (clinker or lime), fuel costs (traditional - fossil fuels; alternative fuels – wastes and biofuels), thermal properties and efficiencies for each fuel, oxygen costs, and oxygen impact on efficiencies and production rates.

In some regions, there is the added economic driver of emission credits (carbon or CO_2) that can be realized through additional alternative fuel substitution or improved thermal efficiencies via oxygen enrichment. While these credits can be significant, they were not included in these analyses due to regional variances and the wide range of carbon equivalencies applied to various alternative fuels. The model can easily incorporate the value of emission credits when they are applicable.

Base case

To perform the analyses Air Products started with the baseline production scenario of a 1.2Mta cement plant firing coal with the option of adding alternative fuels. For the purpose of the comparisons, it is assumed that clinker quality, emissions, feed conditions, etc are held within normal operating limits. Baseline operating parameters are provided in Table 1.

Incremental production

One of the earliest reasons for employing oxygen in a cement or lime kiln was to increase production, especially when the production line was fan limited. By adding oxygen, a fan-limited line could add supplemental fuel and increase production without the burden of the added volume of air (mostly nitrogen). Prior to the late 1990s, the use of oxygen was usually not economical as lime and cement prices were too low to support its added cost. Through the years, lime and cement prices rose while the cost of oxygen decreased due to advances in air separation technology. Additionally, more efficient oxygen injection techniques were developed, helping improve oxygen utilisation and further reducing its cost. As a result, oxygen enrichment became viable at pulp and paper mills (captive lime kilns), commercial lime plants and cement plants during periods of robust market conditions. While current market conditions have lessened this demand in many regions, it is valuable to understand the factors that impact the economics of incremental production gain through oxygen enrichment and under what conditions it is economically feasible.

Incremental production gain results

When evaluating incremental production gain through oxygen enrichment, it is important to note that the economics to support this gain are not burdened with a plant's fixed costs since there is relatively little capital expenditure required for an oxygen enrichment system (see panel). The primary costs for this incremental production are the oxygen, additional fuel, and additional feed. The oxygen cost is a function of its unit price and usage rate. Aside from enabling a production gain, oxygen also helps lower the specific fuel consumption due to improved combustion efficiencies and the fact that many of the thermal losses inherent to baseline operation are not affected by the incremental gain. So as production increases, the thermal energy per tonne of clinker produced generally decreases.

Air Products analysed a targeted production increase of eight per cent (~100,000tpa of clinker) for the baseline operation. From experience with many production lines, Air Products assumed an average oxygen utilisation ratio and specific energy reduction to arrive at annual oxygen and fuel costs. On average, a specific energy reduction of 3.7 per cent was observed for this increased level of production with oxygen enrichment. For the base case as defined, the net gain for the cement plant is US$1.1m/yr (see Table 2, next page).

A sensitivity analysis was performed with the key drivers being clinker value, oxygen cost and the clinker/oxygen ratio. The economics are favourable with current market pricing as long as the incremental clinker tonnes/oxygen tonnes ratio remains above three. The location and design of the oxygen injector are important as they impact oxygen efficiency and the clinker/oxygen ratio.

Alternative fuels

Alternative fuel utilisation continues to increase as lime and cement producers seek to lower operating costs. Alternative fuels are more difficult to combust than traditional fuels due to variations in chemical and physical properties along with higher moisture contents. This negatively impacts temperature profile, air requirement, residence times, kiln stability, etc. which combine to cause the production line to function at a reduced capacity and thermal efficiency. Oxygen can be employed to help regain lost production and/or increase substitution levels that are limited by operating constraints.

For the analyses, Air Products aggregated the alternative fuels into a single fuel with an average cost of US$20/t and calorific value of 3600kcal/kg. These values are within the range associated with various sources of refuse derived fuels (RDF) and some liquid waste fuels. In many instances, there are several different alternative fuels to consider, however plants tend to focus on maximising the substitution of the least expensive fuels which are of the type Air Products has incorporated into its evaluations.

