Jan 8/98.

Jose,

I hope the attached is what your looking for. Please call if you need any further information.

Regards,

Rick

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Low NO_x clinker production

C.G. Manias, Adelaide Brighton Management Ltd
and Dr G.J. Nathan, Adelaide University.

REPRINTED FROM WORLD CEMENT MAY 1994

Low NO$_X$ clinker production

C.G. Manias, Adelaide Brighton Management Ltd and Dr G.J. Nathan, Adelaide University.

General background

Swan Portland Cement Ltd was established in 1927 and began producing cement for sale soon after. It is located at Rivervale, an inner city residential and tourist suburb of Perth, Western Australia and is therefore conscious of strict environmental performance requirements inherent with such a location.

The plant currently operates two wet process rotary kilns with satellite coolers for clinker production, and a third rotary kiln producing quicklime from dry chip feed. The kilns began operation in the 1950s and therefore belong to a previous generation of technology. Kiln 3, the 2.9 m dia. x 77 m wet process test kiln, is fuelled by natural gas, has an output of 10 tph, and utilizes a planetary cooler. Fuel consumption is 7.7 MJ/kg of clinker, and No$_x$ levels at 10% O$_2$ are 450 ppm.

All kilns currently use natural gas fuel, although coal has been used in the past. The kiln burners were replaced in the early 1980s with sophisticated UK designed gas burners. These burners included an axial gas channel, a swirl gas channel and low volumes of high pressure primary air. At the time, these burners were responsible for a marked improvement in kiln operation, refractory life and clinker quality from the Swan Portland Cement gas-fired kilns.

A decision was taken in 1993 to trial a prototype of a new burner design developed in Adelaide, South Australia, with expectations of production efficiency improvements and reduced NO$_x$ emissions, based on the results of earlier trials on a cement plant at Angaston in South Australia.

Gyro-Therm burners

The Gyro-Therm gas burners have been developed over the last two years for rotary kiln use by a joint programme between Adelaide Brighton Management Ltd and Adelaide University. They are based on the new and innovative precessing jet technology invented and patented by Adelaide University researchers. The early development history, results from initial plant trials designed to demonstrate the practical application of the concept, and description of the precessing jet principle have been given in an earlier *World Cement* publication[12].

The precessing jet provides a unique way for mixing natural gas fuel into a surrounding air stream by utilising a gyratory motion of a fluid jet induced by a particular nozzle design, rather than relying solely on jet momentum of the gas or air jets to diffuse the gas fuel into the air stream through turbulence created at the boundary of the two jets. The advantages achieved have been considerable when applied to gas-fired rotary kilns in the cement industry. In particular, the results have shown:

- Rapid large scale mixing of fuel and secondary air giving early heat release at the front of the kiln. This improves heat flux profiles for clinker quality.
- An engulfment of air pockets within the gas envelope, thus giving combustion under fuel rich conditions. This creates soot internally in the flame making it highly luminous for good radiant heat transfer and also suppresses thermal NO$_x$ formation.
- An extremely stable flame burning close to the nozzle over a wide turndown ratio.

These attributes have in practice led to fuel savings, production increases, improved clinker quality and NO$_x$ reductions of 50% or more. This is achieved with a fairly simple gas nozzle arrangement of robust construction and requiring no primary air whatsoever.

Following the development work at Adelaide Brighton Cement's Angaston works, a prototype burner was designed and built which included a co-annular gas jet around the precessing gas nozzle. The flame shape and heat flux profile can be adjusted by varying the proportion of gas passing through the two channels. When all the gas fuel is passed through the precessing gas jet nozzle, the gas air mixing is very rapid, producing a short heat release zone near the discharge end of the kiln. This would require a major readjustment of refractory lining in the kiln to conform with the new heat flux profiles. The co-annular flow around the precessing jet serves to modify the heat flux profile by extending the heat release further down the kiln. An increase in the co-annular flow causes an increase in the length of the kiln burning zone, so that an optimum burning zone length can be established for a given situation. This versatility is an important attribute during commissioning, allowing some adjustment to suit the particular circumstances of a specific kiln. It allows the refractory to be re-adjusted over a normal life span to an optimum design, in line with operating experience using Gyro-Therm on a particular kiln. It is anticipated that some co-annular flow will always be required with the Gyro-Therm burners, as the precessing gas jet nozzle by itself produces a flame which is probably too short for stable kiln operation. However, best fuel efficiency and clinker product quality will result from as short a flame as possible with stable operation, so that each kiln's operation can be adjusted in this direction with Gyro-Therm to achieve the optimum result. The construction of the Gyro-Therm burner is shown in Figure 1.

Gyro-Therm prototype installation

The Gyro-Therm prototype was installed in kiln 3 at Swan Portland Cement in August 1993. The kiln was brought back on line with no abnormal occurrences. The thick full-bodied bulbous nature of the flame's appearance (Figure 2) was a stark contrast to the longer, slimmer and transparent nature of the previous burner flame, but the kiln operators

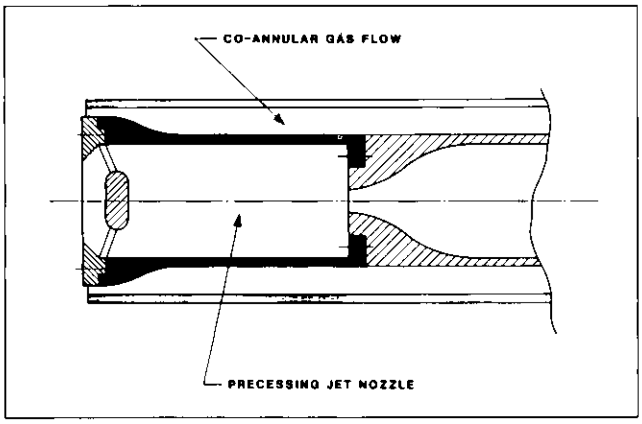

Figure 1. Diagram of Gyro-Therm burner configuration, showing the central precessing jet nozzle and the co-annular gas channel for adjustment of flame shape and heat flux profiles in the kiln.

Figure 2. Gyro-Therm gas flame operating in kiln 3 at Swan Portland Cement.

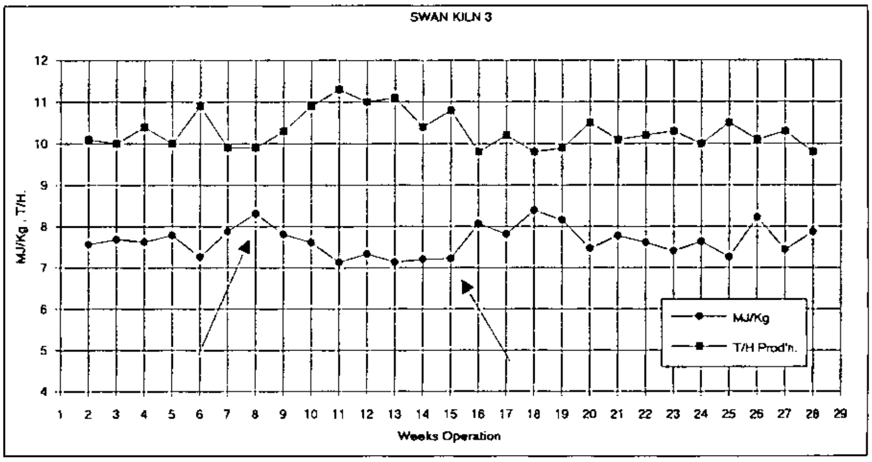

Figure 3. Kiln outputs and fuel consumptions for kiln 3 at Swan Portland Cement covering the period of operation with the Gyro-Therm prototype kiln burner. The Gyro-Therm was installed at week 8 and removed at week 16.

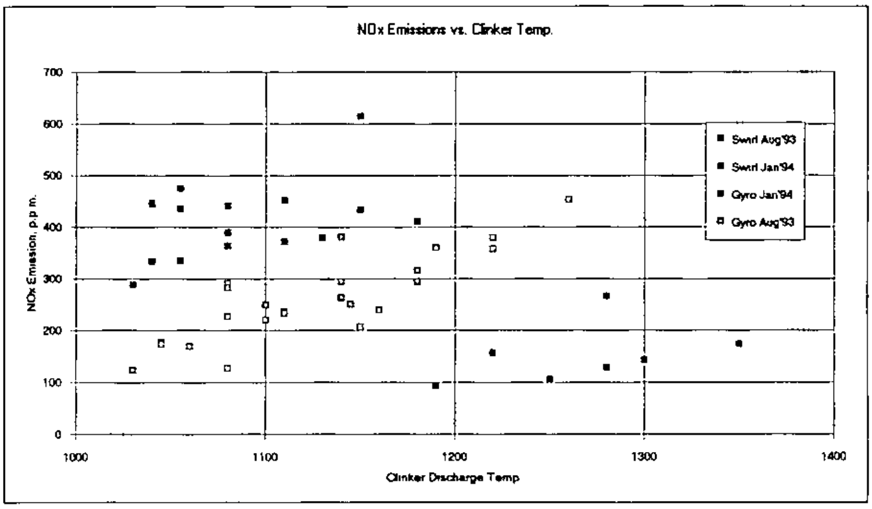

Figure 4. NO$_x$ emissions from kiln 3 at Swan Portland Cement covering the period of operation with the Gyro-Therm prototype and the commercial burner later supplied.

had little difficulty in adjusting to the new look. Kiln operation was very steady with uniform free-lime in the clinker.

Kiln operation was stabilised and optimized over the next week, with an eventual setting on the burner to give 80% of gas flow through the precessing jet nozzle and 20% through the co-annular channel. This prototype burner was operated for several months, during which time data was collected on fuel consumption, production outputs, and NO$_x$ emissions. Eventually, however, the mild steel construction of the prototype burner suffered heat damage, as had been expected, and the original kiln burner was reinstalled.

Orders were soon placed for three kiln burners to replace the existing burners on all of the Swan Portland Cement kilns, on the strength of the excellent results achieved with the prototype. The first of the new burners was installed in late January this year, and performance evaluation was still in progress at the time of writing, however, indications show that the performance of the prototype is at least being met.

Kiln outputs/fuel consumption

Figure 3 is a plot of the average weekly fuel consumption and average weekly outputs for the trial kiln at Swan Portland Cement taken from the normal plant records.

The prototype burner was installed in week 8 of the monitored period, with several weeks afterward spent on adjustments and optimization of the burner itself, while kiln operation was in the normal control of the kiln operators. Firstly, there was a clear downward trend in fuel consumption during the period of the prototype installation, as was anticipated to occur as a result of more effective heat transfer from the flame to the kiln charge. The average fuel saving over the period of Gyro-Therm operation was 5% in comparison to average fuel usage in the months preceding the trial, and in the months following the trial when the original burner was reinstated.

In the same period, kiln average hourly outputs increased by almost 10% compared to the outputs which could be achieved using the original burner. This was due to a combination of better heat efficiency and also the ability of the kiln to burn more fuel with Gyro-Therm without losing operational stability. A further benefit to production was the reduced dust loss from the back of the kiln during the trial period. This was presumed due to the lower back-end temperatures achieved, and hence maintaining of moist slurry further down in the chain section. The increased production was a major boost to Works' economics, given the demand for cement from the Rivervale works.

NO$_x$ emissions

The Swan Portland Cement kilns operate with low efficiency satellite clinker coolers, with secondary air temperatures estimated to be only around 300°C. Consequently, NO$_x$ emissions are lower than what may be expected from a gas-fired wet process clinker kiln.

A good correlation seemed to exist between NO$_x$ levels, as measured at the back-end of the kiln, and clinker discharge temperature from the kiln. Figure 4 shows this correlation for the original Swan Portland Cement burner, with readings taken over two periods of time before and after the prototype Gyro-Therm was installed. The correlation is also shown for the prototype burner, with NO_x levels reduced to approximately 50% of those with the original burner for a given nose ring clinker temperature. A further set of data shows the NOx levels achieved with the final burner design installed in January 1994. For a given nose ring clinker temperature, this shows a spectacular reduction in NO_x emission to approximately 25% of the original level. This kiln is now producing good quality clinker of normal free-lime content, with NO_x levels of 100 - 200 ppm on a 10% oxygen basis. It should also be mentioned at this point that carbon monoxide levels are also maintained at levels typically below 100 ppm with the Gyro-Therm burner. This kiln is operating with what is probably the lowest NO_x levels of any rotary cement kiln anywhere in the world.

Product quality

Clinker quality evaluation to date has been confined to microscopic examination using both the Ono method of 28 day strength prediction and polished section microscopy. This work is continuing, but the results to date show a reduction in alite size to around 30μm with clear reactive crystals having clean well-defined edges (Figures 6 & 7). The Ono evaluation shows a strength improvement of perhaps 5%, but requires further investigation to increase confidence in the results, as the clinker samples show considerable variability due to poor homogenisation of kiln feed. An important observation is that there is no indication of reducing conditions in the clinker produced. Ground cement strengths are not readily interpreted yet, as it is difficult for Swan Portland Cement to isolate clinker from one kiln, and clinker from other sources is also used to supplement the plants production in order to meet its demand.

Figure 5. Commercial Gyro-Therm burner prior to installation.

Refractory life

Evaluation of kiln refractory life can only be established over the longer term, but the kiln has formed a good stable coating throughout the burning zone. Kiln shell temperatures are consistent and generally lower in the burning zone area as a result of the coating, despite the greater concentration of heat load over a shorter distance. It is anticipated that refractory life will improve as a result.

Conclusion

The first installation of a Gyro-Therm kiln burner of commercial design has produced a marked improvement in production efficiency on kiln 3 at Swan Portland Cement, as well as a spectacular reduction in NO_x emissions. Other factors, such as refractory life and cement strengths are still to be properly evaluated, but the indications are that the results will be positive.

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Figure 6. Polished section of clinker produced with the original burner on kiln 3 at 500x magnification. Alite crystal size of up to 90 μm can be seen throughout the sample, indicating a long burning zone section.

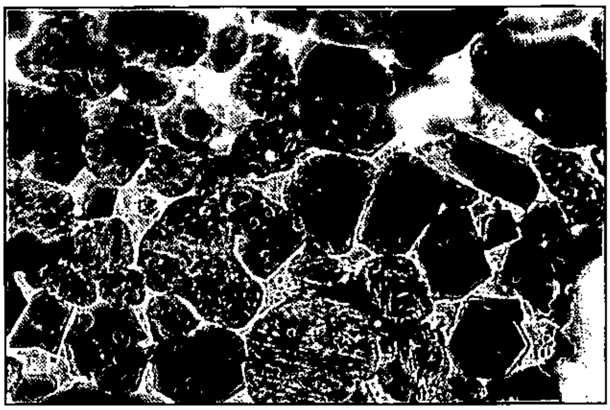

Figure 7. Polished section of clinker at 500x magnification produced with the Gyro-Therm kiln burner in operation on kiln 3. Alite crystal size and shape appear considerably improved.

Burning Issues
FCT
Vol. 1, Edition 6
June 1998
Fuel and Combustion Technology

CONTENTS

'*Burning Issues*' will interest all persons involved in the process industries. Our aim is to provide well informed comment, news of innovations in technology and interesting related articles.

Similar news for publication will be greatly appreciated by the Editor, Mary Ann Robinson - who has moved to a new address. For editorial content, please contact at:

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'Take time to think':

A Thing is complete when you can let it be - Gita Bellin

Cheers for now - Editor, MA

Adelaide Brighton Cement signs FCT Partnering document

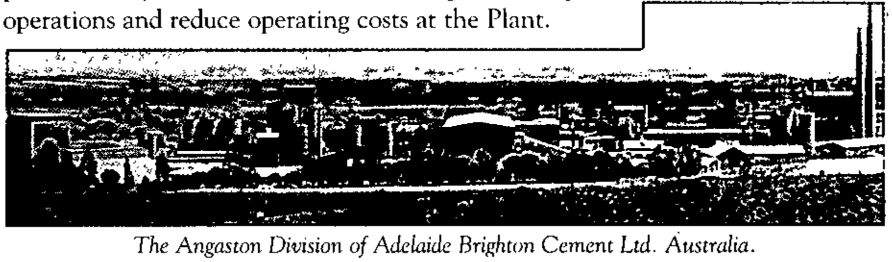
***Dr Dilip Manuel,* FCT Corporate Team Leader for the Agreement - reports:**

Adelaide Brighton Cement is first in Australia to sign with FCT, a ***"General Understanding in Partnering"*** **document.** The formal partnering agreement has been established for the Angaston Works and is set to provide a breakthrough in operational cost savings.

Adelaide Brighton is the largest and most modern manufacturer of cement and lime in Australia. Origins go back to 1882 with the first production of cement at Brighton near Adelaide, South Australia. During 1940, suitable raw materials were not plentiful in the area so an extensive deposit of marble at Angaston was purchased. Work then started on a new cement plant, the first kiln in 1952 producing 100,000 tonnes per year of Ordinary Portland Cement. Subsequent expansion of the Angaston works occurred; second and third kilns with further upgrades lifting production to exceed 300,000 tpy.

A change of direction for operations was heralded with the development of 'Brightonlite' a cement suitable for producing light coloured, architectural concrete. Wool Bay Lime production facilities were purchased by ABCL and in 1972, the smallest kiln at Angaston was converted to manufacture quicklime, with a lime hydrating plant built in 1973. Other technological advances were being made, including 'Austwell', a product suitable for the cementing of oilwell casings. General Purpose cement is no longer made at Angaston, and the plant is now a specialist cement and lime manufacturer.

FCT Engineering Team Leader, **David Retallack,** signed the Agreement with ***Bryan Gillis,*** **General Manager - Angaston Division** (photographed). David is confident that results from the partnering relationship should significantly reduce cost of plant operations. For example, with the current slump in gold prices, markets for lime have recently diminished, hence Angaston Works is keen to reduce operational costs of the lime plant, to increase their market share in Australia. A site survey on (Lime) Kiln 2 is currently in progress. Data collected will enable the Engineering Team to carry out a detailed process analysis and recommend strategies to improve operations and reduce operating costs at the Plant.



The Angaston Division of Adelaide Brighton Cement Ltd. Australia.

SOUTH EAST ASIA

sees first FCT partnering agreement

Dr Dilip Mauel - FCT Corporate Team Leader, Unichamp reports:

UNICHAMP MINERAL SDN. BHD, ***has recently signed a partnering agreement*** **with FCT.**

Established just 6 years ago in 1992, **Unichamp is now the largest producer of quicklime in Malaysia.** Their plant in Kemaman, Terengganu, employs ultramodern processing machinery and is the only company in Malaysia producing milk of lime. Hydrated lime as well as limestone powder are also produced at the fully automated, computerised and integrated plant.

Introductions were made in March last year, when FCT was invited by the management of Unichamp, to advise technicalities on **the options of firing waste fuel in the lime kilns.** *Dr. Dilip* Manuel, FCT Corporate Team Leader for Unichamp, attended the Kuala Lumpur offices and met Technical Manager Mr *Leong Nam Yang* for the discussions.

Unichamp currently produces its lime in a Cimprogetti, double shaft vertical kiln, fired by natural gas. The local supplier, Gas Malaysia, is paid in US$, however, recent crisis events in Asia have created 30% relative depreciation of the Malaysian Ringatte currency. Accordingly, fuel costs on the plant have increased considerably- **hence the requirement by Unichamp to seek alternative fuels.**

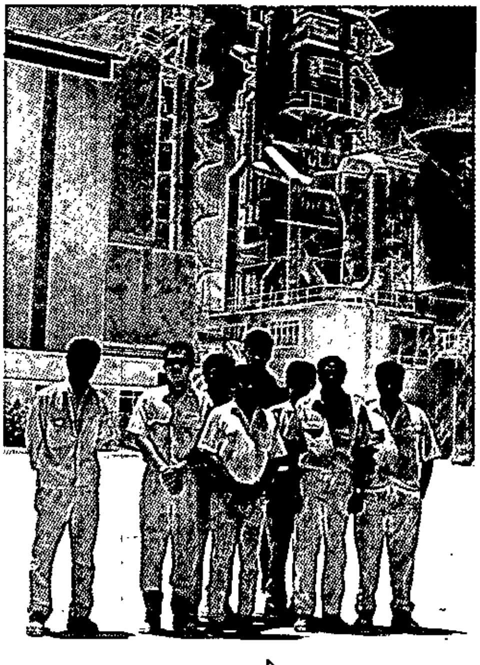
During the recent site survey, partly carried out at evenings, personnel who assisted were *understandably alarmed, when a python of considerable length and girth* **(gad, another version of 'The Full Monty')** *was found keeping warm in the same vicinity near the kiln, a short time after their data gathering activities!*

Photographed, calm after the event are: *(l to r, front row)* Ahmad Nazri Bin Othman and Say Kwee Jin, both of Unichamp, with Dilip Manuel and Aloysius Balendra (Engineering Team Leader, FCT).

Han Tong Juan of Unichamp keeps his hands safely in pockets. Plant Manager, Lim Gaut Beng and Kumar Velugopal are behind, with David Retallack of FCT between them.

In Top Gear *'Downunder'*

Dr Peter Mullinger, **Deputy Chairman and co-founder of FCT** has re-located to Adelaide office for a period of two years. Apart from his role at monthly Board Meetings, **Peter's new purpose is to transfer his experience and that of the Company, to new engineers joining us.** The 'user-friendly' and keyworded information will facilitate our expansion and meet Partnering needs. This extensive task is being achieved by a combination of formal training, mentoring, and working with Mary Ann to prepare a series of Project Profiles, making our 500 or so past projects, electronically accessible.



