# Maximizing alternate fuels using modeling and flexible burner design

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## Introduction

It has been said that after water, concrete is the most used material by man. Cement is the key ingredient that makes our buildings and infrastructure possible.

The cement industry has come a long way in reducing energy consumption since the days of old wet kiln technology. Precalciner and high efficiency cooler technology and more recently waste heat recovery have made significant reductions in the energy consumed. However, fuel is still required for both the kiln and calciner and constitutes a large portion of manufacturing cost. To reduce cost, the use of alternative fuels (AF) such as refuse-derived fuels (RDF) is on the rise.

The use of AF comes with its own set of challenges that must be met. To maximize the benefit to all, the use of AF needs to be properly investigated for the impact it has on the cement manufacturer and the community.

This paper provides a blueprint for how to maximize the use of alternative fuels and minimize any negative effects - such as environmental impact via $CO_2$ and NOx emissions, and reduction in production and quality - using:

- A modeling approach to alternative fuels, to select the appropriate alternate fuel, its preparation, feed location and burner design.
- A new flexible burner design that enables optimization of combustion performance with different combinations of fuels.

## Where should alternative fuels be burnt?

Before we answer that question, we should ask where do we want high-grade and low-grade process heat? Ignoring energy losses, the calcination process consumes the most energy as shown in **Figure 1**. The net energy requirement for producing clinker is low by comparison to calcination due to the exothermic Alite ($C_3S$) formation reaction. Therefore, in modern kilns more fuel is required in the calciner than the kiln.

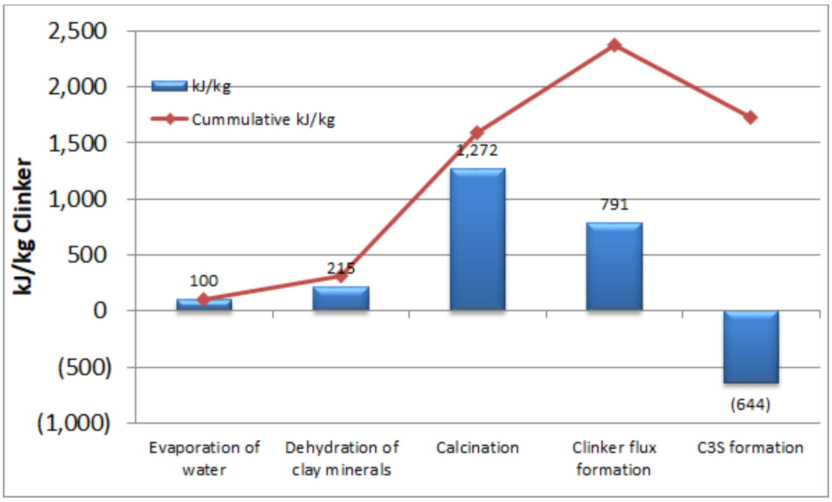


**Figure 1:** Energy consumed in processing raw meal into clinker, excluding thermal losses.

In a cement plant, the suspension preheater tower and cooler grate are heat exchangers used to either preheat or cool, raw meal and flue gas, and combustion air and clinker. The suspension preheater and cooler grate are not where we want to generate energy from combustion, but rather where we recover it. The highest-grade heat is required in the kiln (>>18MJ/kg) due to the high temperature required to process the raw meal into clinker as shown in **Figure 2**. The fuel in the kiln must have sufficient energy density to reach material temperatures in the order of 1450°C so that the meal partially melts contributing to:

- Good clinker nodulization (not fine and dusty, not large and unable to be heated/cooled effectively)
- Stable coating for long brick/campaign life
- Bringing reacting materials into close contact and rapid reaction.