Kiln de-rate

When substituting lower quality fuels for coal, there is generally a corresponding de-rate in clinker production. While production de-rates are recognised, they are difficult to predict and quantify prior to implementing the new fuels since there are many variables that impact operating conditions.

For the purpose of analysis, Air Products applied a one per cent de-rate for every 10 per cent of thermal energy supplied by the alternative fuel specified. For example, at a 25 per cent substitution rate, clinker production was estimated to be 2.5 per cent less than baseline operation. This probably under-predicts the impact at high substitution levels, but provides a reasonable estimate for the purpose of the calculations. In depressed market conditions, kiln de-rates are not a critical issue as lowering operating costs becomes the primary focus.

Reduced thermal efficiencies

Due to higher moisture contents and increased air requirements, thermal efficiency is lower when incorporating many commonly-used alternative fuels. While alternative fuel substitution enables a reduction in traditional fuels, it is generally not on a one-for-one basis due to the reduction in efficiency. To account for this in the analysis, Air Products applied a formula to determine the efficiency penalty compared to coal firing, based on substitution levels and differences in heating values. This is a simplified method for illustrative purposes. A more rigorous approach based on fuel composition is recommended for a more precise evaluation.

Alternative fuel results

When considering the use of oxygen to assist with the combustion of alternative fuels, Air Products analysed two separate scenarios. In the first case, the oxygen was employed to 'recover' the clinker de-rate as a result of alternative fuel substitution

Table 1: baseline operation

Variable	*Baseline*	*Cost/Value/t*
Avg. clinker production (tph)	151.6	US$50
Heat requirement (kcal/t clinker)	730,000	
Primary fuel – coal (kcal/kg)	6400	US$100
Operating days/year	330	

Oxygen supply system and installation requirements

Oxygen is routinely delivered via tanker truck in liquid form to the customer site. The tanker off-loads liquid oxygen into specially-designed storage tanks (see Figure 2). When oxygen is required for the process, liquid oxygen passes through ambient air vaporisers where the liquid is converted to a gas. A pressure regulator controls houseline pressure as the gaseous oxygen exits the vaporisers and enters the piping run upstream of the flow control system. Based on input from the kiln operator, the oxygen flow control system monitors and regulates the flow of oxygen to the production line and is interlocked with the kiln safety protocol.

To implement oxygen, a lime or cement plant needs to provide a site for tank location and run houseline piping from the storage area to the use point. Additionally, electrical connections to the oxygen flow controls must be provided. The supply system is owned and maintained by the industrial gas supplier. Overall, oxygen system installation costs are low and afford lime and cement producers the ability to trial the effectiveness of oxygen enrichment without significant capital risk. Payback periods are typically less than one year and quite often, less than six months.

levels of 25, 35 and 50 per cent. For each of these scenarios, oxygen requirement was based on the additional clinker required to make up the shortfall. In each case, implementing oxygen to avoid de-rates while at the same substitution level provided over twice the benefit of increased substitution with the de-rate penalty when using no oxygen. These results are summarised in Table 3.

Recognising that some level of kiln de-rate may be acceptable, depending on market conditions, further analysis was carried out for the case of increasing substitution of alternative fuels while maintaining the 'de-rated' production level. Based on recent experience under similar conditions, Air Products was able to project oxygen demand for increased fuel substitution at existing production rates. As can be seen from the results summarised in Table 4, similar levels of savings are achieved by maximising substitution with oxygen enrichment.

Additional analyses were run to determine which variables have the greatest impact on net annual benefit.