Email Semaphore

The article included last edition titled ***"Environmental Issues Threaten Low Cost Fuels",*** evoked strong comment from **Richard Boarder of Castle Cement.**

Richard was disappointed that we could *'peddle innuendoes, half truths and untruths and publish the article without views from the cement industry.'* He continues - *'The New Scientist Article was clearly written to be controversial and is not worthy of being repeated.'* And that yours truly *'ought to have more sense than try to give the impression the cement industry did not know or tried to hide the calcination* CO_2*.'*

Richard has not heard of Nick Syred, nor read his paper, but disputes as nonsense the increase in heavy metal deposition mentioned - He explains further, *'heavy metal emissions are divided between volatile and refractory metals. Refractory metals in the fuel are locked in the cement products and volatile metals are excluded from the fuel. Metal emissions arise from the metal content of the raw meal and as such are highly dependent on the dust arrestment efficiency. There is ample evidence the cement industry has been reducing dust emissions and consequently metal emissions.*

Environmental Agencies protocol for BPEO assessment of Castle Cement demonstrated insignificant emissions.'

Richard suggests that Nick Syred has been misquoted or used the wrong data and takes umbrage at the indications of land adjacent to cement plants being unsuitable for agriculture. He concluded, *'the judicial review of the Environmental Agency was thrown out by the High Court'* further suggesting we *'ignored the fact that good quality bituminous coal has a higher carbon content per unit of energy than Cemfuel.'*

Thanks Richard for your input, however, in reply to the query on integrity of the article, a distinguished professor's paper, presented at an international conference would normally be considered well informed. Our intention was for the article to raise awareness in the industry - ***it seems we succeeded!***

- Editor, MA

The Environment

"Action for a Sustainable Future" ©

NOx Emissions from Rotary Kilns

Low level ozone, is a respiratory irritant and the role of oxides of nitrogen (NOx) in its formation, is well documented. Motor vehicles have a major role in the production of these pollutants; despite this fact, environmental enforcement agencies continue to focus on reducing NOx from industrial sources - ***probably because they are easy to track down, don't move and can't vote!***

Unfortunately rotary kilns are also major producers of NOx, (fuel and thermal). Fuel NOx originates from nitrogen in the fuel, and from fixing atmospheric nitrogen by the flame - producing Thermal NOx: formed by the combination of both oxygen and nitrogen radicals, with molecular nitrogen at very high temperatures. Thermal NOx is extremely temperature dependent because the reaction has high activation energy.

Apart from temperature, the final thermal NOx emissions are influenced by the in-flame oxygen concentration and residence time in the high temperature zones.

Most fuels, other than gas, contain nitrogen bound as an organic compound in the structure. When the fuel is burnt, this organic nitrogen converts to a range of cyanide and amine species that are subsequently oxidised to NOx, depending on available local oxygen. Fuel NOx formation is less dependent on temperature than thermal NOx.

Owing to the very high temperatures which occur in rotary kilns, especially cement kilns i.e. above 2000°C (3600°F), thermal NOx is generally the dominant pollutant, but fuel nitrogen makes a substantial contribution to the NOx emissions from coal, oil and petroleum coke firing. In gas fired plant, fuel NOx is absent so all the NOx is thermal. However, **it should be noted** *that the absence of fuel NOx in gas fired kilns does not necessarily lead to a reduction in NOx emissions, since flame temperatures are often higher.*

Kiln operators will come under increasing pressure to reduce NOx emissions. Unfortunately most techniques involve reducing fuel/air mixing rates to reduce oxygen concentration in the flame and hence reduce flame temperatures. Whilst this is effective in reducing NOx, the lower temperature also reduces the heat transfer rates and has a potentially adverse effect on both product quality and output.

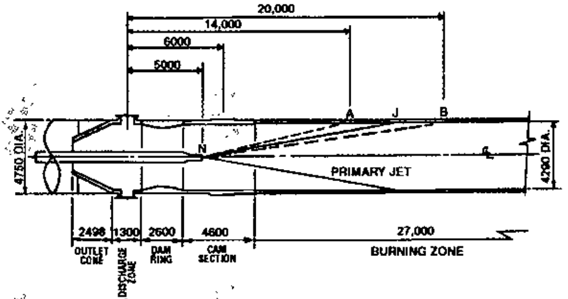
Some of the NOx limits currently being considered by the enforcement authorities **cannot be met by combustion modifications** but will, if passed into law, ***require post process emission control equipment.***

Next edition: NOx reduction techniques.

Technical Tips

Burner Alignment

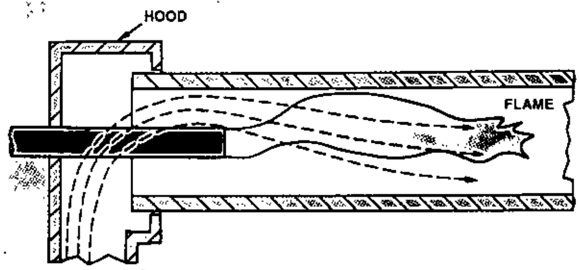
Burner alignment is critically important in rotary kilns, but unfortunately there is no common position suitable for all types of kilns - *optimum location depends on secondary air flow patterns.* The general principle is, that the burner nozzle should be located in the centre of the secondary air stream, enabling the air to be entrained evenly into the fuel and primary air jet. In modern kilns with large hoods, this optimum position is generally on the kiln axis, forward of any dam.



Flame Impingement on Refractory in the Absence of Recirculation.

Note: Dams increase the secondary air velocity, and in doing so, reduce fuel/air mixing rates, lengthening the flame and reducing peak heat transfer. Therefore, if a dam is installed to increase bed depth, it should be as shallow as possible to minimise any adverse effects on the combustion and heat transfer.

Older kilns with small hoods, have poor secondary airflow pattens because the high velocity in the hood causes a downward deflection of the secondary air, often towards the charge owing to an offset cooler chute. In these circumstances, aligning the burner with the airflow involves pointing it towards the charge.



Flame Deflected by High Secondary Air Velocity in Narrow Kiln Hood.

Better fuel/air mixing and hence, **higher rates of heat release** which accompany this alignment, ***improves heat transfer for these older kilns.*** Previously it was commonly thought that direct flame contact with the charge gave the improved transfer of heat.

Aligning the burner towards the charge, in a kiln with good secondary air distribution, will cause it to perform poorly, compared with an axially aligned burner.

Science SCENE

Flame Structures - Order from Disorder

Dr. Peter Mullinger, reports on an enlightening paper presented at the McClaren Vale Workshop.

– *see last Burning Issues.*

When visiting plants, a question often asked of me is - ***"...what do you think of the flame?"*** Working with industrial flames for over thirty years, I have always found it very difficult to assess a flame visually. Expecting some 'pearls of wisdom', inevitably the questioner is disappointed.

Therefore, I was fascinated to meet ***Dr. Godfrey Mungal,*** Associate Professor at Stanford University in California, who has been looking at flames in a different way.

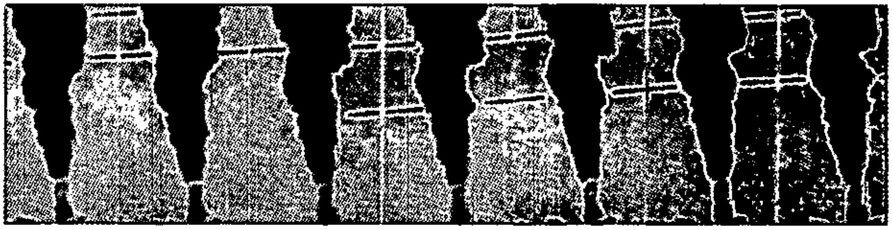
His revealing insight, excites me.
Most of the flames we use in industry, and all rotary kiln flames, are of the turbulent, jet diffusion type. Their structure has been discussed and researched for decades, and as might be expected, the subject is very complex. To date flames have largely defied effective mathematic modelling; requiring over-simplification of time averaged conditions, to produce any useable results.

Godfrey and his co-workers have taken a different approach.
Using various visualisation techniques, they have studied a wide range of jet flames, from the smallest laboratory flame, to those produced by large industrial burners, such as petrochemical flares and even huge rocket motors - see photos adjacent.

The research has revealed that -

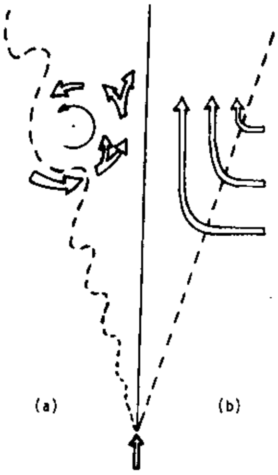
Far from being time averaged, turbulent jet flames have relatively organised structures, that originate close to the jet and persist throughout the flame. A diagrammatic comparison of the difference between the time averaged approach and Godfrey's approach, is shown below.

Top row: *A movie sequence of the flame and exhaust plume from a Titan IV rocket motor. The bright flame is approximately 400 ft (120m) with the overall plume 5000 ft (1500m) high.*



Bottom row: *Processed images showing the evolution of the structure.*

The structured approach (a) ***shows all the lumps and bumps we see so clearly, when we look at an industrial flame, and explains why the flame length fluctuates as we look at it*** - something that could not possibly happen, if it really was time averaged (b). Furthermore, ***the structured approach is compatible with burning pockets of reacting gases being shed from the flame end*** - which is seen both in real life flames, and on the acid alkali models used by FCT.



All this makes a great deal of sense to me and I shall never look at flames in the same way again. **I believe that Godfrey's work will lead to a complete reassessment of flame modlling,** which will become structure based in the near future.

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Kiln flame shape optimisation using a Gyro-Therm gas burner

David Rapson, Advanced Cement Technologies, Brian Stokes, Geelong Cement and Steven Hill, University of Adelaide, chart the ongoing development of a variable flame burner.

Introduction

Optimised combustion is crucial to the efficient operation of a rotary kiln process, particularly for cement manufacture, yet its ability to influence the performance of the whole plant is often under estimated.

The nature of the combustion in the kiln can have a pronounced effect on fuel efficiency, product quality, emissions (CO, SO_x and NO_x), refractory life, output, kiln and flame stability and plant safety. It therefore follows that a given kiln system will require an optimum flame shape and hence heat flux profile to achieve its optimum performance.

Often there is little scope on a kiln burner to adjust the flame significantly and usually there is little science on which to base any adjustment.

It is well documented[1] that cement clinker manufacture is best carried out with a short hot flame burning near the front of the kiln. The best clinker quality is produced when the raw meal experiences a rapid heat up to a high peak clinkering temperature for sufficient time followed by a rapid cooling to freeze the reactive calcium silicate crystal phases. Most microscopic analysis of clinker quality is based on an assessment of the heat flux profile through which the clinker has passed in the kiln. Grindability is also a function of the thermal history of the clinker. A short hot flame is also the most fuel efficient leading to lower back end temperatures, lower average shell temperatures and less over burning of kiln product. Savings can be substantial.

Emission of SO_x and NO_x can also be affected by the length of the burning zone. Each is time and temperature dependant, so the less time that the material and gases spend at high temperature the lower the SO_x and NO_x emissions respectively. If however, the burning zone is too short for a given kiln and its inherent process variability, then kiln stability and refractory life will suffer, leading to unsatisfactory operation. As a consequence, operators may tend to over burn in an effort to improve stability, the results of which can be very costly in terms of fuel efficiency, emissions, refractory life and product quality.

In order to gain the substantial benefits from a short flame, the objective should be to operate with as short a burning zone as possible while still maintaining operating stability. This would normally require a concerted effort to reduce the chemical and physical variability of process inputs, (i.e. feed composition, fuel rate, feed rate, dust return) and any other operationally induced variations which may influence stability. Along with this, a comprehensive operator training programme may be required to realise the full potential benefits and maximise the economic returns.

Given the requirement to optimise the flame in a kiln and knowing that the optimum will differ from one kiln to another, the ability of a burner to give genuine adjustment of flame shape and heat flux profile is a major benefit.

Physical modelling techniques using acid/alkali solutions are now employed in the design stages of a burner project. Accurate scale models of the kiln, cooler and depending on the configuration, the preheater are built for each burner application in order to examine the interaction between the aerodynamics of each system under differing conditions. With this knowledge and a burner with sufficient adjustment capability, flame optimisation is soundly based on scientific knowledge rather than trial and error.

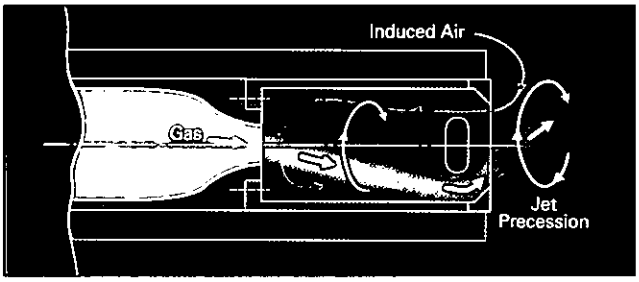

Figure 1. The precessing jet nozzle.

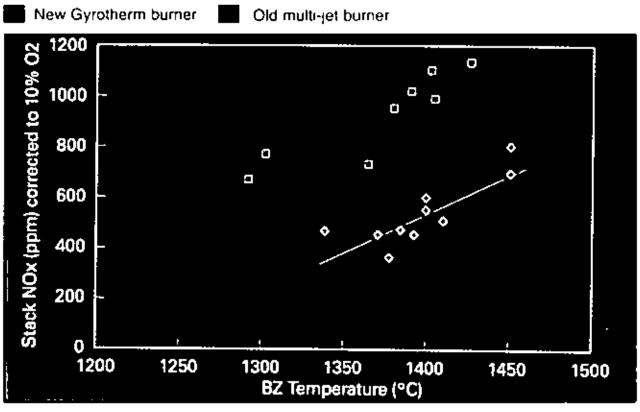

Figure 2. Geelong kiln no. 8: NO_x emissions.

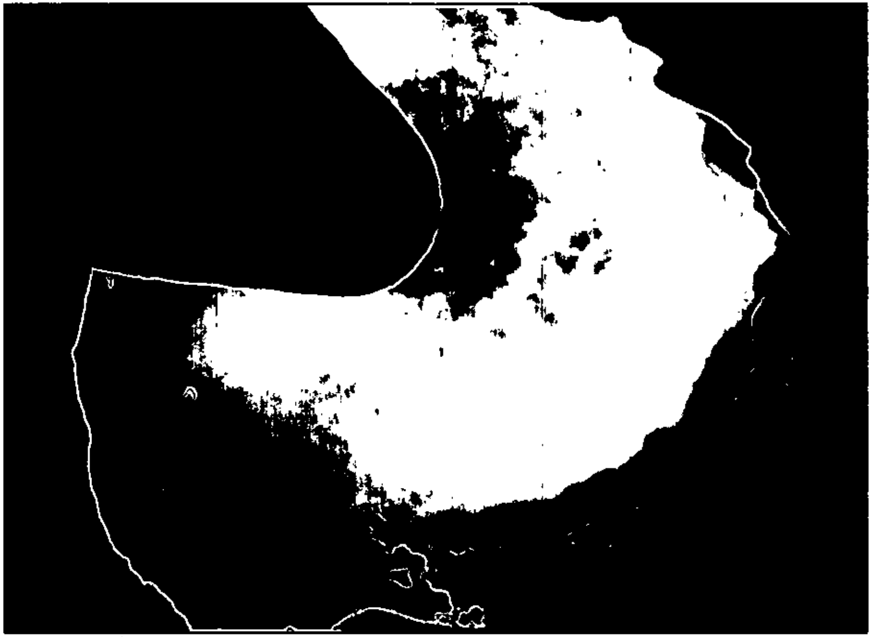

Figure 3c. Gyro-therm flame using centre body jet for flame shaping.

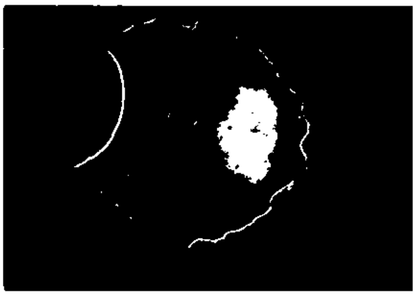

Figure 3a.

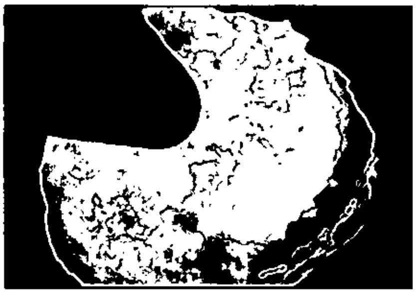

Figure 3b.

Technical background

Natural gas is a convenient fuel to use because it is easy to measure and handle. It does not lead to dust emissions and there are low capital costs associated with its use. However, with natural gas the typical flame produced in a kiln is long and poor in luminosity. This is the opposite of what is usually required for optimum efficiency, product quality and lowest emissions. Furthermore, the poor flame luminosity means that a kiln needs to be 'burnt harder' to achieve the same degree of heat transfer to the kiln charge as would result from a more luminous flame.

The Gyro-Therm burner was developed using the newly discovered and patented precessing jet technology to overcome many of the disadvantages of conventional natural gas flames. The unique mixing mechanism for the gas and secondary air produces a short, highly radiant (luminous) and bulbous flame without the need for any primary air. The flame produced is self-staging, with the majority of gas burned under fuel rich conditions. Soot is formed as a temporary intermediate product which burns out giving the flame its highly luminous character. The fuel-rich combustion mechanism also suppresses formation of NO_x, making the Gyro-Therm burner an extremely cost effective NO_x reduction technology. The development of this revolutionary gas burner, its theory of operation, operating experience and performance has been discussed previously in *World Cement*[2,3].

It became apparent during the development trials that the precessing jet flame was extremely short, even without primary air, and that unless kiln feed and operational variability were minimal, kiln stability would suffer. The burners were therefore developed with the ability to adjust flame length and heat flux profiles.

The initial design included a two channel gas burner, with the precessing jet central channel surrounded by a co-annular axial gas channel as shown in Figure 1. The precessing jet on its own produced an extremely short and broad flame, whereas the co-annular channel on its own produced a long narrow flame. A simple valve arrangement on the burner allowed the proportion of gas between the two channels (and hence flame shape and heat flux patterns) to be adjusted.

The Geelong Gyro-Therm

Geelong Cement is situated 100 km south west of Melbourne, Australia, close to its limestone deposit. The plant operates two wet process kilns which produce cement for the local market. The largest kiln is 4.65 m dia. x 171 m and produces 1,250 tpd of clinker. The kiln was operating with a multi-jet two channel gas burner of European supply, rated at 11 000 m^3/h of natural gas. The flame is shown in Figure 3a.

In June 1994, this burner was replaced with a Gyro-Therm burner of the original precessing jet design with a co-annular gas channel. It included a flame front ignition system, pilot burner and provision to burn waste liquid fuels. The driving force for the burner change was the very low NO_x limits imposed by environmental legislation. It was also expected that additional benefits would include improved fuel consumption, product quality, refractory life and kiln stability. Because the kiln's thermal loading was already excessive at 6.9 million kcal/hr/m^2 (being some 25% above normal), an increase in production was not recommended.

At this time, the techniques for modelling a kiln with a Gyro-Therm burner were still under development. The flame was so markedly different from that of a conventional gas flame in both appearance and performance, that new knowledge was required to validate the modelling.

For the same output, even without modelling, the immediate effects on kiln performance were:

- A reduction in the NO_x levels of around 40% (Figure 2).
- A reduction in the back end temperature of 20 - 30°C.
- A reduction in kiln dust losses of around 15%.
- A wide, bulbous and highly luminous flame filling most of the kiln's cross-sectional area and similar in appearance to an oil flame.

The evidence confirmed that expectations of reduced emissions and improved efficiency were being met with a Gyro-Therm burner. There were no start up or operational difficulties with the benefits continuing for the duration of the campaign while operators became accustomed to the look of the new flame and its heat flux patterns.

The following points are worthy of note during this early period:

- There was a high degree of over burning evident as plant operators became accustomed to the new burner and the very short burning zone.

- There was a loss of 45 mm from the hot face dolomite brick which spalled during the initial light up. This was due to impingement from a lazy flame at 10% of normal gas flow during the start up phase. This has since been rectified. Despite the spalling the initial three month refractory campaign was considerably longer than the previous seven campaigns. This comment must be considered in the context of the extremely high thermal load on the burning zone refractories and the sporadic experimentation with waste fuels (oil and tyres) over recent campaigns.

After this initial period some minor modifications were made to the Gyro-Therm burner in order to enhance performance during a planned tyre burning trial. However, during this trial brown centred clinker became evident, implying severe reducing conditions. Because this had not been noticed previously with the Gyro-Therm it was assumed that the tyres were responsible. However after the tyre burning trial was abandoned the clinker colour did not return to normal. The previous burner modification was reversed, even though this was not thought to be the cause of the problem.

Continued operation revealed that clinker colour was extremely sensitive to burning intensity. With softer burning, kiln operation and clinker colour remained satisfactory for a period until more light brown product was again produced but this time with a loss of cement strength. This problem was due to a significant increase in alkali content of the raw materials which caused kiln instability, harder burning and cement strength reductions.

It was decided that it would benefit kiln operation if the flame shape could be adjusted further. It became apparent that the high thermal load on this kiln had produced a problem not previously encountered. The amount of gas burned relative to the diameter of the kiln resulted in a much wider flame than previous Gyro-Therm installations. Consequently a small change in secondary air temperature and flow patterns caused flame impingement and reducing conditions in the clinker. The short burning zone caused the operators to burn harder to reduce the risk of a dust run, compounding these effects.