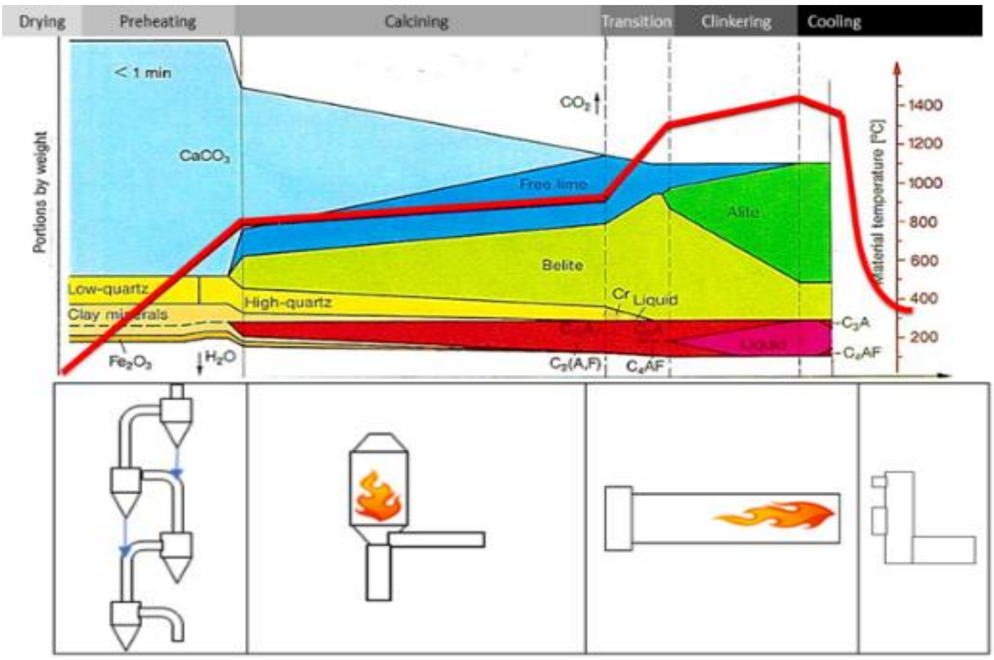


**Figure 2:** Reactions and phase changes and the associated material temperature through the preheater, calciner, kiln and cooler.

In addition, the fuel must burn fast and transfer its heat to the clinker bed close to the discharge end of the kiln to achieve a short burning zone with a rapid rise in material temperature followed by a fast quenching of the clinker. This rapid temperature rise and fall contributes to good Alite ($C_3S$) and Belite ($C_2S$) crystal formation. Alite always decomposes during cooling, therefore the more rapid the cooling the more Alite is maintained. Rapid heating and cooling results in:

- Easy to grind clinker (high cement milling capacity) due to small highly stressed Alite crystals
- The ability to achieve good cement strengths with minimum clinker content due to highly reactive Alite crystals.

A short burning zone and good clinker nodulization also helps to minimize circulation of volatile elements such as K, Na, S and Cl.

The lower-grade heat (<18MJ/kg) is better suited to the calciner where calcination temperatures ~900°C are required.

In the kiln it is important to have most of the fuel burn before falling to the clinker bed. Excessive unburnt fuel in the clinker bed can cause brown cores in the clinker and increase the circulation of volatile elements. Therefore, it is important that the AF fired in the kiln has sufficient surface area for rapid combustion. This means that 2-D and small 3-D AF particles are preferred in the kiln.

Likewise, it is important that most of the fuel fired in the calciner burns within the calciner vessel. Unburnt char exiting the calciner results in reducing conditions at the kiln feed end contributing to volatilization of sulphates and build-up in the riser and preheater. Unburnt fuel exiting the calciner also results in high CO levels and flue gas temperature at the preheater exit, and in turn limits the capacity of the kiln. The residence time in the calciner varies on the fuel size and the calciner design. Larger less energy dense fuels can be used in the calciner.

There are significant differences between the approach to the calciner and the rotary kiln which can be best explained by a real estate versus racing car analogy shown in **Figure 3**.

