Stepping on the Gas

Gaël Le Piver, Fives, and Tom Lowes, OPECS, examine the use of natural gas burners for cement production.

When natural gas became available for industrial use in Europe in the late 1960s, there was a lot of concern over its emissivity for use in cement and other heavy industries. However, for practical use in a cement kiln, it was found that natural gas required no luminous flame, as the optical depth and kiln dust adequately compensated for the more luminous oil and coal flames.

Detailed work at the International Flame Research Foundation (IFRF) in the 1960s and 1970s showed that, by controlling...
early mixing using a swirl, any length or shape of flame that could be produced from coal or oil could also be produced by natural gas. In addition, CEMFLAME trials at the IFRF in the 1990s showed that NO\textsubscript{x} emissions were more strongly dictated by the position of the flame front than the flame temperature (Figure 1).

NO\textsubscript{x} is produced from fuel organic nitrogen (called fuel NO\textsubscript{x}) and from the nitrogen in the air (called thermal NO\textsubscript{x}). Fuel NO\textsubscript{x} reactions have an activation energy of 10 000 cal/mole, while thermal NO\textsubscript{x} reactions have an activation energy of 90 000 cal/mole. This makes it very sensitive to temperature. As natural gas has no organic nitrogen, all the NO\textsubscript{x} that it produces has to be made via the thermal NO\textsubscript{x} route.

While there are over 200 kinetic reactions in the production of thermal NO\textsubscript{x}, from the engineering design viewpoint of a low NO\textsubscript{x} burner, only a few need to be understood. These include the following:

1. \( \text{N}_2 + \text{O} = \text{NO} + \text{N} \)
2. \( \text{N} + \text{O}_2 = \text{NO} + \text{O} \)
3. \( \text{H} + \text{O}_2 = \text{OH} + \text{O} \)
4. \( \text{CO} + \text{OH} = \text{CO}_2 + \text{H} \)

Reaction one has high activation energy and reaction three represents the reaction of O\textsubscript{2} with hydrocarbon radicals, producing the O atoms for reaction one. Therefore, by starving the hydrocarbons of O\textsubscript{2}, it is possible to reduce NO\textsubscript{x} formation. However, the downside of too much O\textsubscript{2} starvation is also lower OH radicals – reaction four – and, thus, more CO. Natural gas burners need to be designed and operated to optimise both low NO\textsubscript{x} and low CO; this requires a large range of tools to modify mixing with secondary air, the oxygen at the flame core, and the internal reverse flow zone.

As natural gas has a lower flame temperature than the volatiles of oil and coal, the level of NO\textsubscript{x} produced from natural gas should be lower. However, this is not often found to be the case. This is down to the fact that natural gas has a high ignition temperature and narrow combustion limits, meaning it is not easy for it to have a short ignition distance.

Fives has overcome these issues and produced a low NO\textsubscript{x} natural gas burner. Thanks to the additive manufacturing process, the company has developed rotative swirler technology (RST) and an advanced flame front stabiliser.

Fives is now also looking to help its customers with Pillard Complete Combustion Solutions. It is also aiming to use its RST technology to overcome mixing, combustion, and heat transfer in calciners.

This article gives details of Fives’ low NO\textsubscript{x} natural gas burner design, as well as examples of how a RST gas system can resolve mixing, heat transfer, and combustion issues in air through and in line calciners.

**A low NO\textsubscript{x} natural gas burner for cement kilns**

In the 1970s, Blue Circle R&D carried out extensive development work on natural gas burners in the UK, Australia, and Mexico. Several types of swirl burner were developed and tested. The tests found the following:

- The momentum provided by the gas is preponderant, but there are some limitations in terms of gas velocity that could be used. Thus, the primary air still needs to reach between 10 N/MW and 12 N/MW. It also needs to mix secondary air efficiently in the jet entrainment zone, which is between 0 and 3 times the kiln diameter (Figure 2).
The higher the thermal load of the kiln, the higher the momentum that is required. This is because, for a high thermal load, more secondary air must be entrained in a limited area. As a rule of thumb, between 10 N/MW and 12 N/MW is needed for a gas burner for a modern kiln.