The requirement was therefore to produce a slightly longer heat flux profile to permit stable operation without the need to burn hard and a narrower flame to eliminate any likelihood of flame impingement on the clinker or refractories.

Flame shape control

Whilst the existing two channel design could provide adequate control over the heat flux profile it could not prevent flame impingement under some operating conditions.

Some timely new discoveries on the flame shape control of Gyro-Therm burners were made by researchers at the University of Adelaide. Flame control was achieved without the co-annular channel. The new technique for flame shape adjustment is based on a high momentum gas jet injected at a critical point into the precessing jet flow field. This jet (termed the centre body jet) is expelled through the centre body of the precessing jet nozzle, modifying the pressure fields within the vicinity of the burner in such a way that the flame is directed more toward the kiln axis. As the proportion of gas is increased through the centre body jet. the flame spread is reduced and the heat flux profile lengthened. Figure 4 shows a cross-section through the modified nozzle.

It was decided to modify the Geelong burner to include this latest innovation for flame shape control. Once again a simple valve adjustment provided a balance of gas flow between the channels allowing changes to the flame shape and the heat flux profile. This control has proven to be far more potent than previous techniques. The dramatic effects on flame shape can readily be seen in Figures 3b and 3c where the centre body gas jet is varied from 0 to 13%. This provides the means for adjusting the flame shape from very short and bulbous, to long and slender with matching heat flux profiles.

The success of the new flame shaping technique has been spectacular. There has been no more light brown clinker, a direct result of the reduced flame spread.

There is also a strong indication that kiln stability is much improved, which is allowing softer burning of clinker, due to the slightly longer heat flux profile produced. Should it become necessary to lengthen the heat flux profile further, this can easily be done during operation. It should be kept in mind that the shortest possible burning zone should always be targeted for best product quality and efficiency. As a result of softer burning, the NO_x emissions are in fact even lower than before the modification, with routine operation of this gas fired wet kiln now possible at around 600 ppm NO_x at the kiln exit.

It is also anticipated that improved refractory life and further reductions in fuel consumption will result from softer burning. The refractory coating has been a little thinner through the burning zone, but it is more stable and more evenly distributed. A propensity for ring formation in the upper transition zone, which was evident prior to the Gyro-Therm installation has reduced, whilst thicker coating is observed in the lower transition zone.

There is no doubt that NO_x levels have reduced by 40% and kiln efficiency has improved significantly. Other factors such as the continued sporadic use of supplementary fuels and the variability of raw materials have made the quantification of other benefits more difficult.

Conclusion

A Gyro-Therm burner installed at the Geelong Works has produced some very positive effects with huge reductions in NO_x emissions and with improved kiln efficiency. In this installation it was thought to be of further benefit if the flame spread could be reduced.

The existing means for controlling flame shape incorporated into the Gyro-Therm had worked well in all previous installations. However, in this case the flame spread had to be reduced more than normal because of the unusually high thermal load in the burning zone.

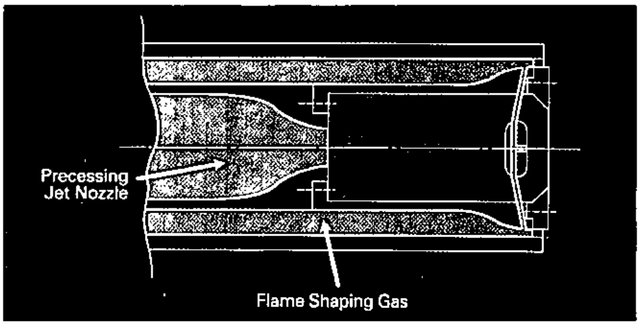

Figure 4. The Gyro-Therm burner nozzle, MkII.

A newly developed means for controlling the flame spread of the Gyro-Therm was added to the Geelong burner with spectacular success. Controlling flame spread and heat flux profile is by a simple valve adjustment. This modification was put in place without any detrimental effect on the ability of the Gyro-Therm to slash NO_x emission and to improve operating efficiency. It appears that these benefits have been further enhanced by this development. Clinker and cement quality has been consistently excellent through this recent period.

Physical modelling techniques have now been developed for the Gyro-Therm burner and are employed to optimise the flame for a given kiln and provide accurate prediction of flame shapes and heat flux profiles. This ensures optimum burner design and removes a great deal of the trial and error associated with commissioning.

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Optimising precalciner design and performance

Dr. Peter J. Mullinger and Dr. Barrie G. Jenkins,
Fuel and Combustion Technology International, discuss the use of
combustion process modelling to improve precalciner design and performance.

Introduction

The principle advantages of precalciner kilns include, increased output, reduced thermal stresses on the kiln, improved process stability and lower NO_x emissions. However the precalciner itself is a difficult environment for combustion with its relatively low temperature and high dust concentration. Some types of calciner using kiln gas as the source of oxygen for combustion have the additional disadvantage of a low oxygen concentration. It is little wonder therefore that the combustion is often less than perfect, with high emissions of carbon monoxide and other unburnts. Furthermore NO_x emissions are sometimes disappointingly high. Natural gas is particularly difficult to burn in precalciners owing to its narrow flammability limits and high ignition temperature, a fact that takes most process engineers by surprise. Very low volatile fuels, such as petroleum coke are equally difficult to burn under the conditions prevailing in calciners.

The combustion and heat transfer regime in a precalciner is fundamentally different from that which occurs in a rotary kiln. Product heating in rotary kilns is determined by the flame's heat flux profile. By way of contrast a flash calciner, is effectively an isothermal system with heat being removed by the calcination reaction almost as soon as it is liberated by the combustion process.

The importance of the flame on rotary kiln processes was first recognised by Martin[1] in the late 1920's when studying the rotary cement kiln. In attempting to overcome the traditional limitations of rotary kilns Martin built the first flash calciner but it was abandoned following a withdrawal of funding. A method of optimising the flame for an individual kiln was first developed in the early 1970's by Moles and Jenkins[2]. Early applications of this technique, dubbed Flame Control by Moles, were very successful[3]. These early techniques used empirical formula together with physical modelling. With the advent of the PC heat transfer modelling was also utilised.

This article is concerned with the application of both physical and computer modelling techniques to the optimisation of combustion and heat transfer in commercial precalciners. The increasing use of these techniques leads to improved process stability and a more consistent product, reduced fuel consumption and emissions, more stable plant operation and improved refractory life.

Combustion and heat transfer in precalciners

Combustion is the oxidation of fuel to release heat. The objective of the combustion engineer and plant operator is to obtain a steady heat release at the required rate. The chemistry of the oxidation of hydrocarbon fuels is very complex and has been described previously in *World Cement*[4,5]. None of the reactions can take place until the oxygen in the air is brought into contact with the fuel. As a result all combustion processes take place in the following stages:

Mixing
⇓
Ignition
⇓
Chemical reaction
⇓
Dispersal of products

The rate of combustion is dependent on the slowest of the above stages. In most industrial combustion systems, the mixing is slow whilst the other steps are very fast. The rate and completeness of the combustion process is therefore controlled by the rate and completeness of fuel/air mixing. Insufficient mixing produces unburnt CO in the flue gases, wasting fuel. For good combustion, it is necessary to ensure that adequate air is supplied and that the burner mixes the fuel and air streams effectively and efficiently, hence the combustion is controlled by the rate and completeness of the fuel/air mixing i.e., if its mixed, its burnt.

For kiln burners, fuel/air mixing occurs as a result of jet entrainment. Figure 1 shows a fuel jet issuing from a burner nozzle in a rotary kiln. Friction occurs between the boundary of the jet (which is normally fuel and primary air) and its surroundings, causing the surrounding secondary air to be locally accelerated to the jet velocity. The accelerated air is then pulled into the jet thus expanding it. This process is momentum controlled and continues until the velocity of the jet is the same as that of its surroundings. The greater the momentum of the jet, the more rapidly the surrounding secondary air is entrained into the fuel and the shorter the flame.

In precalciners the fuel/air mixing is more complex. The burners are often installed through the wall and much of the mixing is in cross flow, Figure 2. Since most of the combustion air must still be entrained into the primary air and fuel jet, the air flow patterns within the calciner have a huge effect on the fuel/air mixing. The aerodynamics are largely determined by the design of the calciner vessel and the tertiary air inlet. The combustion is also greatly affected by the flame buoy-

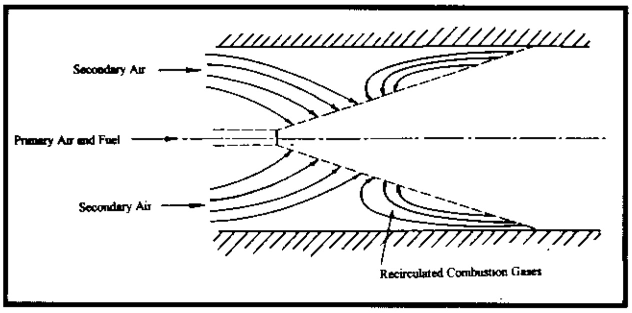

Figure 1. Entrainment and recirculation in a confined jet.

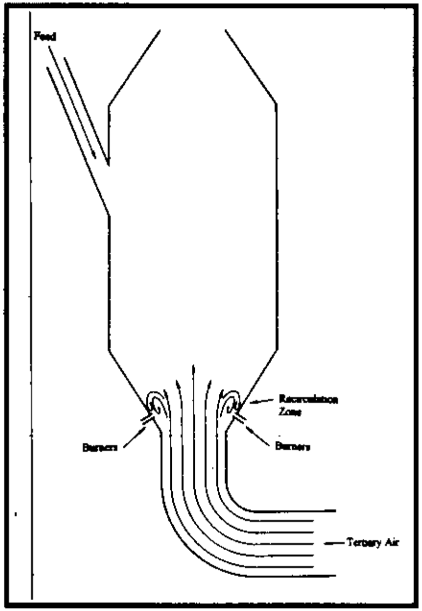

Figure 2. Typical arrangement of burners in a precalciner.

ancy, feed concentration and flow patterns since the calcining feed absorbs heat from the combustion process which lowers the combustion reaction rates, and can in extreme circumstances cause a 'flame out'. Thus the 'mixed is burnt' assumption mat not be completely true for flash calciners.

As a result the design of the calciner vessel and its tertiary air inlet, the position and type of burners and the feed inlet arrangements all significantly affect the combustion and calcination process. Any effective modelling of the precalciner process must take these factors fully into account.

NO_x formation in precalciners

The NO_x formation in flames is generally by both thermal and fuel routes (for coal, oil and petroleum coke). In gas fired plant, fuel NO_x is absent so all the NO_x is thermal NO_x. However, it should be noted that the absence of fuel NO_x in gas fired plant does not necessarily lead to a reduction in NO_x emissions, since flame temperatures can be higher.

Thermal NO_x is formed by the combination of atmospheric nitrogen and oxygen at high temperatures, generally over 1200°C. The high temperatures are required because of the high activation energy of the reaction, it is therefore highly temperature dependent. The reaction takes place between oxygen radicals, nitrogen radicals and molecular nitrogen in the Zeldovich reaction couple. Apart from temperature, the in-flame oxygen concentration and the residence time in the high temperature zones influence the final thermal NO_x emissions.

Most fuels, other than gas contain nitrogen bound as an organic compound in the structure. When the fuel is burnt this organic nitrogen becomes converted into a range of cyanide and amine species which may be subsequently oxidised to NO_x, depending on the local oxygen availability, but this mechanism is less dependent on temperature.

Heat transfer

A precalciner is a relatively well mixed system with most of the heat transfer taking place by convection owing to the intimate mixing between the hot gases and the feed. By way of contrast, rotary kilns are much more complex with significant variations in gas concentrations, heat release, and temperature both along the flame and through its cross section. In pre-calciners the combustion, heat transfer, and with it the degree of calcination, can be adversely affected if the air or feed flow patterns are unstable.

Common precalciner problems

Incomplete combustion

Carbon monoxide and unburnt hydrocarbon emissions are often higher from precalciners than older wet and dry process kilns. Whilst some of these increased emissions may arise from poor fuel/air mixing in the kiln as the result of the use of low primary air burners, most arise from poor fuel/air mixing or by flame quenching in the calciner itself. These problems are normally more severe in natural gas fired calciners, because of this fuel's narrow flammability limits, or calciners using difficult fuels, such as petroleum coke.

This poor combustion is often considered an inevitable feature of precalciner operation but, in reality, it is the result of inadequate design procedures, and combustion efficiency can often be greatly improved by the application of modelling techniques and implementation of the results on the full size unit.

Unstable operation

Where the combustion process is particularly poor, or where the feed flow patters are unstable, calciners can be subject to unstable operation with cyclic or random variations in degree of calcination, outlet temperature, oxygen, NO_x, and CO concentrations. Modelling leads to rapid identification of the real cause of such problems and usually can provide an effective low cost solution.

Excessive NO_x formation

Since heat is rapidly absorbed by the calcination of the feed and bulk temperatures do not exceed 1000°C thermal NO_x should be very low. However NO_x emissions are often higher than expected as a result of a 'hot core' in the combustion process. Where this is the case and it is required to reduce the NO_x emissions this can be achieved by modelling both the combustion process and the feed distribution to ensure as even temperatures as possible throughout the vessel.

Material build-up

Local overheating or excessive material residence times in high temperature zones can cause material build-ups due to surface melting of the material or re-combination to form calcium carbonate. This problem can generally be minimised or eliminated by improving the combustion, and the aerodynamics of the feed distribution. Again modelling can be used to identify the cause of the problem and provide a solution.

Modelling of precalciners

Combustion and heat transfer are very complex subjects which are not readily amenable to rigorous mathematical analysis. Prediction of the performance of burners and combustion equipment and associated plant is therefore extremely difficult. There are essentially three choices for designing combustion and heat transfer systems:

- Guesswork,
- Simple calculations combined with the extrapolation of experience,
- Modelling the system.

To obtain the best potential performance from any precalciner, it is absolutely essential that the combustion and feed distribution is optimised to give the most stable operation at relatively low temperatures and high feed concentrations. This will in turn give the best product, and requires that the aerodynamic characteristics of the calciner and feed concentrations are taken fully into account when designing the system. This can only be achieved using process modelling.

Effective modelling requires that the important parameters of the process being studied are identified and represented in the model. Since it is not possible to scale nature, physical modelling can only give part of the answer.

Mathematical modelling is similarly limited both by computing power available and our ability to describe the combustion and heat transfer process mathematically. As a result each modelling technique represents a partial understanding of the process. The objective is to provide predictive techniques which work for real flames in real systems and contribute to improved performance. To achieve this objective normally requires the use of several modelling techniques simultaneously.

Physical modelling of flames

Despite the growth in computer modelling, physical modelling is still the most effective method for determining flame length and shape in rotary kilns and stationary calciners. Acid/alkali modelling was developed by Sir William Hawthorne[6] at MIT as long ago as 1938 and is used to model the combustion process where fuel/air mixing determines the flame characteristics. A physical model of the plant is constructed to an appropriate scale in clear acrylic plastic. The fuel is represented by dilute caustic soda solution containing phenolphthalein indicator, whilst the combustion air is represented by dilute hydrochloric acid. The concentration of the alkali and the stoichiometric ratio of alkali to acid is chosen to represent the correct air/fuel requirement for the particular fuel. The flow of acid is adjusted to simulate different excess air levels, hence determining the relationship between flame envelope and excess air. The phenolphthalein becomes colourless at the boundary where the mixing is complete, thus the model flame envelope is defined by the coloured region. The aerodynamics of the full size system are reproduced on the physical model thus allowing an accurate simulation of the fuel/air mixing characteristics and hence flame envelope under representative conditions. A typical acid/alkali model of a cement kiln precalciner is shown in Figure 3.

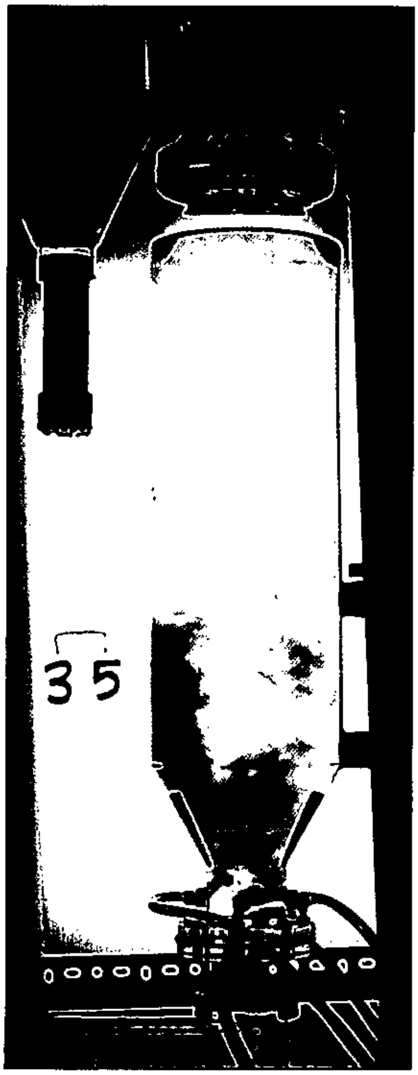

Figure 3. Typical acid/alkali model of combustion in a precalciner.

Heat transfer modelling

The combustion process and its integration into energy transfer equipment design, is the most complex of all process engineering problems, requiring the simultaneous solution of heat, mass and momentum transfer. Owing to the significant differences between rotary kilns and flash calciners many different factors must be taken into account if modelling of combustion and heat transfer is to be effective. Mathematical modelling is used for a wide range of combustion and heat transfer processes including the burnout of oil, coal and coke particles, heat transfer and the residence time and concentrations of feed and product in the process.

A flash calciner is a relatively well mixed system and the simple well stirred furnace model developed by Hottel[7] can be used. By way of contrast, rotary kilns are much more complex with turbulent jet diffusion flames and significant variations in gas concentrations, heat release, and temperature both along the flame and through its cross-section.

Computational fluid dynamic modelling

FCT is currently using the commercially available PHOENICS computational fluid dynamics (CFD) package as a design tool for an increasing number of flow problems, particularly problems involving materials in suspension, such as feed in a precalciner. The calculation commences by sub-dividing the solution domain into cells, thus forming the computational grid. When the grid has been constructed, the fluid properties and boundary conditions are specified. Having specified the grid, the fluid properties and the boundary conditions, discretised versions of the Navier-Stokes partial-differential equations that govern the dynamics of fluid flow are generated internally and solved by PHOENICS using a variety of finite-volume techniques.

PHOENICS can solve for up to 50 dependent variables, but the most common variables solved are pressure, three velocity components for each phase present, enthalpy, turbulence properties and concentrations of the various chemical species present. Auxiliary variables such as temperature, density, Mach number or absolute velocity are normally deduced directly from the solved

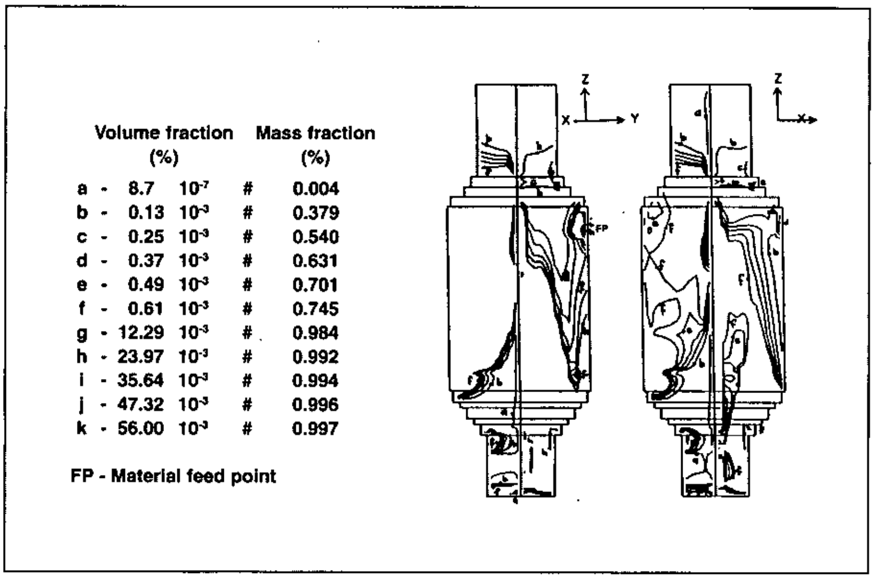

Figure 4. Typical CFD model results showing particle concentrations in a precalciner at three cross sections.

variables outlined above, and the values are stored at each computational cell for subsequent analysis or plotting.

CFD Modelling[8] can play an important role in the design of the precalciner feed systems where it is used to study the particle trajectories, concentrations and residence times, Figure 4, in flash calciners, and to optimise these by suitable adjustments to the feed inlet position and velocity. These techniques result in optimised designs for new plants and improved output for existing units.

Validation of modelling

It is one thing to produce a predictive method, and quite another to ensure that its predictions are correct i.e., in agreement with experimental observations. Consequently, considerable effort has been made by FCT. to 'validate' these computer models. The method is to make detailed comparisons between predictions and experiments; to interpret whatever discrepancies are discovered in terms of computational inaccuracies, inadequacies of the assumptions, and imprecisions of measurement; and then to implement improvements which result finally in the reduction of the discrepancies to acceptably-small values. FCT's computer models have been sufficiently validated for designers and operators of equipment to use reliably.

Application of modelling to plants

Modelling can be used to solve problems with existing plants, optimise the performance of existing systems, assess the effect of fuel or other process changes in advance of the changes being made or optimise the design of new precalciners. FCT uses modelling for all these purposes. Typically more than one modelling technique is used for a particular application because each technique provides only part of the answer required. Acid/alkali modelling is used to simulate the combustion whilst the well stirred method of heat transfer is used to predict heat transfer from the flame to the product, with CFD modelling used to predict the particle trajectories and residence times.