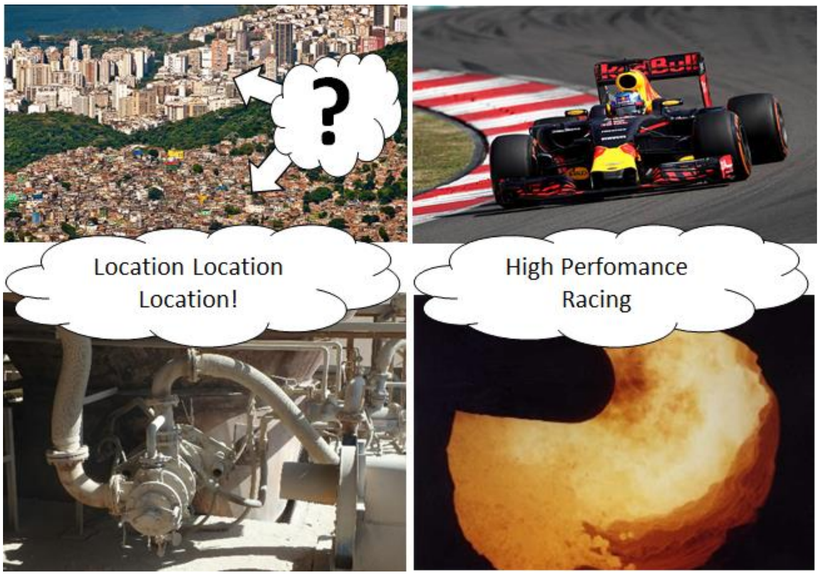


**Figure 3:** Real estate versus racing car analogy for calciner and kiln burners.

In the calciner, the vessel geometry and the momentum of tertiary and kiln exhaust gas dominate the aerodynamics. When introducing new fuels there is often no obvious position that burners should be located. Firing AF in the same location as existing fuels may not be the best option. Therefore, the location and number of the calciner burners or fuel entry points is more important than the burner design itself. The real-estate adage "Location Location Location" may be applied to the calciner.

In the kiln the reverse is true. There is only one location for the kiln burner and its design and momentum contribute significantly to the performance of the kiln. One might say that choosing a kiln burner is like choosing a "high-performance racing car".

A winning performance on the track is dependent on: the engineering of the car; the choices made in the setup of the car specific to each track; and the skill of the driver and pit crew.

A winning performance in the kiln is dependent on: the engineering of the burner; the choices made in the setup of the burner specific to each kiln; and the skill of the operator and engineers.

When changing fuels or optimising existing fuels the approach is therefore different between the calciner and the kiln. For the calciner, modeling is essential in determining the best location and method for feeding the new fuel. Without modeling, quality, production output and fuel efficiency can be compromised, and efforts are a trial and error affair. For the rotary kiln, the location of the burner is well defined with small variations from kiln to kiln. Burner design rules are underpinned by a combination of modelling and experience. Modeling of kiln burners with common fuels and common kiln geometries is not essential. However, where there is a high degree of complexity (very large number of fuels or unusual fuels) or the customer wants to quantify the benefits prior to installing a new burner, modelling plays an important role.

AF is normally co-fired with coal. If problems occur with the AF delivery system, then the kiln will revert to being fired by coal only. Sources of AF can also change. Therefore, it is important that the operator has a burner with the flexibility to fire both 100% coal and high levels of varying AF and be able to maintain production, clinker quality and low emissions (NOx emissions) under all circumstances. FCT Combustion's approach to both modeling AF and burner design for AF will be examined in more detail.

## The modeling approach to alternative fuels

FCT Combustion has been employing modeling to solve combustion problems since 1984 using a variety of techniques from computational to experimental.

When considering a new AF, or improving performance with an existing AF, FCT Combustion uses the following steps:

1. Detailed site survey
2. Process calculations and evaluation
3. CFD modeling of existing case (model calibration)
4. CFD modeling of potential solutions
5. Select the solution that best meets the customer's requirements.

## Case study: Cement Plant in Europe

The following case study is for a calciner and shows the approach to trialing different operating conditions (eg: entry/burner locations) to improve AF combustion. The plant is in Europe operating a 1,200t/d 5stage inline calciner kiln firing coal and RDF both in the kiln and calciner and whole tyres at the kiln inlet. The firing rate of RDF in the calciner was limited by high levels of carbon monoxide at the preheater exit. The objective was to increase the use of AF and reduce build-up caused by volatile elements in the process.

### 1. Detailed site survey

Our engineers visit the site to take measurements with our calibrated instruments, collect drawings, material samples and historic operational data from the control room, and discuss operational issues with site personnel. At the end of this stage, there is a very good representation of the real process and some conclusions are already possible.

General conditions of the process are known, however, the internal workings of the kiln or calciner are not yet revealed.


**Figure 4:** Site survey measurement and data collection.

### 2. Process calculations and evaluation

The data collected is organized and evaluated. A mass and energy balance is developed and key process and combustion parameters calculated. With the data available, it is possible to understand how the current installation behaves.