The swirl produced before the burner tip was not adequately transferred along the burner body to the flame, due to skin friction losses. As a result, in order to be used effectively, the swirl had to be generated at the burner tip.

At that time, NO\textsubscript{x} was not thought to be an issue, but it was noted that the single hole sonic jet, with its long ignition distance, gave more than 2000 ppm in a preheater kiln. However, this could be reduced significantly by pulling the burner back over the nose ring, where it was noted that the ignition distance dropped due to faster mixing in the cross flow.

As shown in Figure 3, the IFRF’s movable block swirl generator (MBSG) revealed that NO\textsubscript{x} could be reduced significantly by generating a swirl-induced internal reverse flow zone. This stabilised the flame on the burner, enhanced with a short quarl with a length to diameter ratio of 0.5. It should be noted that, while not at the burner tip, the IFRF’s MBSG only had a short distance to travel and, consequently, the tangential momentum was adequately maintained.

In the 1970s, the IFRF also showed that swirl number was only a scaling criterion for forced vortex rotation; this is not produced by swirl vanes or the MBSG, where more of an intermediate vortex is produced.

To generate a swirl-induced internal reverse flow zone with the MBSG, the swirl number was found to vary between 0.5 and 1, depending on the axial velocity of the combustion air. However, it occurred at the same MBSG setting. Since that time, the IFRF never referred to swirl numbers in its document again, instead replacing it with swirl ratio.

The IFRF also found that, with the swirl-induced internal reverse flow zones, there were precessing vortex cores that appeared to help flame stability. The use of a swirl on a cement kiln burner, at a level that does not produce a swirl-induced internal reverse flow zone, only widens the flame, and does not shorten its ignition distance. This means that when petcoke or alternative fuels are used via the burner, the swirl setting is normally at the minimum level.

Fives has developed and patented an improved concept of MBSG that is adapted to rotary kiln firing on all its gas burners (Figure 4). The efficiency has been improved, with tangential path flow directly at the burner tip. The Pillard Novaflam® system has successfully replaced the previous fixed gas swirler. The innovative RST system has been successfully applied at many plants and has been the standard solution for gas firing for more than four years.

The RST is used to produce a variable swirl on the natural gas with an axial primary air channel, as needed. The second important feature is that the gas cross section is adjustable. This allows a sufficient level of momentum to be maintained in case of the burner not operating to its normal capacity, if the gas is cofired with another fuel, or if low heat value, and thus flow, is varying. This is generated in a large majority with gas from the gas burner itself.

Maintaining a high and optimised level of momentum, no matter what the kiln operation is, can be achieved – ensuring good mixing and gas combustion. This would help to maintain a
low kiln back-end CO level, even with between 1% and 2% $O_2$ – this is also a great help with keeping NOX as low as possible.

Figure 5 shows how the Pillard Novaflam design has decreased the NOX produced by the burner that it replaced, averaging about 800 mg/Nm$^3$ at 10% $O_2$.

In addition to an increase to the stability of the flame front, two extra features have also been added. Firstly, there is a flame front stabiliser, which is based on the experience at the IFRF in the CEMFLAME trials, which had up to 5% of the burner natural gas in special Pillard-patented BLUEMIX Technology.

Secondly, as the best design will fail if tips are not maintained in a constantly clean state (especially with sticky material and a dusty kiln), Fives has developed a maintenance tool with special scraper 3D printing. This is to be inserted in the burner’s central jacket pipe, to allow for safe and efficient burner tip cleaning during burner operation (Figure 6).

The Pillard RST is designed to go up to a maximum of 45° of swirl, and a swirl-induced internal reverse flow zone is normally established at a 50/50 split of swirl to axial air.

With these design aspects in a Pillard Novaflam for natural gas (with a gas pressure up to 0.9 bar, whatever the fuel mix, gas flow, or gas lower heating value is, as well as a primary air fan or blower providing the extra momentum and flame shaping as needed), kilns can be expected to operate and maintain a good output of 800 mg/Nm$^3$ or lower at 10% $O_2$ on pure natural gas alone.