It is vitally important that valid operational data is used in the modelling. This is particularly relevant where unstable operation is being investigated. In certain circumstances site measurements may be required using specialist instrumentation. Figure 5 shows acid/alkali modelling of unstable combustion conditions in a calciner. This unit was modelled following an extensive site investigation. Initially the combustion conditions flipped between the two conditions shown and the problem was resolved by relocation of the burners. This was implemented on the plant and it was found that the more stable the calcination process the better the product quality and the lower the fuel consumption. The characteristics of the fuel also significantly affect process stability owing to their different combustion characteristics and hence different heat release patterns they produce.

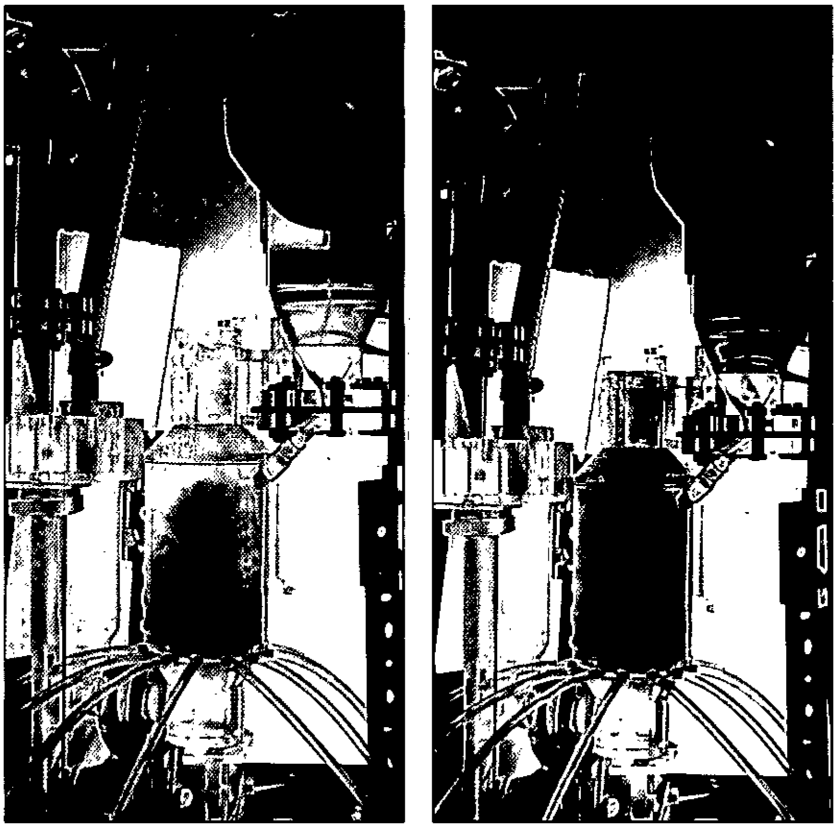
Normal combustion regime **Incomplete combustion**

Figure 5. Acid/alkali model of unstable combustion in a precalciner.

Conclusions

The success of the modelling process is more dependent on the engineer's skill at interpreting the plant data and determining the relevant modelling techniques to use than the elegance of the techniques themselves.

Only engineers adequately trained in modelling generally, and computer modelling of combustion in particular, can be used to 'operate' these models.

One technique used alone rarely gives sufficient information to provide a reliable solution. Engineers using modelling must therefore be skilled in the use of all the methods so that they do not favour the use of one technique above the others in possibly unsuitable circumstances.

The application of modelling techniques to precalciners has resulted in improved stability of operation, increased output, reduced specific fuel consumption and reduced emissions

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COMBUSTION OPTIMIZATION IN, AND NO$_X$ EMISSION CHARACTERISTICS OF, ROTARY KILN FLAMES

By

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ABSTRACT

Guesswork, simple calculations combined with the extrapolation of experience and model the system are the options for designing combustion systems for rotary kilns. While pure guesswork is rare, simple calculations and extrapolation are still the norm despite the availability of proven modelling techniques. This paper provides a brief background to combustion, heat transfer and NOx formation in rotary kilns and demonstrates how these modelling techniques, a detailed knowledge of the interaction of the combustion process with the process itself and a consideration of NOx formation chemistry can be successfully applied to rotary kilns particularly when considering conversion of kilns from solid fuels to gas firing, product quality improvements, and waste and multiple fuel firing. Any one modelling technique gives only part of the answer and several methods have to be used to provide reliable answers for real industrial problems. Major benefits that can be realised taking this approach are reduced costs and increased profits for the kiln operator with reduced environmental impact. Much of the future emphasis will be directed towards NOx reduction while maintaining and improving predictability and product quality.

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INTRODUCTION

Rotary Kilns are used for the processing and production of many materials in industry. Typical examples are: Cement clinker, lime, alumina, calcination of petroleum coke and many other ore beneficiation processes. There are similarities between all rotary kilns; they are all cylindrical, rotate at between 0.5 and 4 rpm and are fired by a single flame. However, here the similarity ends. Kiln configurations are process dependent, the required process temperatures vary widely, secondary air temperatures are highly variable as is firing system employed. This is in combination with a wide range of fuel types that are typically fired. But by far the largest industry using the rotary kiln is the cement industry with circa 2000 cement rotary kilns worldwide. Consequently, this paper is principally concerned with the cement rotary kiln but the general approach to resolving combustion problems, improving process efficiency and consideration of the complex interaction between the combustion process and the process itself is applicable across the range of processes employing the rotary kiln technology.

Optimisation of the energy consumption and process efficiency of cement kilns involves both fossil fuel and electrical energy. This paper is principally concerned with the former. Optimisation encompasses minimising fuel consumption, unburnts, NOx, SO_2 and cement linker grinding energy.

Cement clinker with small crystals and sharp boundaries assists easy grinding and gives the cement a high early strength. The crystal growth is strongly influenced by the heat transfer from the flame, favourable conditions being rapid heating from calcining temperature to sintering temperature and sudden quench in the cooler to freeze the crystal structure. These conditions are produced by a flame with a high heat flux close to the burner nozzle. Flames with very flat heat flux profiles give slow rates of heating and large crystals. The resultant clinker is hard to grind and produces cement with poor early strength. To compensate and meet market requirements the raw mix is sometimes adjusted, the kiln burnt harder, and the cement ground finer, thus increasing the energy consumption both in the kiln and in the grinding mill. The difference in energy consumption in the kiln and grinding mill between clinker produced by an optimised flame and a poor flame can be as much as 10%. With energy being a major cost in cement manufacture (between 40-50% of production costs) a poor flame heat flux profile therefore imposes a high economic cost as well as a significant increase in atmospheric emissions.

The importance of the flame on the cement clinker manufacturing process was first recognised by Martin (1) back in the late 1920's. A method of optimising the flame for an individual kiln was first developed by Moles and Jenkins (2) in the early 1970's. Early applications of this technique, dubbed Flame Control by Moles, were very successful (3). These early techniques used empirical formula together with physical modelling. The advent of the PC in the early 1980's permitted heat transfer modelling to be included. Today, with much more powerful PCs available, computational fluid dynamic modelling is also utilised.

This paper is concerned with the application of both physical and computer modelling techniques to the optimisation of combustion and heat transfer in commercial cement plants. The increasing use of these techniques leads to improved product quality, reduced fuel consumption and emissions, more stable kiln operation and improved refractory life. A section is also included on NOx and techniques to control NOx emissions.

MODELLING OF COMBUSTION AND HEAT TRANSFER

Combustion and heat transfer are very complex subjects which are even today not readily amenable to rigorous mathematical analysis. Prediction of the performance of burners and combustion equipment and associated plant is therefore extremely difficult. There are essentially three choices for designing combustion and heat transfer systems:

1 Guesswork

2 Simple calculations combined with the extrapolation of experience

3 Modelling the system

Fortunately the use of simple guesswork is probably quite rare but the majority of kiln burner systems are still designed using simple calculations with the extrapolation of experience. Since the secondary air provides most of the combustion air in cement kilns, its temperature, velocity and flow distribution has a significant effect on the performance of the burner. There are unique differences between kilns (even those of the same size and nominal design) in respect of cooler and hood and hence secondary air temperature, velocity and flow distribution. This vital fact is largely ignored by most kiln builders and burner suppliers. It is little wonder therefore that kiln performance is often unsatisfactory, with the resulting problems giving unstable operation, poor clinker quality, high fuel consumption and CO emissions, and poor refractory life.

Combustion in Cement Kilns

Combustion is the oxidation of fuel to release heat. The objective of the combustion engineer and plant operator is to obtain a steady heat release at the required rate. The chemistry of the oxidation of hydrocarbon fuels is very complex but none of the reactions can take place until the oxygen in the air is brought into contact with the fuel. As a result all combustion processes take place in the following stages:-

MIXING - IGNITION - CHEMICAL REACTION - DISPERSAL OF PRODUCTS

The overall rate of combustion is dependent on the slowest of the above stages. In most industrial combustion systems, the mixing is slow while the other steps are very fast. The rate and completeness of the combustion process is therefore controlled by the rate and completeness of fuel/air mixing. Insufficient mixing produces unburnt CO in the flue gases, wasting fuel. For good combustion, it is necessary to ensure that adequate air is supplied and that the burner mixes the fuel and air streams effectively and efficiently, hence the combustion is controlled by the rate and completeness of the fuel/air mixing i.e.;

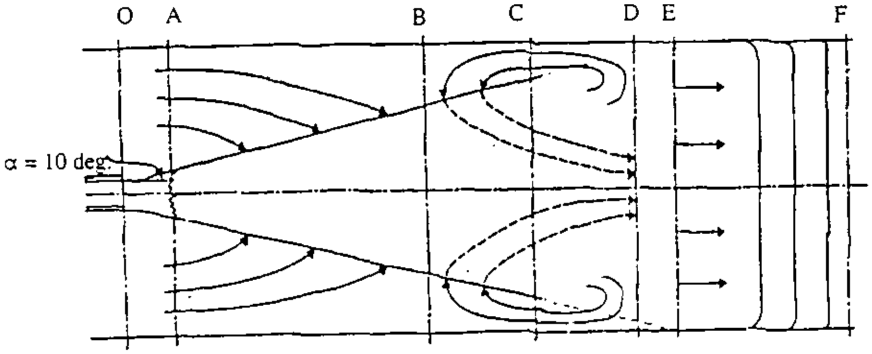
IF IT'S MIXED, IT'S BURNT

For kiln burners, fuel/air mixing occurs as a result of jet entrainment. Figure 1 shows a schematic of a fuel jet issuing from a burner nozzle in a rotary kiln. Momentum exchange occurs between the boundary of the jet (which is normally fuel and primary transport air) and its surroundings, causing the surrounding secondary air to be locally accelerated to the jet velocity. The accelerated air is then pulled into the jet thus expanding it. This process is momentum controlled and continues until the velocity of the jet is the same as that of its surroundings. The greater the momentum of the jet, the more rapidly the surrounding secondary air is entrained into the fuel.

If the jet has momentum in excess of that required for the complete entrainment of the secondary air, then recirculation will occur. A moderate degree of recirculation is a positive indication that fuel/air mixing is complete, while its absence is a clear indication that not all of the secondary air has been entrained into the fuel jet up to the point at which the fuel jet impinges on the kiln refractory wall. In the latter case, the production of significant levels of carbon monoxide is normal, as hot reducing gases will then be in direct contact with the coating and refractory, tending to "wash" away the coating and causing subsequent brick failure. The recirculating gases from a high momentum flame, however, provide a 'cushion' of cooler neutral gases which prevents this direct impingement of the flame on the coating and refractory.

Since the secondary air must be entrained into the primary air and fuel jet, the secondary air flow patterns and temperature have a huge effect on the fuel/air mixing. The aerodynamics are determined by the design of the cooler and secondary air inlet system (hood). As a result the design of these items significantly affects the combustion in the kiln. Any effective modelling of the combustion process must take these factors fully into account.

Typical Gas Flow Pattern in the Burning Zone



OA - Ignition distance
B - Position by which all secondary air is entrained into the jet boundary
C - Mid-point between B and D, "Eye" of recirculation bubble
D - Position by which all secondary air is mixed into the jet axis
E - Impingement point of non-swirl primary air jet on kiln shell (N.B. Not flame)
F - End of "Effective" flame

Figure 1 Entrainment and Recirculation in a confined jet

For any given kiln, the flame length and heat transfer are determined by the fuel/air mixing rate and the quantity of excess air. Increasing either the fuel/air mixing rates or excess air gives a shorter flame. The fuel/air mixing rate is dependent on the ratio of the momentum between the combined primary air and fuel jet and the momentum of the secondary air. Thus, the higher the velocity and mass flow of the primary air, the more rapid the fuel/air mixing.

Kiln operators will invariably run the kiln to give the best product he can achieve. If the fuel/air mixing is poor the kiln has to be operated at a higher excess air to shorten the flame to give adequate heat transfer. Operating at a relatively high excess air is detrimental to the kiln thermal efficiency, figure 2 This shows the relationship between the oxygen level and the measured daily heat consumption for a semi dry process cement kiln. Increasing the oxygen level in the kiln from 1% to 5% causes an increase in the heat consumption of more than 10%.

To obtain the best potential performance from any kiln, it is absolutely essential that the flame is optimised to give the best product crystal structure at low excess air. This requires that the aerodynamic characteristics of the kiln are taken fully into account when designing the burner.

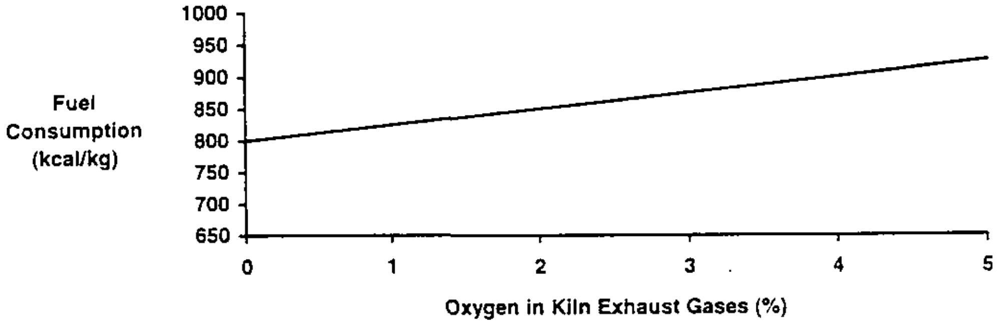


Figure 2 Effect of Excess Air on Kiln Fuel Consumption

Modelling of Combustion and Heat Transfer in Cement Kilns

Effective modelling requires that the important parameters of the process being studied are identified and represented in the model. Since it is not possible to scale nature completely, physical modelling can only give part of the answer. Mathematical modelling is similarly limited both by computing power available and our ability to describe the combustion and heat transfer process mathematically. As a result each modelling technique represents a partial understanding of the process. The objective is to provide predictive techniques which work for real flames in real kilns and contribute to improved kiln performance. To achieve this objective normally requires the use of several modelling techniques simultaneously.

Physical modelling of flames

Despite the growth in computer modelling, physical modelling is still the most effective method for determining flame length and shape in rotary kilns. Acid/alkali modelling was developed by Sir William Hawthorne (4) at MIT as long ago as 1938 and is used to model the combustion process in rotary kilns where fuel/air mixing determines the flame characteristics. A physical model of the cooler, hood and kiln is constructed to an appropriate scale in clear acrylic plastic. The fuel is represented by dilute caustic soda solution containing phenolphthalein indicator, while the combustion air is represented by dilute hydrochloric acid. The concentration of the alkali and the stoichiometric ratio of alkali to acid is chosen to represent the correct air/fuel air requirement for the particular fuel. The flow of acid is adjusted to simulate different excess air levels, hence determining the relationship between flame length and excess air. The phenolphthalein becomes colorless at the boundary where the mixing is complete, thus the model flame envelope is defined by the coloured region. The aerodynamics of the full size system are reproduced on the physical model thus allowing an accurate simulation of the fuel/air mixing characteristics and hence flame length under representative conditions.

These model results have to be corrected since the model is run under isothermal conditions, while in the kiln, considerable changes in temperature usually occur as combustion takes place. This results in a reduction in the gas density and an increase in volume giving a longer flame in the kiln than in the model. For most practical purposes the model flame length has only to be corrected for the density changes. When the corrections are applied to the model results a series of curves of predicted flame length against excess air are produced see Figure 3.

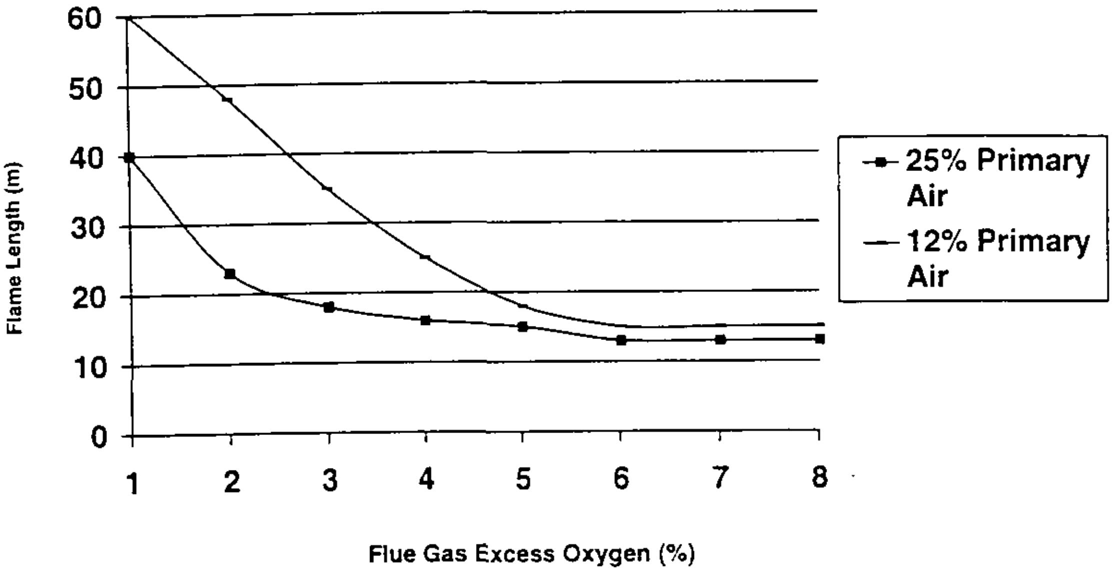


Figure 3 Predicted Effect of Excess Air on Flame Length for Various Primary Airflows

Heat Transfer Modelling

The combustion process and its integration into energy transfer equipment design, is the most complex of all process engineering problems, requiring the simultaneous solution of heat, mass and momentum transfer. For effective modelling of combustion and heat transfer in a rotary kiln many factors must be taken into account. Rotary kiln flames are turbulent jet diffusion flames which are fortunately relatively well understood owing to the work of Thring and Newby (5), Craya and Curtet (6), and Becker (7). Their analysis of momentum transfer in free and confined jets has yielded theories to predict the macro-turbulent entrainment characteristics for both cold and hot systems. Mathematical modelling is used for a wide range of combustion and heat transfer processes including the burnout of oil, coal and coke particles, heat transfer and the residence time and concentrations of feed and product in the process.

For heat transfer modelling the kiln is divided into axial slices, typically 100mm thick, and the mixing rates, combustion heat release, and radiative effects of the gases and particles calculated within each slice to determine the radiant heat transfer to the product and walls. Convective heat transfer effects are also calculated within each slice. By stepping the calculation through the system, a realistic estimate of the burnout, gas temperature, heat transfer and product temperatures can be obtained. The flame itself and the combustion products absorb, and emit, thermal radiation. Both gases and particulate material present in the flame contribute to the absorbing propensity of the flame. Within the flame, the chemical effects of the combustion process are secondary, since the reaction time constants are orders of magnitude faster than the diffusional mixing constants. Thus, the combustion process can be reduced, with a 'mixed is burnt' assumption controlling the rate of heat release. The mathematical model used by FCT for calculating the heat transfer from flames in rotary cement kilns takes these factors fully into account and is described in reference 8.

Computational Fluid Dynamic Modelling

FCT uses commercially available CFD software packages (PHOENICS, CFDS FLOW-3D, FLUENT) as design tools for an increasing number of flow and combustion problems, particularly problems involving materials in suspension, such as feed in a rotary kiln precalciner and the incineration of sewage sludge in a vortex combustor. In simple terms, the calculation commences by sub-dividing the solution domain into cells, thus forming the computational grid. When the grid has been constructed, the fluid properties and boundary conditions are specified. Having specified the grid, the fluid properties and the boundary conditions, discretised versions of the Navier-Stokes partial-differential equations that govern the dynamics of fluid flow are generated internally and solved by the applicable CFD solvers. More complex systems including two phase and combustion flows are also mathematically simulated.

NOx assessments

The NOx formation in kiln flames is generally by both thermal and fuel routes (for coal, oil and petroleum coke which contain fuel nitrogen). Owing to the very high flame temperatures which occur i.e., above 2000°C thermal NOx is generally the dominant mechanism and typically accounts for circa 70% of the total

NOx emission dependent on secondary air preheat temperature. In gas fired kilns fuel NOx is absent so all the NOx is thermal NOx. However, it should be noted that the absence of fuel NOx in gas fired kilns does not necessarily lead to a reduction in NOx emissions, since gas flame temperatures are often higher than of coal or oil. Apart from temperature, the in-flame oxygen concentration and the residence time in the high temperature zones influence the final thermal NOx emissions.