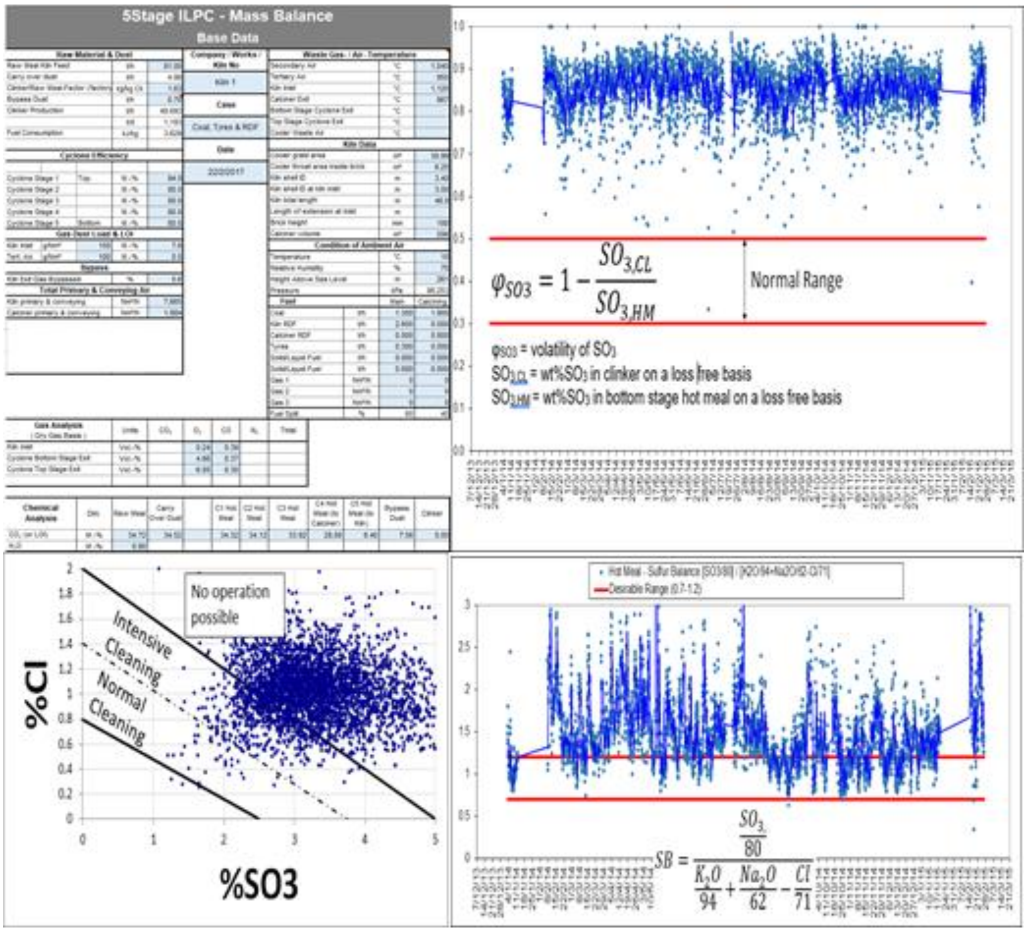


**Figure 5:** Data evaluation

## 3. CFD modeling of existing case (model calibration)

The data collected is applied to a computer model and the current conditions are simulated. Model assumptions and parameters are adjusted to calibrate the model in order to have the same results in the model as in real life.

For the calciner modeling example there is a high velocity, caused by the kiln flue gas, along the wall in front of the coal burner on level 3 as shown in **Figure 6A**. As a result, the coal conveying and primary air from the burner on level 3 is pushed straight up the wall, shown in **Figure 6C**. The mixing chamber at the top of the calciner helps to mix unburnt fuel with remaining oxygen, however, as shown in **Figure 7**, only a portion of the flue gas and fuel travel around the chamber and mix as a large amount bypasses the mixing chamber altogether.