Table 2: incremental production increase

Case	*Production (Mta)*	*Spec. E (kcal/t clinker)*	*Fuel cost (US$m/yr)*	*Additonal material costs (US$m/yr)*	*Additional clinker value (US$m/yr)*	*Benefit (US$m/yr)*
Base	1.2	730,000	13.7	–	–	–
8% production gain w/ oxygen	1.3	703,000	14.2	3.2	4.8	1.1

Additional material costs include additional feed and oxygen

Table 3: recovered clinker de-rate at same substitution level

	Production (Mta)	*Spec. E (kcal/t clinker)*	*Fuel cost (US$m/yr)*	*Oxygen costs (US$m/yr)*	*Clinker value (US$m/yr)*	*Net benefit (US$m/yr)*
Base	1.2	730,000	13.7	–	–	–
25% Alt. fuels w/ 2.5% de-rate	1.17	770,000	11.8	–	1.3	0.6
25% Alt. fuels w/ oxygen	1.2	715,000	11.3	0.8	–	1.6
35% Alt. fuels w/ 3.5% de-rate	1.16	787,000	11.0	–	1.8	0.9
35% Alt. fuels w/ oxygen	1.2	720,000	10.5	1.1	–	2.1
50% Alt. fuels w/ 5.0% de-rate	1.14	814,000	9.8	–	2.5	1.4
50% Alt. fuels w/ oxygen	1.2	727,000	9.3	1.5	–	2.9

Lost clinker value is on a net basis accounting for avoided cost of associated incremental feed

Table 4: clinker de-rate w/ increased substitution level

	Production (Mta)	Spec. E (kcal/t clinker)	Fuel cost (US$m/yr)	Oxygen costs (US$m/yr)	Clinker value (US$m/yr)	Net benefit (US$m/yr)
Base	1.2	730,000	13.7	–	–	–
25% Alt. fuels w/ 2.5% de-rate	1.17	770,000	11.8	–	1.3	0.6
36% Alt. fuels w/ oxygen, 2.5% de-rate	1.17	727,000	9.9	0.9	1.3	1.6
35% Alt. fuels w/ 3.5% de-rate	1.16	787,000	11.0	–	1.8	0.9
51% Alt. fuels w/ oxygen, 3.5% de-rate	1.16	737,000	8.6	1.3	1.8	2.0
50% Alt. fuels w/ 5.0% de-rate	1.14	814,000	9.8	–	2.5	1.4
74% Alt. fuels w/ oxygen, 5.0% de-rate	1.14	752,000	6.7	1.8	2.5	2.7

Lost clinker value is on a net basis accounting for avoided cost of associated incremental feed

For the 35 per cent substitution case, the differential in price between coal and alternative fuels had substantial impact on the calculated benefits. Every US$10/t increment in coal cost affected the annual benefit by US$0.5m. Every US$10/t increment in alternative fuel cost exhibited an even greater impact, roughly US$0.9m in annual benefit. This is due to the difference in heating values between the two fuels as a greater volume of alternative fuels is required to replace coal on an equivalent energy basis.

Air Products also looked at the impact of the alternative fuels' heating value but concluded that heating value is unlikely to affect substitution economics since alternative fuels' cost are often directly related to their heating value. A fuel's heating value tends to drive demand and subsequently price. If this is not the case for a specific fuel, a new analysis would be warranted. Compared to the reference alternative fuel, an independent increase in heating value would improve on the economics presented.

Summary

These scenarios all represent operating conditions that warrant investigation of oxygen enrichment. Oxygen can provide strong economic incentive to help plants maximise alternative fuel substitution rates by providing up to twice the annual benefit of substitution alone. This relationship holds for the cases studied and the actual benefits will shift depending on clinker valuation, fuel cost differential and oxygen efficiency.

This model enables Air Products to determine which operating option is most economical for specific production and market conditions.

It should be noted that alternative fuel substitution economics is further enhanced when carbon emission credits are applicable. With minimal capital investment, cement plants can implement oxygen enrichment on an as-needed basis to either reduce operating cost through greater substitution of alternative fuels and/or to achieve production targets that are otherwise constrained by combustion limitations.

Figure 2: oxygen tanker delivering liquid oxygen into storage tanks. Ambient air vaporisers are adjacent to the storage tanks