The formation of NOx is complex and still not a well understood process consequently, modelling these of the NOx formation process is still very difficult. Some of the currently available models are capable of predicting the trends of NOx formation with change in flame conditions and fuel type, but the accuracy is poor and sometimes little better than orders of magnitude. Currently, the most reliable methods of predicting NOx emissions from full scale flames is by empirical scale up from test flames. FCT has achieved good results using the data from the test work undertaken by The International Flame Research Foundation for the **CEMFLAM 1** consortium (9) and the main results of this work are described in some detail in a subsequent Section of this paper. In addition, for prediction of NOx in rotary kilns, FCT utilise a customised version of the FACSIMLE kinetic package produced by AEA Technology. This computer package consists of a suite of closely related programmes for the modelling of complex steady state and time-dependent chemical reactions including an extensive NOx modelling capability. To allow for acceptable NOx predictions to be made in industrial combustion processes, FCT have modified the code to take account of gas temperature-time history and fuel air mixing. This latter data is generated from the associated physical and heat transfer modelling. To date results have been encouraging with predictions of NOx emissions from an existing "dead burned" dolomite kiln being within 10% of measured values. Further validation of this programme over a broad range of combustion processes is currently in being undertaken by FCT.

Validation of Modelling

It is one thing to produce a predictive method, and quite another to ensure that its predictions are correct i.e., in agreement with experimental observations. Consequently, considerable effort has been made by FCT. to "validate" these computer models. The method is to make detailed comparisons between predictions and experiments; to interpret whatever discrepancies are discovered in terms of computational inaccuracies, inadequacies of the assumptions, and imprecisions of measurement; and then to implement improvements which result finally in the reduction of the discrepancies to acceptably-small values. To date FCT'Is computer models have been sufficiently validated for designers and operators of equipment to use reliably.

APPLICATION OF MODELLING TECHNIQUES TO REAL KILNS

Modelling can be used to solve problems with existing kilns, optimise the performance of existing kilns, assess the effect of fuel or other process changes in advance of the changes being made or optimise the design of new plant. FCT uses modelling for all these purposes. Typically more than one modelling technique is used for a particular application because each technique provides only part of the answer required. Within the kiln itself acid/alkali modelling is used to simulate the combustion while the zone method of heat transfer is used to predict heat transfer from the flame to the product. For flash calciners both techniques can be used together with CFD modelling of the particle trajectories and residence times.

The major benefits are reduced costs and increased profits for the kiln operator with reduced environmental impact. The former is attributable to reduced fuel consumption, improved refractory life, and shorter downtime, with potentially greater sales resulting from longer production runs and improved product quality. The reduced emissions are the result of reduced flue gas volumes and less unburnt fuel. A few examples are described below.

Kiln conversions to gas firing

FCT first applied these techniques to lime kilns over ten years ago during the conversion of a lime kiln in the Cheddar Gorge to gas firing. The first cement application came a year later with the conversion of Cockburn Cement's kilns in Western Australia to gas firing. Cockburn Cement operates three cement kilns and two rotary lime kilns. Four of the kilns at Cockburn Cement had originally been oil fired and then converted to coal using a very difficult local coal. The coal firing systems were designed using Moles and Jenkins Flame Control Techniques back in 1981. The initial conversion to gas firing was undertaken using the traditional technique of simple calculations combined with the extrapolation of experience. While these burners were satisfactory in the two smaller cement kilns they gave serious problems with product quality on the largest cement kiln and on one of the lime kilns. FCT was called in and asked to assist with identifying and resolving these problems and designing a burner for the second lime kiln. Acid/alkali modelling of the combustion and mathematical modelling of the heat transfer was undertaken for both kilns and new burners designed and successfully installed.

Product quality improvements

Adelaide Brighton Cement operated a gas fired preheater kiln rated at 2000 tonnne/day using a high velocity gas burner without primary air. The plant management used the Ono method for assessing burning conditions in the kiln and this indicated a slow rate of heating of the charge. The kiln flame was modelled using the acid/alkali technique which confirmed a long slow mixing flame, Figure 4. Heat transfer modelling confirmed a flat heat flux profile consistent with large crystals and high proportion of glass phase.

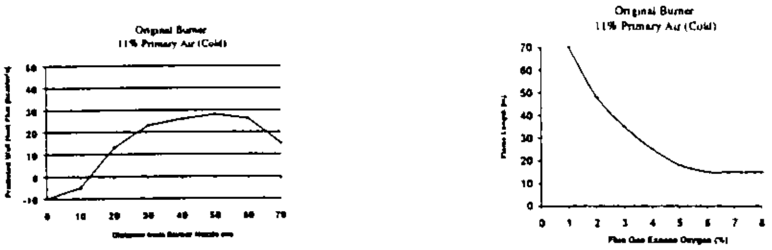


Figure 4 Flame lengths and Heat Flux Profiles for Existing Combustion Conditions

Improving the heat flux profile by better fuel air mixing is a matter of increasing the burner jet momentum relative to the secondary air momentum. With the maximum gas velocity already in use this could only be achieved by adding some primary air to the burner, hence increasing the overall mass flux of the burner jet. To achieve the most suitable flame length and heat flux profile the flowrate and velocity of this primary air has to be optimised. This is essentially a trial and error technique with the equivalent of various primary air flows and velocities tried on the acid/alkali model. This is a time consuming business but much quicker than a similar trial and error exercise on the full size kiln! Once conditions are optimised then the heat transfer model is used to assess the heat flux profile. The modelling confirmed that improving the mixing by using some primary air would produce considerable benefits in terms of flame length excess air and heat flux profile, Figure 5. A suitable burner was designed and installed.

Following commissioning of the new burner there were several significant improvements in kiln operation including improved stability, better coating and improved clinker quality. CO emissions and specific energy consumption were reduced. The clinker was also easier to grind.

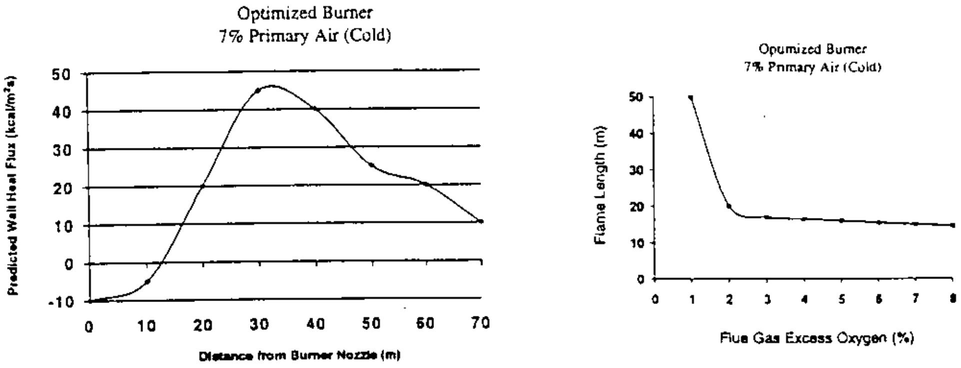


Figure 5 Flame lengths and Heat Flux Profiles for Optimised Combustion Conditions

Precalciner conversion modelling

Later this kiln was converted to a precalciner kiln and the new kiln process conditions modelled. Operation in precalciner mode requires lower primary air flowrates and velocities than preheater mode for optimum performance. Modelling also played an important role in the design of the calciner with acid/alkali modelling used to determine the optimum position for the burners. In more recent times CFD modelling has been used to study the particle trajectories, concentrations and residence times in flash calciners (10) and to optimise these by suitable adjustments to the feed inlet position and velocity. These techniques result in improved output for existing units.

Waste fuels and multiple fuels

The modelling techniques outlined above can cope with multiple fuel firing. Hence waste derived fuels can be effectively utilised with minimum disruption to both the kiln and environment by the use of modelling to ensure that the fuel/air mixing is excellent. This allows unburnts to be minimised while optimising the heat flux profile produced by the combination of waste and main fuel firing.

NOx FORMATION IN ROTARY KILNS

NOx Formation Mechanisms

Thermal NOx is formed by the combination of atmospheric nitrogen and oxygen at very high temperatures. The high temperatures are required because of the high activation energy of the reaction, due particularly to the energy required to break the bond in the nitrogen molecule. The reaction is therefore highly temperature dependent. The reaction takes place between oxygen radicals, nitrogen radicals and molecular nitrogen and oxygen in the Zeldovich reaction couple. Apart from temperature, the in-flame oxygen concentration and the residence time in the high temperature zones influence the final thermal NOx emissions.

Most fuels, other than gas, contain nitrogen bound as organic compounds in the fuel structure. When the fuel is burnt this organic nitrogen becomes converted into a range of cyanide and amine species which are subsequently oxidized to NOx, depending on the local oxygen availability, but this mechanism is less dependent on temperature.

A third mechanism of NOx formation has been identified by some workers which involves the fixation of nitrogen by hydrocarbon compounds in fuel rich areas of the flame. This mechanism is known as prompt NOx. The formation mechanisms of prompt NOx, thermal NOx and fuel NOx are described in more detail below.

Thermal NOx

The common approach for explaining the formation of thermal NOx is to base the theory on two basic Zeldovich reactions.

$$O + N_2 \underset{k_{1b}}{\overset{k_{1f}}{=}} NO + N \qquad \text{- (R1)}$$

$$N + O_2 \underset{k_{2b}}{\overset{k_{2f}}{=}} NO + O \qquad \text{- (R2)}$$

K_{1f} is strongly dependent on the local temperature. $[N_2]$ and $[O_2]$ are traditionally set to the equilibrium conditions at the prevailing temperature but in coal flames the temperatures are probably too low for this equilibrium assumption to be valid for $[N_2]$ and it is virtually impossible to measure $[O]$ using currently available techniques.

The above is a limited and greatly simplified approach to the theory of thermal NOx formation and is included to allow an appreciation of the complexity of the theory and the difficulty of making theoretical predictions of thermal NOx emissions. Figure 6 shows the extreme temperature dependence of thermal NOx formation.

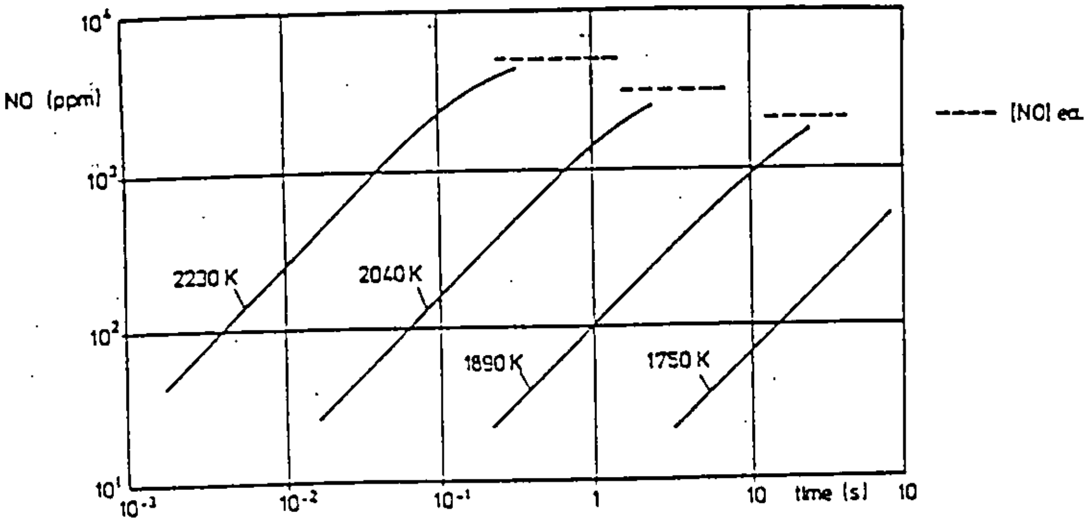


Figure 6 Dependence of Thermal NOx Formation Rate on Temperature

Fuel NOx

Fuel NOx is generally associated with coal or petroleum coke combustion which contain nitrogen chemically bound within their structures, and to a lesser extent with oil. Most studies on fuel derived NOx have been performed on coal and the main focus of this section is related to fuel NOx derived from coal combustion. The mechanisms by which NOx is formed from the chemically bound nitrogen in coal is extremely complex, even the structure of the nitrogen in the coal is subject to considerable conjecture. The nitrogen is believed to be in the form of pyridine, pyrrol and amine type structures, Figure 7. The actual structure in any coal or oil is believed to be strongly dependent on coal type or the origin of the oil. The predominant forms of nitrogen in most coals are the pyrrolic and pyridine forms and that the former tends to decrease with increasing coal rank. However, at present, the importance of the structure of the nitrogen in the coal on the final NOx emissions is not well established.

When coal is burnt in suspension as in rotary kilns, it is heated very rapidly to high temperatures and pyrolysis occurs, producing solid and gaseous products. The nitrogen present will divide between these with typically 20% of the nitrogen in the char and 80% in the gaseous phase, the latter both as the light fractions and tars. For any coal, the distribution of nitrogen between the gaseous phase and char is heavily dependent on the conditions in the flame such as heating rate, peak temperature, and residence time at high temperature.

A simplified NOx formation path is shown in Figure 8. Most of the gaseous nitrogen pyrolyses either directly or indirectly to HCN. This complex process is not instantaneous but dependent on the conditions in the flame. The HCN then oxidizes to NO, Figure 9, with this reaction being both temperature and time dependent, Figure 10.

Prompt NO

In low temperature fuel rich flame zones, NO is found to form more rapidly than predicted from considerations of the thermal NO mechanism. The difference is due to the so called "Prompt NO" formation mechanism. Prompt NO is formed by the rapid fixation of atmospheric nitrogen by hydrocarbon fragments. Reactions of the following form are involved:

$$CH + N2 = HCN + N$$

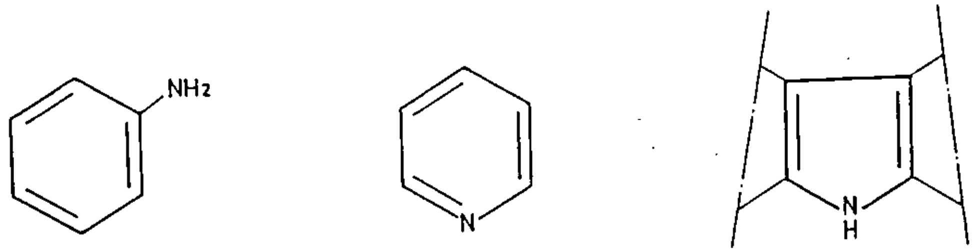
$$C + N2 = CN + N$$

NO is subsequently formed from the oxidation of the nitrogen atom:

$$N + O = NO$$

HCN and CN also react to form NO by reactions important in the fuel nitrogen conversion mechanism. Prompt NO is formed in all combustion systems but its contribution to the total NOx emission is combustion system and fuel dependent. In cement kilns its contribution to the total NOx is negligible.

To control NOx emissions it is important to identify the dominant source during the combustion process. If thermal NOx is dominant, reduction in flame temperature is required or reduced residence time at high temperature in the flame gases. This, however, may compromise process requirements. If fuel NOx is dominant, manipulation of the fuel air mixing ,creating fuel rich zones (restricting oxygen availability during volatiles combustion) where fuel bound nitrogen can react to molecular nitrogen as opposed to NOx, offers significant potential. Work performed within the aforementioned CEMFLAM research programme at the IFRF (9) demonstrated a very important feature of rotary kiln flames. Dependent on burner type, primary air momentum and primary air percentage, a distinct ignition delay is generally observed before the flame is initiated. During this pre-ignition period, secondary air is being entrained into the primary air/fuel jet. The greater the ignition delay distance, the greater the amount of air entrained into the fuel jet prior to ignition. This results in higher flame temperatures resulting in increased thermal NOx formation and a more oxygen rich flame environment with consequential more effective conversion of fuel bound nitrogen to NOx. Experimental results confirming this effect is shown in Figure 11 where NOx levels are plotted



Amine (Aniline)

Pyridine

Pyrrole

Figure 7 Characteristic Forms of Nitrogen in Coal

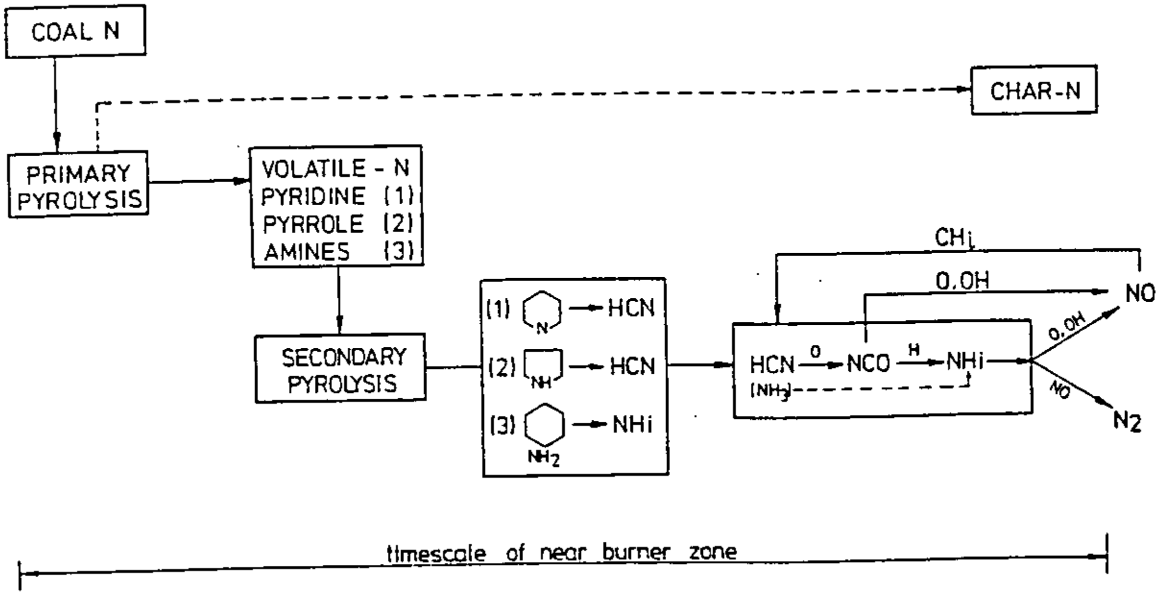


Figure 8 Outline of Fuel NOx Formation Path

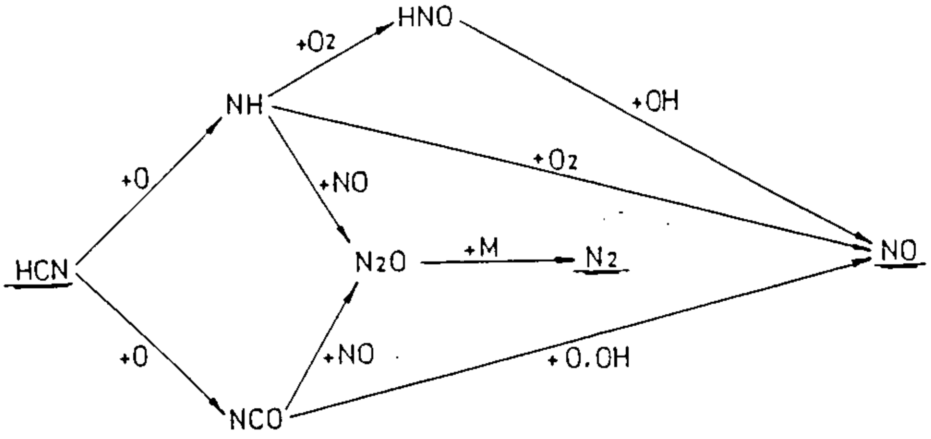


Figure 9 Mechanism for Conversion of HCN to NO in Flames

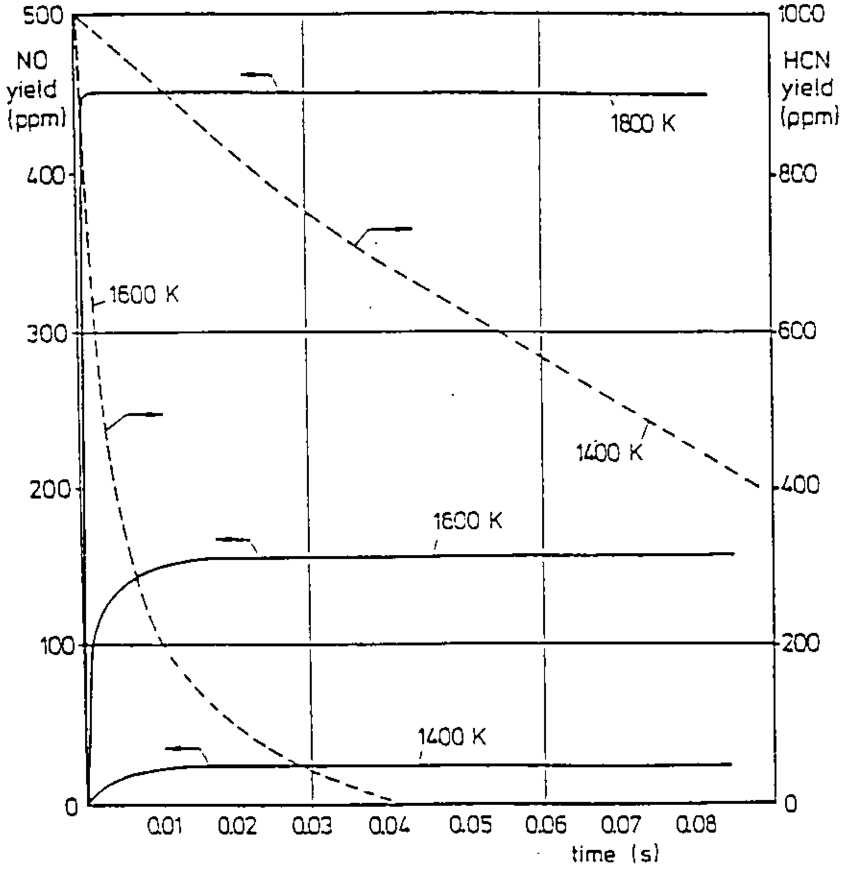
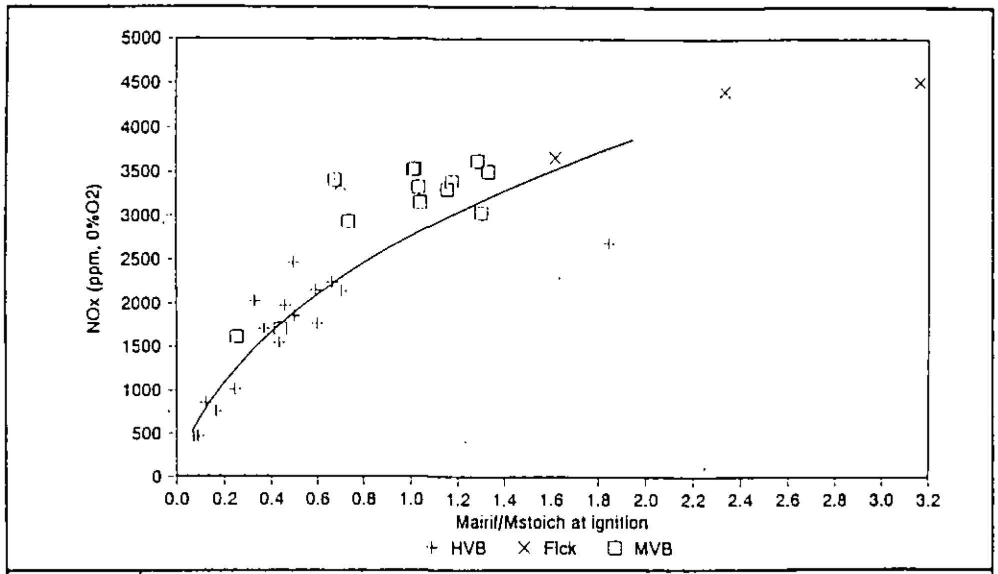


Figure 10 Effect of Temperature on the Rate of Conversion of HCN to NO in Flames

against calculated amount of air entrained into the fuel jet at the point of ignition. FCT are actively exploiting this phenomenon in the design of low NOx rotary kiln burners.