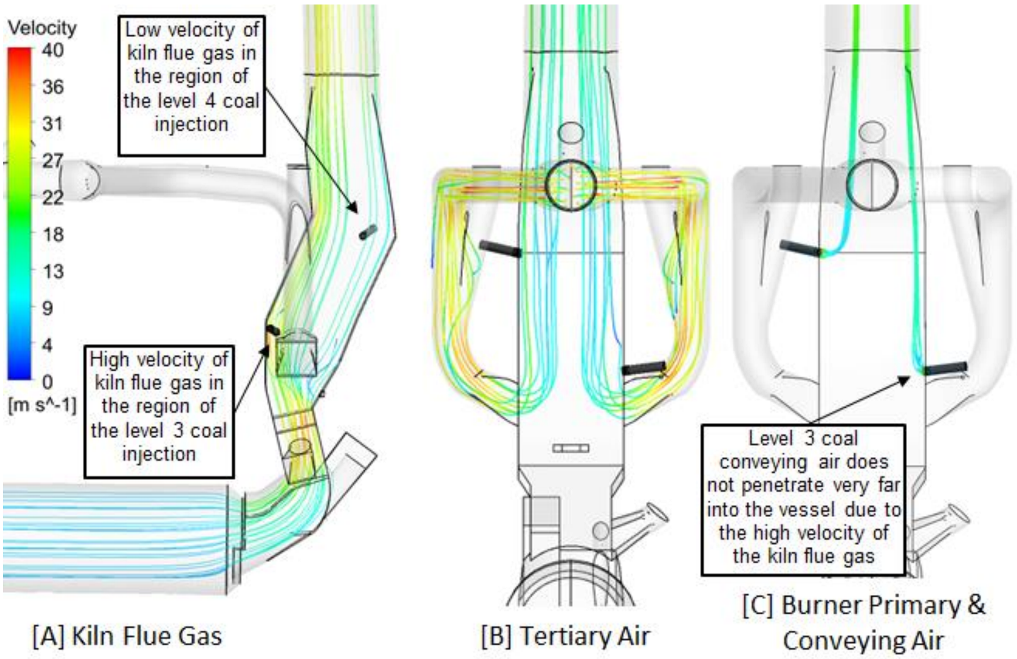


**Figure 6:** Kiln flue gas, tertiary air and primary /conveying air flow paths coloured by velocity.

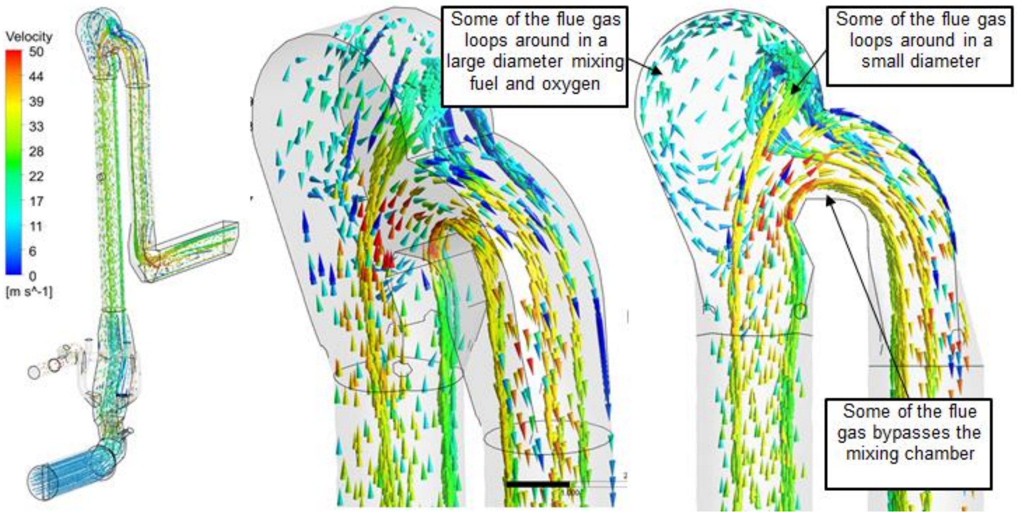


**Figure 7:** Aerodynamics in the calciner top mixing chamber

**Figure 8B** shows the coal particles from the burner on level 3 are pushed up the wall, by the kiln flue gas, resulting in poor dispersion. **Figure 8B** shows that the coal from the burner on level 4 disperses much better. However, as the burner on level 4 burner is one floor above the level 3 burner the coal has a lower residence time meaning that whilst almost all the coal from the level 3 burner has finished burning before reaching the mixing chamber the coal from the level 4 burner continues burning up into the mixing chamber. This is demonstrated in **Figure 8C&D** where the coal partcles path lines change from Red (indicating a large amount of unburnt char) to Blue (indicating a low amount of unburnt char, mostly ash).