Enhanced calciner performance on natural gas

When natural gas is used in a calciner of any type (separate line, in line, or air through), the main issues are the following:

- To have enough local mixed $O_2$ to ensure ignition.
- To ensure enough injector momentum for good mixing with the kiln and tertiary air $O_2$, as well as the meal from the splash boxes.

Via its Pillard Complete Combustion Solution drive, Fives is now helping its customers to obtain a better performance from their calciners, in terms of lower NOX output – with the help of computational fluid dynamics if needed (Figure 7).

A typical example of a problem with air through and in line calciners is the need to assess the penetration and the entrainment of the natural gas jet in the upward flow of the riser/calciner gases. The following is an equation that was developed from the pre-computational fluid dynamics work in the 1960s. It has been modified by recent practical experience and comparisons with good level mineral interactive computational fluid dynamics predictions.

- **Entrainment into a jet of cross:** $M_j/M_o = 1.75 \times (0.32 + 0.8S) \times (x/d_o) \times (T_o/T_s)^{1/2}$
- **Cross flow jet:** $y/d = 1.0 \times \lambda^{**-0.85} \times (v/d)^{**n}$
- $n = 0.34$
- $\lambda = \sqrt{(p_u/p_j) \times v_u/V_j}$

Figure 6. Fives burner cleaning tool CLEANTIP™.

Figure 7. Computational fluid dynamics of the temperature profile in a calciner.

Figure 8. The mixing of burner and riser/calciner flows.
The cross flow jet equations give the curves shown in Figure 8.

**Case study one**
An air through calciner, with four simple natural gas injectors with 0.6 bar located at various positions in the riser, was experiencing a more than 8% increase in fuel consumption and a drop in output when using 20% natural gas in the riser.

The Fives Pillard assessment was that the four momentums of the natural gas injector were not sufficient to penetrate to the centre of the riser. This was leading to a need to entrain the O₂ from the kiln in the upflowing riser gas. The simple injector was replaced with two RST systems with swirl settings of 30°, giving a swirl number of 0.4 (2/3tan(30)) and a pressure of 1.2 bars. The result was better natural gas mixing into the riser and the improved combustion of the riser O₂ as well as more heat transfer to the meal. This has allowed specific consumption to be improved and production to increase.

**Case study two**
This is similar to case study one, except it concerns a calciner where the heat transfer to the meal was not good enough. This had resulted in a 50/50 fuel split and high free lime clinker.

Four low NOₓ natural burners with 0.3 bar had been injected at the same locations as the meal splash boxes, 1 m above the tertiary air duct. They penetrated the riser even less than that shown in Figure 9 and, hence, did not entrain the tertiary air fast enough to provide good heat transfer to the meal.

The solution to the problem was to have two adjustable burners, properly designed, with 1.2 bar and 30° of swirl, injected horizontally 1 m directly below each tertiary air duct.

**Conclusion**
As many plants will certify after suffering from an unsuccessful switch from coal to gas, burning gas in cement kilns and calciners is not as easy as it seems. The process requires a large range of tools and tailor-made solutions for both the kiln and the calciner. A high and practical level of expertise is required, that takes into account past learning and research. In addition, modern numerical tools should be used, and there should be a dedicated team that validates innovative solutions onsite. All these are the essential prerequisites for making the challenge of fuel switch a success for overall kiln performance (including NOₓ-specific consumption and production levels).

Fives has almost 100 years of experience in combustion and is backed up with a R&D team with in-house computational fluid dynamics modelling and has recently inaugurated one of the most modern combustion test centres in Europe (Figure 11). With over 150 Pillard gas firing kiln burners successfully operating around the globe on cement kilns and calciners, Fives is a world leader when it comes to helping the cement industry to fire natural gas.

**About the authors**
Tom Lowes spent 15 years in Academe/International Flame Research Foundation, followed by 35 years working in cement for Blue Circle, Lafarge, Holcim, and Cinar. He is now a Director of OPECS, providing solutions to process, emissions, and quality issues in cement production.

Gaël Le Piver joined Fives Pillard in 2001. After five years as a commissioning engineer, he joined Fives Pillard Technical Direction in 2006 and is now responsible for the Mineral Activities Department.