IFRF

Fig. 6.1: NOx versus $M_{airinflame}/M_{stoich}$ at ignition (mono channel)

Figure 11 NOx Emissions as a Function of the Amount of Air Entrained into the Fuel Jet at the Point of Ignition Relative to Stoichiometric

NOx Reduction with Natural Gas

The Gyro-Therm burner uses the patented Precessing Jet (PJ) nozzle developed at the University of Adelaide, in combination with other jet flows, to provide a high radiation, low NOx flame tailored for a given application. To date its principal application has been in gas-fired rotary lime, alumina, cement and zinc oxide kilns but new developments are in progress and it is anticipated that it will soon find application using other fuels and in other processes.

Precession is a term used to describe the "gyroscopic" like rotation of a body about an axis other than its own centerline, such as a spinning top that is leaning to one side. In the case of a precessing jet, at any instant the jet is directed at an angle to the nozzle axis, about which it precesses. The precession creates a much larger scale of mixing than occurs in a conventional jet, as well as increased spreading of, and entrainment by, the jet. The precessing motion is generated without any moving parts by the patented Gyro-Therm nozzle. A naturally occurring fluid-mechanical phenomenon is established when the nozzle dimensions are correctly selected. This causes rapid jet precession (typically 10 Hz, depending on the burner size and flow rate), so that the flame itself does not precess. Rather the effect is to produce large-scale mixing, via the "stirring" type action of the jet, and a flame which spreads rapidly. In addition the rapid precession also generates a low pressure region along the nozzle axis which limits the total spread of the jet by causing the precessing jet to bend inward toward the nozzle axis. The consequence of this is that, although the flame spreads more than that from a conventional single jet nozzle, the amount of spread is limited and can be controlled, figure 1. This fact is important in cement kilns where direct impingement of a flame on the clinker would produce reducing conditions, which would be detrimental to product quality.

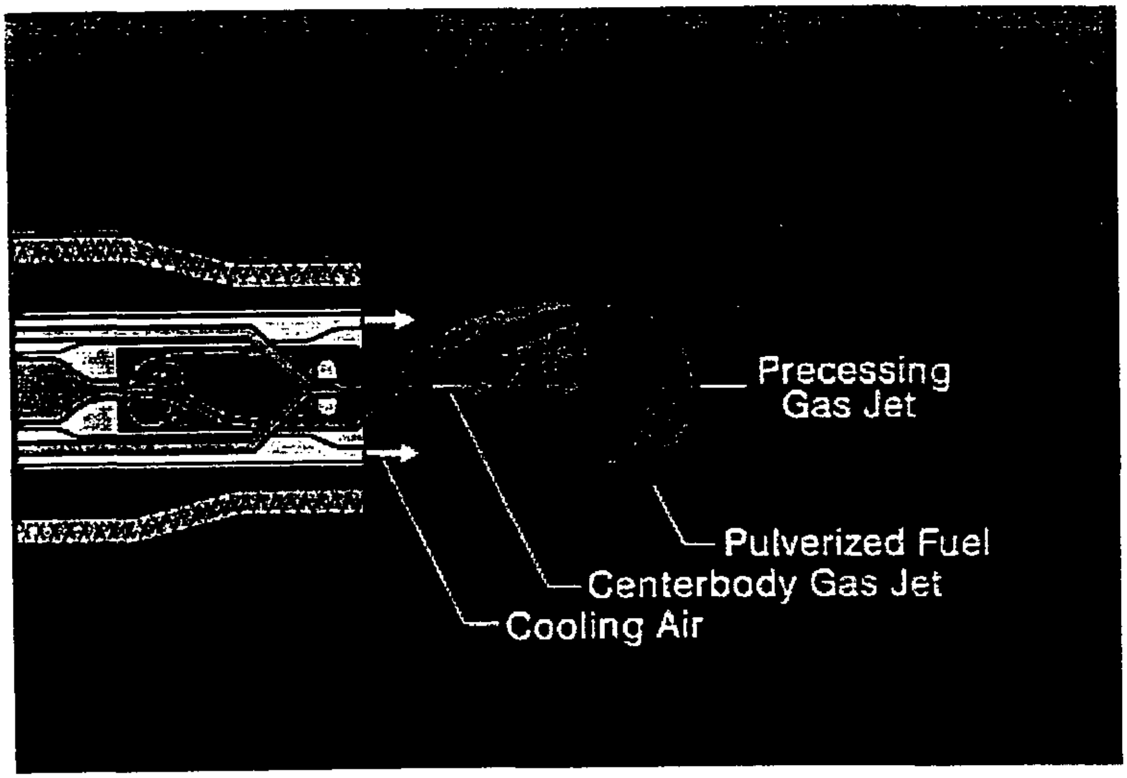


Figure 1 Precessing Jet nozzle with a simplified schematic of the flow-field generated

The effect of the jet precession on a gas flame is dramatic. Measurements conducted in industrial plants and in recognized research institutions have shown that in general there is a simultaneous increase in flame luminosity, reduction in peak flame temperatures, reduction in NOx emissions and an increase in flame stability. While the extent of the these changes depends upon specific conditions, they tend to be significant. For example, in a simulated boiler configuration in the 2 MW gas fired facility at the International Flame Research Foundation (IFRF), the Netherlands, the characteristic flame temperatures were about 150^{0} C lower than the equivalent swirl burner and the NOx emissions were about 50% lower (Nathan, Luxton and Smart, 1992). In a cement kiln, the increased radiation translates to increased heat transfer to the product near the front of the kiln which improves specific fuel consumption, product quality and output. While the extent of these changes depends upon the type of burner to which it is being compared, the reductions in NOx emissions are typically 30-60%, and the reduction in fuel consumption 3-5%. Because the Gyro-Therm flame generally produces a shorter heat release profile than the burner it replaces, a reduction in the back-end temperature of the kiln by 20-60 degrees typically follows, which can also result in reduced dust losses. Likewise the increase in bed temperatures at the front of the kiln, typically by 100 degrees, are beneficial for product quality in cement and lime kilns (Manias & Nathan, 1993, Balendra, Manias & Rapson, 1996).

The reduction in NOx emissions caused by jet precession is, at least in part, a direct consequence of the increased size of the largest scales of turbulence. In contrast to the intense, fine-scale mixing of a high momentum jet burner, which produce produces intense combustion with high temperatures and a clear blue colour in natural gas flames, the precessing jet flow produces fuel-rich combustion at the interface of the fuel and air within large pockets. This causes cracking in the flame which in turn produces a luminous, lower temperature flame front and minimises the NOx produced. Any soot produced is a local phenomena and burns out completely within the flame. The CO emissions are comparable with other well designed burners.

The mixing generated by the precessing jet nozzle is produced directly by the gas stream, utilising the potential energy which is available in the high pressure gas supply rather than requiring a high momentum ``primary" air stream. This means that the primary air fan size can be reduced relative to most burners, or eliminated in some cases. In most high temperature rotary kilns a Gyro-Therm burner is typically designed to use a small quantity of primary air, say 1-3% of the total air. The primary air is used at low firing rates for flame shaping and for cooling the burner in the event of a kiln stoppage. Being able to reduce the primary air has the dual advantage of reduced operating and maintenance costs of a primary air fan and, more importantly in many applications, increased thermodynamic efficiency. The efficiency gains occur when cold primary air is introduced at the expense of reduced amounts of hot secondary air, such as in a rotary kiln with a product cooler.

Flame Shaping and control of Heat Flux

The precessing jet nozzle, by itself, produces a gas flame which spreads rapidly and releases a lot of radiant energy close to the burner. In some applications, such as many of the larger rotary cement kilns, such a flame could create impingement problems or result in reduced kiln stability. To provide a simultaneous reduction in the spread of the flame and a lengthening of the heat release profile, the Gyro-Therm incorporates a centre-body jet into the precessing jet nozzle design. The centre-body jet is a high momentum jet located on the axis of the burner which, acting alone would create a conventional high momentum, low luminosity flame with a relatively long heat release profile. By adjusting the ratio of flows between these two jet streams, an intermediate flame can be obtained although the interaction between the two flows is complex and non-linear, figure 2.

A relatively small proportion of gas introduced through the centre-body jet, typically 10-30% of the total gas flow, is sufficient to provide good flame shaping in rotary cement, lime, and alumina kilns (Rapson, Stokes & Hill, 1995). Within this range the center-body gas flow appears to have only a secondary influence on NOx emissions, that is through its effect on the temperature profile of the bed which, in turn, effects the secondary air temperature and the radiant feedback to the flame (Hill, Rapson & Nathan, 1995).

The formation of NOx in flames is generally by both thermal and fuel routes (for coal, oil and petroleum coke and other fuels containing fuel bound nitrogen). The total NOx emission is always made up of contributions from both sources. The dominant source, however, is dependent on the amount of nitrogen contained in the fuel and the flame temperature with the latter being highly dependent on secondary air preheat temperature and the thermal requirement of the material being processed. Secondary air temperatures can vary from ambient in the case of petroleum coke calcination to in excess of 1100°C for the production of cement clinker. Dependent on the process, reactions can be exothermic of endothermic or the process may merely require the material in the kiln to be heated to a pre-specified temperature. If NOx emissions are an issue for a particular process, the dominant source of NOx in the flue gases must be identified if the appropriate NOx reduction technology is to be employed to facilitate it's reduction without compromising the process thermal requirements. In the cement industry specifically, with the kiln fired with solid or liquid fuels, very high flame temperatures occur i.e.., above 2200°C, and thermal NOx is generally the dominant mechanism accounting for between 60 and 70 % of the total NOx appearing in the flue gases.

In gas fired plant, by contrast, fuel NOx is absent so all the NOx is thermal NOx. However, it should be noted that the absence of fuel NOx in gas fired plant does not necessarily lead to a reduction in NOx emissions, since flame temperatures are often higher.

FUTURE DIRECTION

With over two hundred examples of the aforementioned modelling techniques successfully applied to a wide range of real plants over the past 15 years the authors have considerable confidence in the use of these techniques. Much of the future emphasis of FCT's work will be directed towards NOx reduction while maintaining and improving predictability and product quality.

CONCLUSIONS

1. The success of the modelling process is more dependent on the engineer's skill at interpreting the plant data and determining the relevant modelling techniques to use than the elegance of the techniques themselves.

2. Only engineers adequate trained in modelling generally, and computer modelling of combustion in particular, can be used to 'operate' these models.

3. One technique used alone rarely gives sufficient information to provide a reliable solution. Engineers using modelling must therefore be skilled in the use of all the methods so that they do not favour the use of one technique above the others in possibly unsuitable circumstances.

4. The users and designers of combustion equipment have tasks to perform of such magnitude that failure is not to be contemplated. No one should be willing to employ predictive means which have not been validated and in which they do not have complete faith.

5. A thorough understanding of the various NOx formation mechanisms in combination with a detailed knowledge of the combustion process and the thermal and chemical requirements of the material being heated in a rotary kiln is necessary to design an effective low NOx combustion system.

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The above is a limited and greatly simplified approach to the theory of thermal NOx formation and is included to allow an appreciation of the complexity of the theory and the difficulty of making theoretical predictions of thermal NOx emissions. Figure 6 shows the extreme temperature dependence of thermal NOx formation.

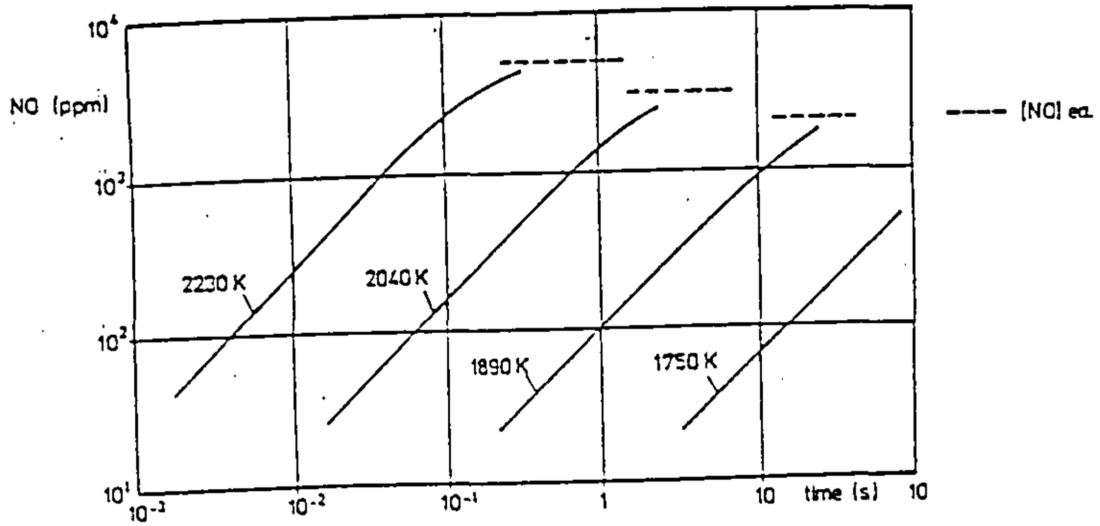

Figure 6 Dependence of Thermal NOx Formation Rate on Temperature

Fuel NOx

Fuel NOx is generally associated with coal or petroleum coke combustion which contain nitrogen chemically bound within their structures, and to a lesser extent with oil. Most studies on fuel derived NOx have been performed on coal and the main focus of this section is related to fuel NOx derived from coal combustion. The mechanisms by which NOx is formed from the chemically bound nitrogen in coal is extremely complex, even the structure of the nitrogen in the coal is subject to considerable conjecture. The nitrogen is believed to be in the form of pyridine, pyrrol and amine type structures, Figure 7. The actual structure in any coal or oil is believed to be strongly dependent on coal type or the origin of the oil. The predominant forms of nitrogen in most coals are the pyrrolic and pyridine forms and that the former tends to decrease with increasing coal rank. However, at present, the importance of the structure of the nitrogen in the coal on the final NOx emissions is not well established.

When coal is burnt in suspension as in rotary kilns, it is heated very rapidly to high temperatures and pyrolysis occurs, producing solid and gaseous products. The nitrogen present will divide between these with typically 20% of the nitrogen in the char and 80% in the gaseous phase, the latter both as the light fractions and tars. For any coal, the distribution of nitrogen between the gaseous phase and char is heavily

PROCESS OPTIMIZATION AND FUEL COST REDUCTION IN CLINKER PRODUCTION. THE APPLICATION OF FLAME CONTROL

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Fuel and Combustion Technology Ltd

INTRODUCTION

Fuel costs are normally a major factor in cement production costs whatever fuel or manufacturing process is used. The relative cost of fuel as a proportion of the manufacturing costs is, of course, different for the different processes but fuel savings normally result in significant cost savings and increasing profits for the operator/owner, whatever the manufacturing process.

Cement manufacture requires a very precise rate of heating and cooling of the charge in order to complete the chemical reactions and achieve the appropriate crystaline structure.

To achieve the appropriate charge heating rates, the flame must produce the correct heat flux to the product (1). Too low a heat flux produces high free lime material whilst too high a heat flux produces overburnt clinker with excessive liquid phase. In both cases poor cement strengths result. In practice the plant operator adjusts the heat flux to the product by changing the flame length by altering the excess air, figure 1. Increasing the excess air, shortens the flame and increases the heat flux to the charge. At the same time the increased air flow carries more heat to the preheating zone of the kiln and hence to the atmosphere thereby increasing the kiln heat losses and hence increasing the fuel consumption.

In a cement kiln the increased air flow through the coolers also causes a reduction in the secondary air temperature, and therefore a reduction in the flame temperature, thus requiring even more fuel to heat the charge to the required sintering temperature. The total increase in fuel consumption due to excess air is much greater than that necessary to heat the excess air to back-end temperature alone.

Reducing the excess air increases the flame length and reduces the heat flux to the charge. The reduced air flow through the kiln carries away less heat and hence the fuel consumption is lower. Figure 2 shows the effect of kiln oxygen level on the measured heat consumption for a pulverised coal fired cement kiln (2). It can be seen that the effect of excess air on kiln thermal efficiency is very considerable.

There is a clear advantage in low excess air operation, since the kiln fuel consumption is minimised. However, it is not possible to operate at low excess air if the kiln flame is too long and the heat flux is inadequate to make good clinker. This is the reason that, the instructions to plant operators by senior works staff to reduce oxygen levels, during and following the energy crisis in the early 1970's, appeared to fall on deaf ears. It was not possible for kiln operators to reduce the kiln oxygen level and still manufacture satisfactory clinker. Since the operator got into more trouble for making bad clinker, than for running the kiln at a higher oxygen level than was ideal for fuel economy, his choice of action was obvious.

Effect of Burner Design on Combustion Efficiency

The burner is one of the most critical components of the kiln system. It is only in recent years that the real importance of burner design has become recognised. However, even today, it is unusual for the burner to be considered as an integral part of the kiln and cooler system, which is essential for optimum operation of a cement kiln. Most kiln burners will operate in most kilns reasonably satisfactorily but in many cases it is difficult to achieve oxygen levels below 2-4% without carbon monoxide and still maintain product quality. To operate consistently at an oxygen level of 1-2%, and maintain product quality, requires that the burner is matched to the aerodynamics of the kiln/cooler system. This technique, pioneered by Moles of the Fuels and Energy Group at the University of Surrey is known as "Flame Control" (3). It can typically save in the order of 5% of the fuel which would otherwise be used on a kiln utilising a burner which was not matched to the kiln aerodynamics. Flame control applies equally to oil, gas or pulverised coal firing.

Combustion In Rotary Kilns

The heat producing components of oil, coal and natural gas are carbon and hydrogen and these are oxidised to release heat. The chemistry of this oxidation process is a very complex chain reaction. However, for our purposes we can reasonably simplify the chemistry to three basic equations:-

1. The Complete Oxidation of Carbon

$$C + O_2 \longrightarrow CO_2 + 394 \text{ kJ/mol}$$

2. The Complete Oxidation of Hydrogen

$$2H_2 + O_2 \longrightarrow 2H_2O \begin{array}{l} \nearrow \begin{array}{c} +572 \text{ kJ mol} \\ \text{water condensed} \end{array} \\ \searrow \begin{array}{c} +484 \text{ kJ/mol} \\ \text{water as steam} \end{array} \end{array}$$

The difference in the physical states of the water vapour produced as a result of the oxidation of the hydrogen is the reason for the complexity of the net and gross calorific values for hydrocarbon fuels.

3. The Incomplete Oxidation of Carbon

In the event of imperfect fuel/air mixing not all of the carbon in the fuel will be oxidised to carbon dioxide but a proportion will remain as carbon monoxide. The main effect of carbon monoxide production is to reduce the heat released from the fuel, this is because the oxidation of carbon to carbon monoxide releases less heat than the oxidation to carbon dioxide.

$$2C + O \longrightarrow 2CO + 221 \text{ kJ/mol}$$

It can be seen that only just over half of the heat is released in the production of carbon monoxide compared with the production of carbon dioxide. Thus, any burner producing carbon-monoxide, as a result of bad fuel/air mixing, will cause a significant reduction in combustion efficiency and a consequent increase in the heat consumption of the kiln.