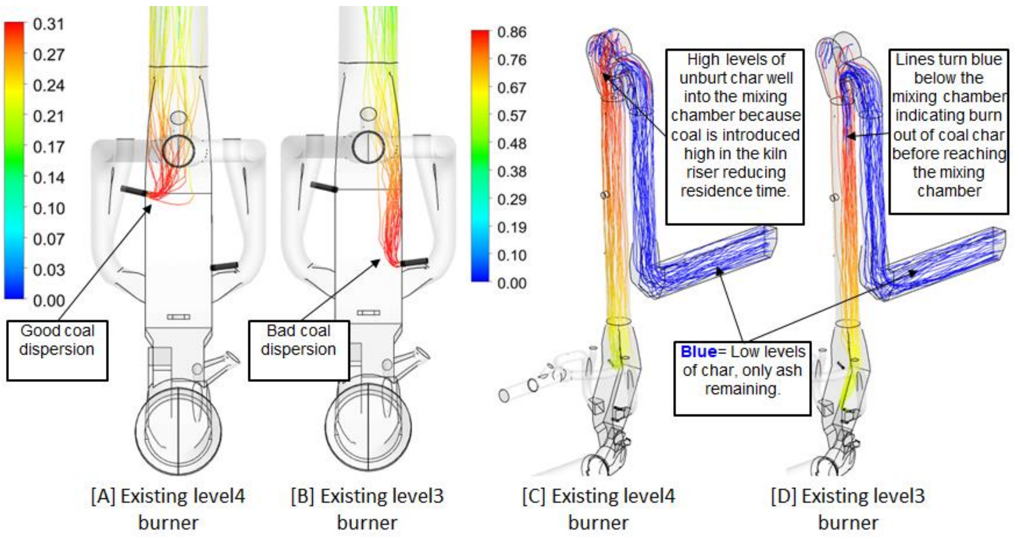


**Figure 8:** Coal particle traces coloured by volatile mass fraction for Existing Burners

Burnout of RDF in the calciner was found to be incomplete. Larger particles of unburnt RDF fell directly into the kiln and smaller char particles exited the calciner unburnt with the flue gas resulting in high CO levels in the preheater tower and unburnt char collected in the bottom stage cyclone entering the kiln with the hot meal. **Figure 9** shows path lines of difference size fractions of RDF coloured by the residence time of the particles in the calciner. Particles smaller than 0.5cm have a residence time of 2-8 seconds and are carried away rapidly by the gas stream, however the burntout time for many of these particles exceeds the residence time. Particles in the 0.5-2cm range bounce around more with a few falling into the kiln and burning whilst those that exit the calciner with the flue gas have a residence time between 8 and 24 seconds. The burnout time for these particles exceed the residence time. Finally, many particles larger than 2cm fall into the kiln and burn whilst those that exit with the flue gas have a residence time of ~24seconds and a burnout time far exceeding this.

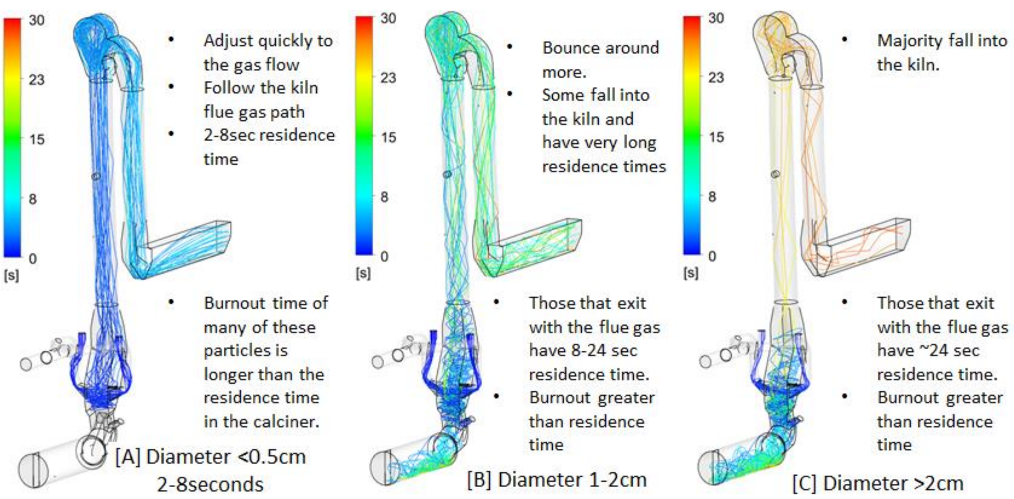


**Figure 9**: RDF particle residence times

## 4. CFD modeling of potential solutions

Potential solutions are tested using CFD modeling to understand the individual and collective impact of each change to the system.

**Figure 10** shows one of the burner relocation options tested. **Figure 11** and **Figure 12** show the improved coal dispersion and the improved coal char burnout resulting from the burner relocation.

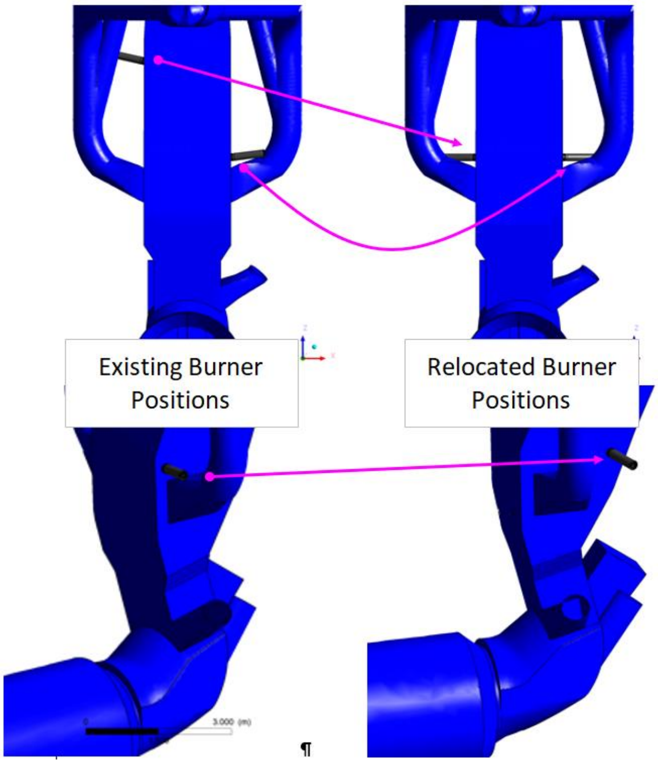


**Figure 10:** Relocation of calciner burners

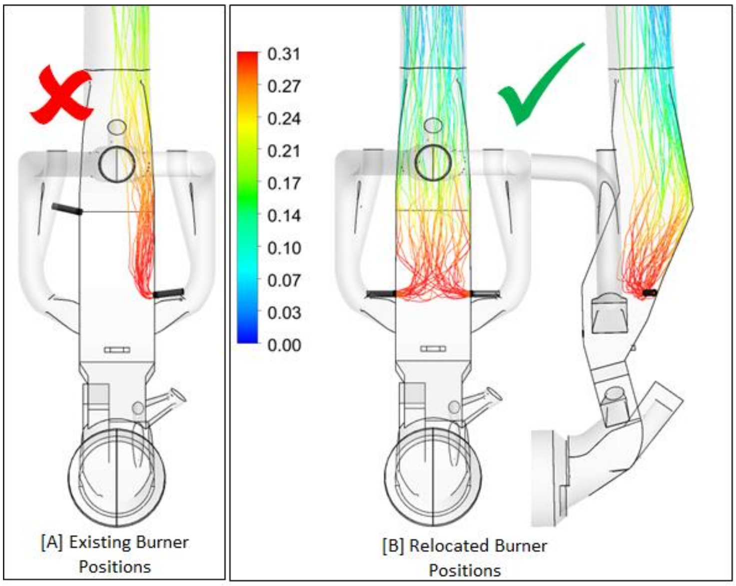


**Figure 11:** Improved coal dispersion with relocation of burners (coal traces coloured by char mass fraction)

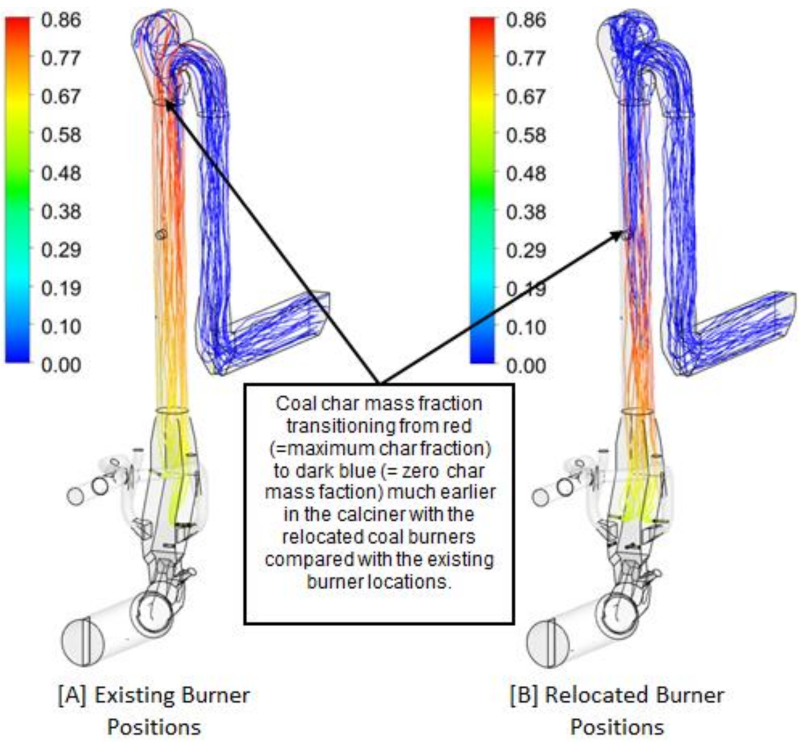