Stage in Combustion

Even an apparently instantaneous explosion does not, in fact, take place instantaneously but all combustion processes take place in the following stages;

MIXING - IGNITION - CHEMICAL REACTION.

The rate of combustion is dependent on the slowest of the above stages. In most industrial combustion systems the mixing is slow whilst the ignition and chemical reaction are very fast. The rate and completeness of combustion are therefore controlled by the rate and completeness of fuel/air mixing hence the saying of combustion engineers;

"IF ITS MIXED, ITS BURNT".

Figure 3 shows the heat loss in the flue gases plotted against the excess air level. As the excess air level is reduced so the heat loss in the flue gases is also reduced until a minimum is reached. Reducing the excess air level further causes a rise in heat loss in the flue gas due to the incomplete combustion of the carbon. The more efficient the burner, the lower the excess air level at which this minimum occurs. The position of this minimum is almost entirely a function of the efficiency of fuel/air mixing of the burner system. Furthermore, the nearer to zero excess air at which the minimum occurs, the lower is the quantative heat loss at the minimum condition.

The process design of kiln burners often occurs in isolation from the kiln system itself, and only factors such as fuel flowrate and primary air are considered. However, in practice, a kiln burner system consists of: the burner itself, the primary air system, the fuel supply system and the secondary air. Since the majority of the combustion air is secondary air supplied from the cooler directly into the kiln, the kiln and cooler aerodynamics play a critical part in the fuel/air mixing and hence the overall performance of the burner. It is therefore absolutely essential when designing a burner for a cement kiln firing system to ensure that the burner is correctly matched to the individual kiln aerodynamics.

Flame control in rotary kilns consists essentially therefore, of matching the burner characteristics to the aerodynamics of the particular kiln.

Factors Controlling Fuel/Air Mixing

Fuel/air mixing occurs as a result of jet entrainment. Friction occurs at the boundary between the fast moving primary jet and the slower secondary air, Figure 4. As a result of this friction the secondary air near to the jet boundary accelerates to the jet velocity, which is thereby slightly reduced by momentum transfer. The jet expands because of the increased mass resulting from the entrained air. This process continues until the jet velocity is the same as the velocity of its surroundings. If the primary jet has sufficient momentum to entrain all the secondary air and still has a greater velocity than its surrounding atomosphere, the excess momentum will entrain flame gases from further up the kiln. This phenomenom is known as 'recirculation', see Figure 5. The presence or absence of recirculation has a great effect on the flame characteristics. A moderate degree of recirculation is a positive indication that fuel/air mixing is complete, whilst the absence of recirculation is a clear indication that not all of the secondary air has been entrained into the primary jet. Furthermore, in the absence of recirculation there is a tendency for the primary jet to expand until it impinges on the brickwork. Figure 6 shows the primary jet in a planetary cooler kiln. The jet expands such that the theoretical point of impingement is at J. Rapid wear occurred to the brickwork between A and B and led to repeated and early failure of the kiln lining.

The onset of recirculation for axial flow burners can be calculated using the Craya-Curtet (4) parameter M:-

$$M = -1.5\, R^2 + R + \frac{KR^2}{(do/D)^2}$$

where K = 1 for cement kilns and

$$R = \frac{(Uo - Ua)\left[\frac{do}{2}\right]^2}{Ua\left[\frac{D}{2}\right]^2 + (Uo - Ua)\left[\frac{do}{2}\right]^2}$$

Uo = nozzle velocity
Ua = Secondary air velocity
do = nozzle diameter
D = kiln diameter (inside bricks)

For Craya-Curtet parameters of less than 1.5 recirculation is absent, whilst for Craya-Curtet parameters greater than 1.5 recirculation occurs.

The effect of swirl on the primary jet is to open the primary jet and increase the rate of entrainment. Internal recirculation occurs but the risk of jet impingement on the kiln brickwork is greatly increased. It is much more difficult to calculate the conditions for the onset of recirculation with swirl burners than for axial flow burners. The modified Thring-Newby parameter is normally used for calculating the onset of swirl for swirl burners. However, this parameter does not really apply within the close confines of the cement kiln. In fact, the benefits of swirl are greatly reduced within the close confines of a cement kiln compared to, for example, a water tube boiler or petrochemical heater. In recent years the use of swirl to enhance fuel/air mixing has become less fashionable and higher combustion efficiencies have been achieved using axial flow burners and paying detailed attention to the overall system aerodynamics.

Matching the Burner to the Kiln Aerodynamics

The flow of secondary air into the kiln is considerably affected by the design of the cooler uptake and hood system, or in the case of planetary coolers, by the cooler elbows. To obtain the optimum potential performance from any kiln it is absolutely essential that the aerodynamic characteristics of the kiln are taken fully into account when designing the burner.

Unfortunately, aerodynamic theory is not sufficiently well developed to permit analytical solutions or even realistic mathematical modelling for real aerodynamic systems. Such mathematical models as do exist for kiln systems (5.6) assume a symmetrical non swirling secondary air flow, a situation far from realistic for the majority of rotary kilns. The use of mathematical models to predict combustion characteristics in kiln systems is therefore limited to very rough approximations only. In order to model the combustion and fuel/air mixing in a burner/kiln system, physical modelling must be resorted to.

The Fuels and Energy Research Group at the University of Surrey have made extensive tests of kiln aerodynamics using water/air model tests and full size investigations (7). Typical aerodynamics for a grate cooler kiln are illustrated in Figure 7, which shows air flow patterns for high and low momentum jets. It can be clearly seen that there is a significant difference between the secondary air flows in the two cases, in particular the size and strength of the recirculation zones which decrease with decreasing jet momentum and eventually disappear.

The relationship between the jet momentum and the secondary air velocity has a significant effect on the flame length and heat transfer. Kilns with very low jet momentum have poor fuel/air mixing and long flames, whilst a high jet momentum gives rapid fuel air mixing and short flames. Long flames often result in underburnt clinker. Low momentum burners therefore, have to be operated at high levels of excess air in order to shorten the flames sufficiently to make good clinker.

Physical Modelling of Rotary Kiln Flames

To investigate fuel/air mixing in rotary kilns acid/alkali modelling is used (8,9). A physical model of the kiln and cooler is constructed to an appropriate scale in clear acrylic plastic.The actual scale to which the model is manufactured is dependent on the size and complexity of the original system but it is important that dynamic similarly is maintained otherwise misleading conclusions may result. The fuel is represented by dilute caustic soda soulution containing phenolphalein indicator, whilst the combustion air is represented by dilute hydrochloric acid. The phenolphalein becomes colourless at the boundary where the mixing is complete thus the model flame envelope is defined by the coloured region, Figure 8.

To translate these model results into predictions for the combustion conditions in the full size kiln requires considerable skill. The model is run under isothermal conditions whilst in the full size plant considerable changes in temperature occur as combustion takes place, resulting in a reduction in the gas density and an increase in volume, hence the real flame is longer than the model flame, owing to the volumetric increase. A further increase in flame length occurs with heavy oil, pulverised coal and petroleum coke flames owing to the time required to burn the particles once fuel/air mixing is complete. Except for low volatile fuels such as anthracite and petroleum coke, this effect is minimal hence the "IF ITS MIXED ITS BURNT" hypothesis holds. Therefore, for most practical purposes the model flame length has only to be corrected for the density changes. However, where flames of very low volatile fuels are being modelled it is ncessary to use the physical modelling data as an input to a mathematical model which predicts the particulate burn out to determine the actual flame length.

Thus by using acid/alkali modelling and, where necessary, mathematical modelling of particulate combustion, it is possible to assess the performance of any burner in any kiln system. Furthermore, the effect of excess air on the flame length can be predicted, Figure 9. It is now possible to assess the effect of changes such as burner design and position, primary air quantity and velocity and changes in fuel type very rapidly for any kiln system without any disruption to the operating plant.

Application of Flame Control to Rotary Kilns

Rotary kilns are used for processing a wide variety of materials such as titantium, iron oxide, petroleum coke, etc. as well as cement and lime. In order to match the flame to the process requirements of the kiln it is therefore necessary to have a good understanding of the time/temperature characteristics which are necessary for processing the particular material concerned.

An exhaustive investigation of the combustion and heat transfer in a small cement kiln (10) showed that the optimum heat flux to the charge in the sintering zone was 110 kW/m². To ensure optimum product quality this heat flux had to be maintained within a range of ± 2%. A lower heat flux produced underburnt clinker with high free lime whilst too high a heat flux produced overburnt clinker with too much liquid phase.

Subsequent mathematical modelling, backed up by practical operating data (11) has shown that the combustion intensity required in wet and dry process cement kilns to produce the optimum product is given by the following expression:-

$$H_r = \frac{m_f C_v}{L_f \ D}$$

Where:- H_r = Combustion intensity KW/m²

m_f = Fuel flowrate Kg/s

C_v = Nett calorific value KJ/Kg

L_f = Flame length m

D = Kiln internal diameter m

Special consideration must be given to precalciner kilns and detailed mathematical modelling is required for these kilns to establish the optimum combustion characteristics. Once the combustion characteristics required for optimum kiln operation have been defined it is possible to use the physical modelling techniques described above to determine the burner characteristics (primary air flowrate, nozzle velocity, etc.) required to produce the correct flame at 0.5 - 1.5% oxygen, while maintaining the carbon monoxide level at below 600 ppm.

Kiln burners designed using these techniques are thus uniquely matched to the kiln for which they are designed and the optimum kiln fuel consumption and output is ensured by low excess air operation, combined with minimal fuel waste due to incomplete combustion.

The practical consequences of this approach to kiln burner design is that two burners designed for two kilns of similar production rates and heat consumption may require quite different primary air flow rates and velocities owing to the different aerodynamic characteristics of the two kilns.

Acid/Alkali Modelling as a Combustion System Design Tool

Acid/alkali modelling is often used to investigate operational problems with existing combustion systems. The solutions which are determined can then be applied on the full size plant. The real value of acid/alkali modelling, however, is as a process design tool. The flame characteristics required by the particular process for which the burner is to be designed are reproduced on the model. From a knowledge of the aerodynamics and mixing of the system, the fuel burn out and heat transfer is then calculated. Provided these meet the system requirements, detail design may proceed, otherwise the model system is modified until the plant requirements are satisfied.

Once the basic design has been completed using the techniques described above, the detail mechanical design is undertaken. Equipment specifications are prepared and detail drawings made.

An example of the use of acid/alkali modelling as a practical design tool is the work undertaken in connection with re-burnering a lime kiln to burn natural gas with a liquid fuel firing standby system.

Conversion of a Lime Kiln to Natural Gas Firing

FCT was asked to consider the conversion of a kiln manufacturing metallurgical lime from liquid fuel firing to natural gas firing. Lime manufacture is an energy intensive process and the quality of the product is critically dependent on the combustion characteristics of the system. From the clients point of view, therefore, both the product quality and the energy consumption are critical. Either a deterioration in product quality or even a small increase in fuel consumption renders the process uneconomic.

A diagram of the lime kiln, which is a modern dry process kiln, is shown in figure 10. Limestone enters the preheater at ambient temperature and is preheated to calcining temperature (850°C) before entering the rotary kiln. In the rotary kiln section the remaining carbon dioxide is driven off to leave lime which then falls into the cooler. The combustion air is supplied to the flame via two paths: primary air through the burner and secondary air through the bed of lime in the cooler. Thus, the secondary air is preheated to between 780°C and 900°C. The actual preheat temperature depends on the operating conditions of the kiln and cooler.

The predominant mode of heat transfer in the rotary section is by radiation. The conversion from liquid fuel firing to natural gas firing could seriously reduce the radiant heat transfer owing to the lower flame emissivity of the natural gas flame unless steps are taken to increase the peak flame temperatures. This is accomplished by increasing the combustion intensity at a reduced excess air level thus compensating for the reduced flame emissivity. Furthermore, natural gas generates a greater quantity of flue gas than liquid fuel, and therefore the stack losses are higher for a similar temperature.

A complete investigation of the gas flows and temperatures was undertaken with the kiln operating on liquid fuel. Table 1 shows the operating conditions during these tests and Table 2 the resultant heat balance. The tests showed that the existing liquid fuel burner was operating with significant levels of carbon monoxide at the kiln inlet. The net heat input, after allowing for the latent heat in the flue gas, was 7511 kcal/s.

For optimum product quality and heat consumption, combustion should be complete at the kiln inlet and no carbon monoxide should be detected. Conversion of the kiln to natural gas firing, therefore, provided the opportunity to improve the combustion performance of the system, thereby maintaining the fuel consumption at the current level, in spite of the potentially higher stack losses expected from natural gas firing.

It is not possible to deduce, with any accuracy, the heat transfer characteristics in the rotary section from the heat balance data. It was, therefore, decided to model the existing burner system, as well as the proposed natural gas burner to determine the existing flame characteristics, and hence calculate the flame temperatures and heat fluxes within the rotary kiln. From this data it is possible to determine the optimum combustion characteristics for the proposed new burner.

A model of the kiln and cooler was manufactured in clear acrylic plastic to a scale of 1:50. The rotary section, kiln hood, shaft cooler and secondary distributor were faithfully reproduced. It was not necessary to model the preheater section since this is downstream of the areas of interest.

Tests were undertaken on the model simulating the existing liquid fuel burner, the new dual fuel burner firing natural gas and the new dual fuel burner firing liquid fuel. Both the existing burner and the proposed new burner featured annular primary air nozzles and were represented on the model by a simple plain jet. The jet area, however, was not scaled linearly, as was the rest of the model, but the nozzle was scaled to maintain jet similarity using the Craya-Curtet parameter. Therefore, a different model burner was required for each of the three tests. The modelling criteria are summarised in Table 3.

Three basic factors affect the flame characteristics of a burner firing into a rotary kiln:

1) Momentum ratio between the primary jet and the secondary air.

2) The physical position of the burner relative to the kiln hood.

3) The excess air level in the kiln.

The object of modelling is to produce a burner giving both optimum heat transfer and complete combustion, without residual carbon monoxide at the minimum practical excess air level (2-5%). The main variables in this study were primary jet momentum and nozzle position. Using acid/alkali modelling as a design tool, the burner can be engineered to precisely match the process requirements. Moreover, it can be installed in the correct location for the individual kiln.

Figure 11 shows the effect of excess air on flame length, as predicted by the modelling tests for both the liquid fuel burner and the natural gas burner. It can be seen that the objective of increasing the combustion intensity, by reducing the flame length at a lower excess air, has been achieved with the natural gas burner aligned on the nose ring.

The flame temperatures and heat fluxes calculated by mathematical modelling (7) from the results of the acid/alkali modelling are given in figure 12. It can be seen that while the heat flux with natural gas firing is redistributed, compared with liquid fuel firing (owing to reduced flame emissivity), the actual quantity of heat transferred to the charge in the rotary section (area under the graph) remains similar.

The physical and mathematical modelling predicted that the kiln could be converted to natural gas firing and maintain the product quality without an increase in the net heat consumption. The dual fuel burner, shown in figure 13, was designed, constructed and installed.

Following the installation of the new burner, the kiln produced top quality product within 5 hours of feed on, and was at full production within 12 hours. After four weeks of highly satisfactory operation the guarantee trials were undertaken. The results are shown in Table 4. It can be seen that the temperature distribution throughout the kiln system is similar to that prior to conversion. The kiln heat balance is summmarised in Table 5. The net heat input of 7579 kcal/s is comparable to that in Table 2. The range of experimental error from these kiln tests was ± 3%. Thus the net heat consumption, following conversion to natural gas firing, is therefore, similar to the heat consumption for liquid fuel firing, within the limits of experimental error.

Conclusions

When physical modelling is used in conjuction with mathematical modelling as a process design tool, it is possible to eliminate guess work from burner design and, therefore, to match the flame characteristic produced by the burner to those required by the process.

The commissioning period is also reduced compared with the conventional approach, since the optimum position for the burner is known prior to installation, and time consuming trial and error optimisation is eliminated. Therefore, the plant achieves full production within days rather than weeks and months.

The practical benefits of this approach are better product quality and reduced costs for the client. Immediate cost benefits arise from a greatly reduced commissioning period. However, the real savings are continuous and on-going because the fuel consumption of the plant is minimised through efficient combustion and optimum heat transfer.

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10. Jenkins B.G. Heat Transfer in Rotary Cement Kilns. Ph.D Thesis. Univ. of Surrey. 1976.

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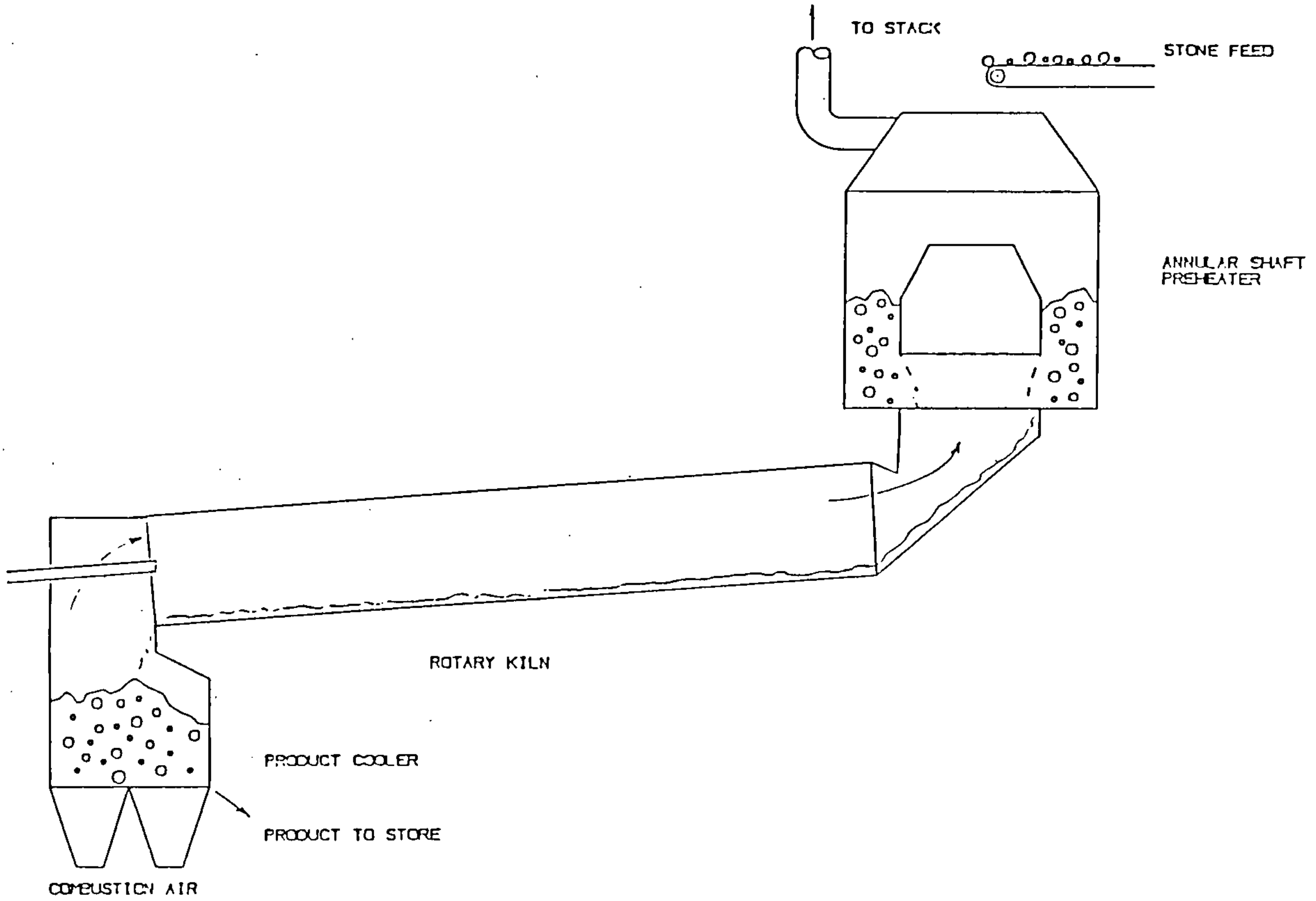

FIGURE 10 LIME KILN SYSTEM

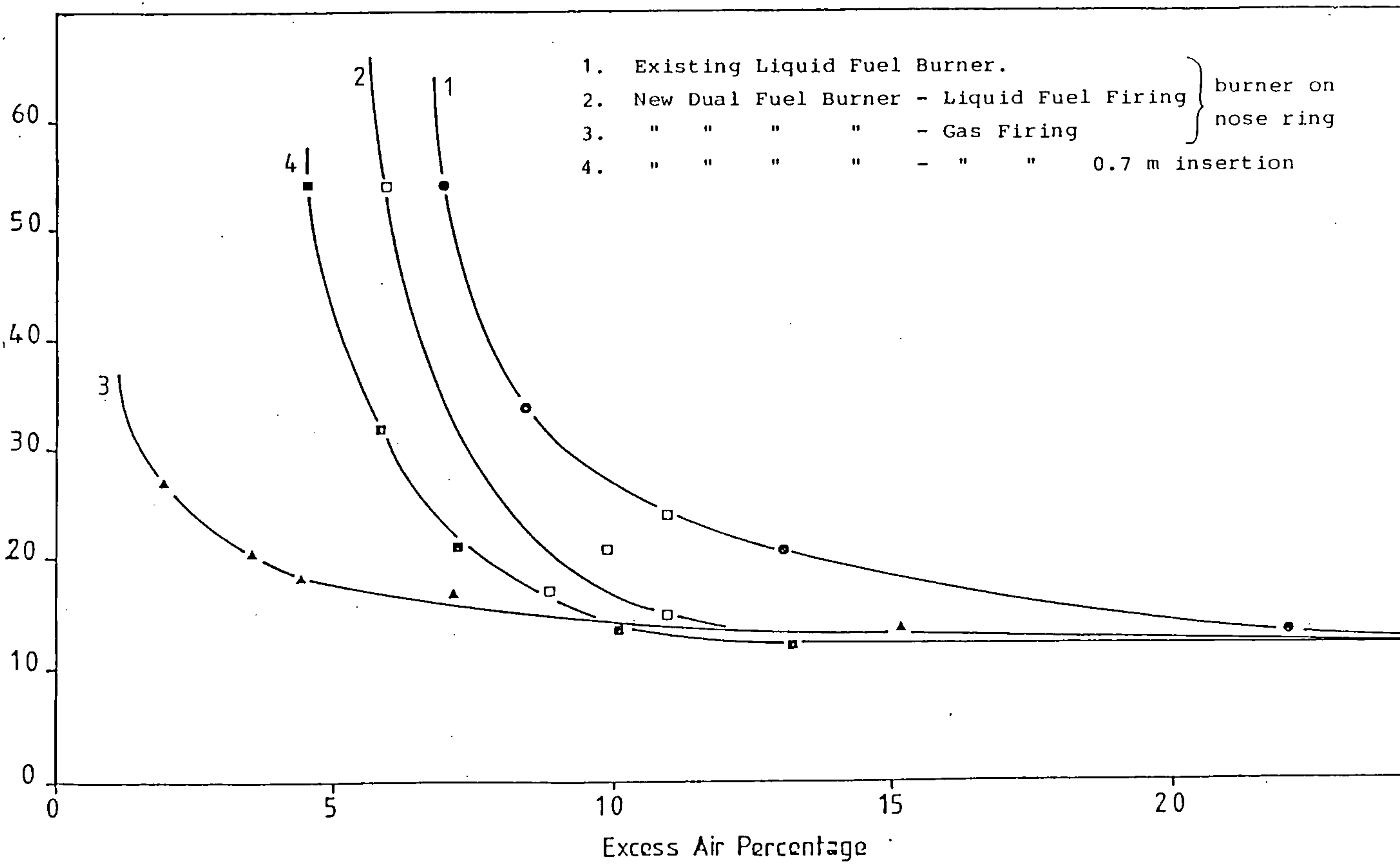

FIGURE 11 EFFECT OF EXCESS AIR ON FLAME LENGTH FOR LIQUID FUEL & NATURAL GAS BURNER

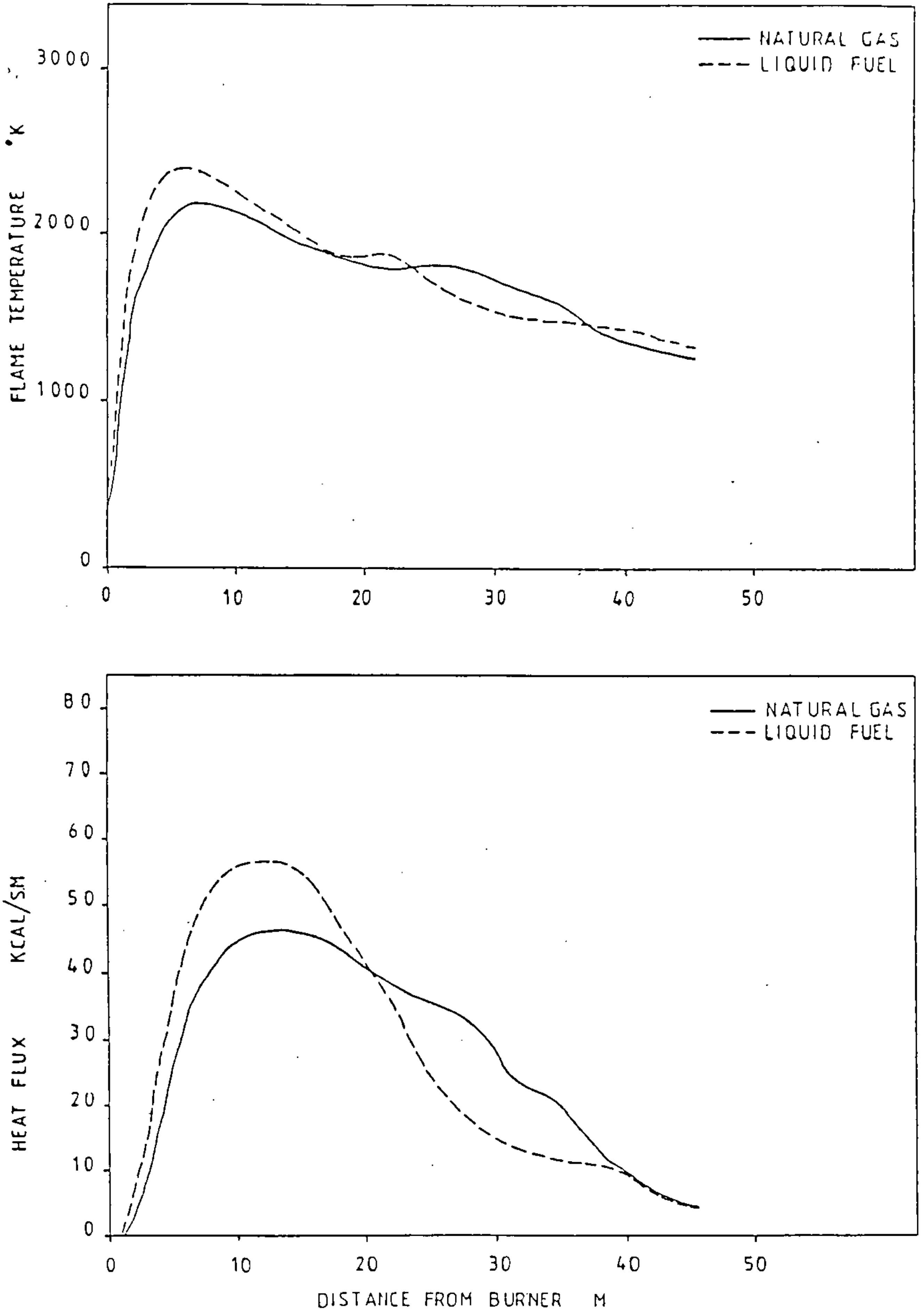

FIGURE 12 PREDICTED FLAME TEMPERATURE AND HEAT FLUXES

Ambient temperature 18°C

TIME	10.00	10.20	10.40	11.00	Average
Sec Air Temp (°C)	870+-5	870	875	860	869
Gas Temp at (°C) Kiln inlet	1348	1341	1350	1348	1346
Flue gas temp (°C) South	248	288	295	289	281.5
Flue gas temp (°C) North	283	278	265	270	
Kiln inlet (%) CO_2	21-22	21-22	22-23	21-22	21.75
Kiln inlet (%) CO	2.7-3.3	3-3.5	2.5-3.5	2-3.5	3.0
Kiln inlet (%) O_2	0.3	0.3	0.3	0.3	0.3
Duct South No.1 (%) CO_2	27-27.5	26	26	probe blocked	26.8
Duct South No.1 (%) CO	0.02-0.09	0.1-0.4	0.2-0.3		0.11
Duct South No.1 (%) O_2	5.4	6	5.9		5.8
Duct North No.2 (%) CO_2	27	27-27.5	26	27.5	
Duct North No.2 (%) CO	0.03-0.06	0.03-0.06	0.09-0.15	0.02-0.05	
Duct North No.2 (%) O_2	5.9	5.8	6.4	5.3	
Product Temp °C ex kiln	1120	1150	1130	1150	1137.5
Product Temp °C in cooler	940	940	950	940	943
Product Temp °C ex cooler	130-140	140-165	130-140	130-140	140

TABLE 1 LIME KILN OPERATING CONDITIONS - LIQUID FUEL FIRING

Heat In (k cal/s)		Heat Out (k cal/s)	
Fuel (gross)	8294	Heat of reaction	4513
		Heat in product	197
		Heat in exhaust gas	1546
		Latent heat to flue gas	783
		Heat loss from shell	1123
Heat In	8294	Heat Out	8162
Heat In nett	7511		

Heat Unaccounted for 132 k cal/s

Table 2. Lime Kiln Heat Balance - Liquid Fuel Firing

	Liquid Fuel Burner	Dual Fuel Burner	
		Natural Gas Firing	Liquid Fuel Firin
Stoichiometric Air Fuel Ratio	15.4	16.5	15.4
Fuel Flowrate	0.70	0.68	0.70
Primary Air (% of Stoichiometric)	16	12	16
Excess Air Level %	5	5	5
Craya-Curtet Parameter	1.4	1.8	1.8
Equivalent) Full Size Nozzle) Diameter) Model (mm)	129 10.2	115 8.8	115 9.4

TABLE 3 MODELLING CRITERIA

Ambient temperature 15°C

TIME	12.00	13.00	14.00	15.00	Average
Sec Air Temp ($^{\circ}$C)	780	780	760	760	770
Gas Temp at ($^{\circ}$C) Kiln inlet	1361	1359	1357	1361	1359
Flue gas temp ($^{\circ}$C)	295	295	293	296	295
Kiln inlet (%) CO	0	0	0	0	0
O_2	1.2	1.1	1.3	1.2	1.2
Product ex kiln	1280	1310	1300	1340	1307
Temp $^{\circ}$C in cooler	950	940	920	925	934
ex cooler	185±15	150±20	160±10	150±40	161

TABLE 4 LIME KILN OPERATING CONDITIONS - NATURAL GAS FIRING

Heat In (k cal/s)		Heat Out (k cal/s)	
Fuel (gross)	8633	Heat of reaction	4466
		Heat in product	197
		Heat in exhaust gas	1665
		Latent heat to flue gas	1054
		Heat loss from shell	1025
Heat In	8633	Heat Out	8407
Heat In nett	7579		

Heat Unaccounted for 226 k cal/s

Table 5. Lime Kiln Heat Balance - Natural Gas Firing

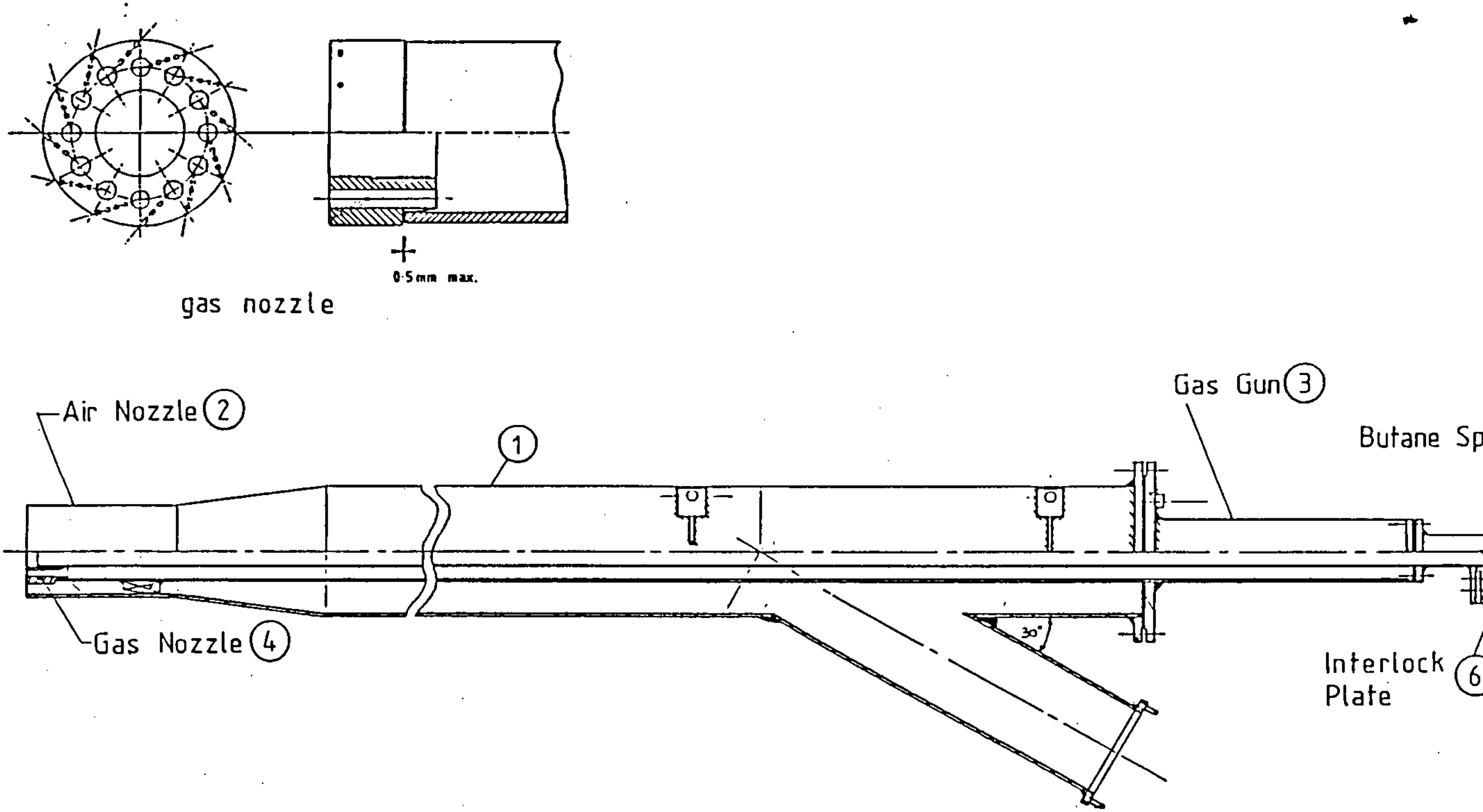

FIGURE 13 THE DUAL FUEL BURNER

Department of
Environmental Protection

Lawton Chiles
Governor

Virginia B. Wetherell
Secretary

January 8, 1999

CERTIFIED MAIL - RETURN RECEIPT REQUESTED

Mr. Joe Anderson, III
President
Suwannee American Cement Company, Inc.
PO Box 410
Branford, Florida 32008

Re: Additional Request for Additional Information
DEP File No. 1210465-001-AC (PSD-FL-259)
Proposed Portland Cement Plant

Dear Mr. Anderson:

The Department previously sent a letter dated December 29, 1998 requesting additional information required to make your application complete for an air construction permit for a Portland cement plant at US 27 at County Road 49, east of Branford. The Department has determined it has additional questions regarding this application. Please also submit the additional information requested below. Should your response to any of the below items require new calculations, please submit the new calculations, assumptions, reference material and appropriate revised pages of the application form.

1. The segment description of the application for the in-line kiln/raw mill for natural gas usage shows the proposed maximum annual rate is equivalent to operating the pyroprocessing system continuously on natural gas. This is inconsistent with the segment comment that natural gas is to be used as a startup and supplemental fuel. Please comment. Also, please evaluate the feasibility of operating the pyroprocessing system exclusively on natural gas, or primarily on natural gas with coal and petcoke used for supplemental or backup fuels. Provide an estimate of emissions of all pollutants under these scenarios. Please provide an estimation of the number of truck trips that would be reduced by these scenarios considering the offset of coal and petcoke that must be delivered to the proposed plant site by truck.
2. Please evaluate the feasibility of using low NOx burner technologies such as precessing gas jet burners (Gyro-Therm from Fuel and Combustion Technology, Inc.) or other burner technologies. Please provide a detailed cost analysis for these technologies in terms of overall and marginal cost effectiveness (annualized dollars/ton of nitrogen oxides removed) for NOx control using these technologies, including all references and assumptions.

Rule 62-4.050(3), F.A.C. requires that all applications for a Department permit must be certified by a professional engineer registered in the State of Florida. This requirement also applies to responses to

"Protect, Conserve and Manage Florida's Environment and Natural Resources"

Department requests for additional information of an engineering nature. If there are any questions, please call me at 850/921-9519.

Sincerely,

Joseph Kahn, P.E.
New Source Review Section

/jk

cc: Mr. Frank Darabi, P.E.
Mr. Steve Cullen, P.E.
Mr. Gregg Worley, EPA
Mr. John Bunyak, NPS
Mr. Chris Kirts, NED
Mr. Jim Stevenson, DEP Ecosystem Mgmt.
Mr. Tom Workman, DEP Recreation & Parks
Ms. December McSherry
Mr. Svenn Lindskold
Mr. Tom Greenhalgh
Mr. Al Mueller
Mr. Dave Bruderly

Fold at line over top of envelope to

Is your **RETURN ADDRESS** completed on the reverse side?

SENDER:
- Complete items 1 and/or 2 for additional services.
- Complete items 3, 4a, and 4b.
- Print your name and address on the reverse of this form so that we can return this card to you.
- Attach this form to the front of the mailpiece, or on the back if space does not permit.
- Write *"Return Receipt Requested"* on the mailpiece below the article number.
- The Return Receipt will show to whom the article was delivered and the date delivered.

I also wish to receive the following services (for an extra fee):
1. ☐ Addressee's Address
2. ☐ Restricted Delivery

Consult postmaster for fee.

3. Article Addressed to:
Mr. Joe Anderson, III, Pres.
Suwannee American Cement
PO Box 410
Branford, Fl
32008

4a. Article Number
Z333 612 588

4b. Service Type
☐ Registered ☒ Certified
☐ Express Mail ☐ Insured
☐ Return Receipt for Merchandise ☐ COD

7. Date of Delivery
1-20-99

5. Received By: *(Print Name)*

8. Addressee's Address *(Only if requested and fee is paid)*

6. Signature: *(Addressee or Agent)*
X

PS Form **3811**, December 1994 102595-97-B-0179 **Domestic Return Receip**

you for using Return Receipt Service.

Z 333 612 588

US Postal Service
Receipt for Certified Mail
No Insurance Coverage Provided.
Do not use for International Mail *(See reverse)*

Sent to Joe Anderson	
Street & Number Suwannee American	
Post Office, State, & ZIP Code Branford Fl	
Postage	$
Certified Fee	
Special Delivery Fee	
Restricted Delivery Fee	
Return Receipt Showing to Whom & Date Delivered	
Return Receipt Showing to Whom, Date, & Addressee's Address	
TOTAL Postage & Fees	$
Postmark or Date 1210 465-001-AC PSO-F1-259	1-8-99

PS Form **3800**, April 1995

INTEROFFICE MEMORANDUM

Sensitivity: COMPANY CONFIDENTIAL

Date: 08-Jan-1999 12:56pm
From: Joseph Kahn TAL
KAHN_J
Dept: Air Resources Management
Tel No: 850/921-9519

To: Alvaro Linero TAL (LINERO_A)

Subject: Gyro-Therm Burner

Al,

This morning I contacted Fuel and Combustion Technology, Inc. in Malvern, PA (610-725-8840) and spoke with Rick Schnarre about the Gyro-Therm precessing gas jet burner for cement plants and other kilns. He said that FCT markets the Gyro-Therm burner, other burners, and mechanical changes to kilns and precalciner facilities to reduce emissions and improve combustion. The Gyro-Therm burner technology has been available for 5 to 6 years and is presently being used in a LaFarge facility in Vancouver, BC and is being tested at an Ash Grove facility in Oregon. The burners are available as natural gas or dual fuel (gas and coal). The Gyro-Therm burner is intended to be used for the kiln burner, not the precalciner burner. Emission of NOx is reduced as a result of reducing thermal NOx from the gas combustion through lower temperature combustion and better mixing. Combustion efficiency is improved with the dual fuel burner as a result of better mixing of the coal and gas. They have not developed a burner that will fire gas and petcoke. FCT will evidently specify a percentage emission reduction they expect to achieve in comparison to a manufacturer's burner, but it is not possible to specify a general NOx limit achievable because the burners are custom-designed for each kiln.

I have written an additional incompleteness letter to Suwannee American asking them to evaluate this type of technology. I have also asked them to provide emission information based on assuming the natural gas would be the only fuel or the primary fuel.

ALACHUA COUNTY

OFFICE OF THE COUNTY ATTORNEY
Post Office Box 2877
Gainesville. Florida 32602-2877
(352) 374-5218
Fax (352) 374-5216

Mary A. Marshall
County Attorney

RECEIVED
JAN 05 1999
BUREAU OF
AIR REGULATION

RECEIVED
DEC 2 - 1998
DIVISION OF AIR
RESOURCES MANAGEMENT

Clair - pls comply
Howard 1/5/99

AL
IMPORTANT 1/5

December 23, 1998

Mr. Kirby Green, Secretary
3900 Commonwealth Blvd, MS 10
Tallahassee, FL 32399-3000

Dear Secretary Green:

The Alachua County Board of County Commissioners has requested that it receive all Notices of Intent to Issue Permits by the Department of Environmental Protection regarding the proposed cement plant in Suwannee County. Accordingly, please place the Board on the mailing list for all future Notices of Intent to Issue for that project. The mailing address is:

Alachua County Board of County Commissioners
Chuck Clemons, Chair
P.O. Box 2877
Gainesville, FL 32602

Thank you for your assistance in this matter.

Sincerely,

Mary A. Marshall

Mary A. Marshall
County Attorney

RL:eeh

pc: All Members, Board of County Comissioners
Richard D. Tarbox, County Manager
Department of Environmental Protection, Northeast District
7825 Baymeadows Way, Suite B-200, Jacksonville, FL 32356
Department of Environmental Protection, Air Resource Management
2600 Blair Stone Road, MS 5500, Tallahassee, FL 32399-2400