**Figure 12:** Coal traces coloured by char mass fraction for existing and relocated burner positions.

**Figure 13** shows the alternate upper hot meal entry point tested and the resulting increased temperature at the bottom of the calciner. **Figure 14** shows that the meal relocation has little impact on 3D wood char burnout.

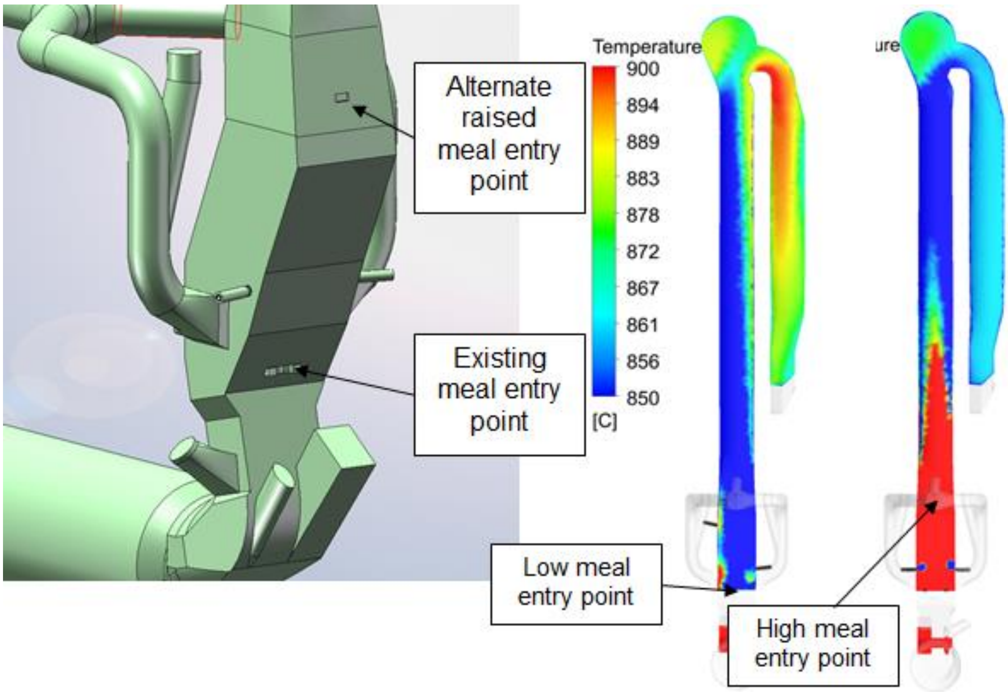


**Figure 13:** Temperature distribution through the calciner showing large red(very hot) region as a result of raising the hot meal entry point.

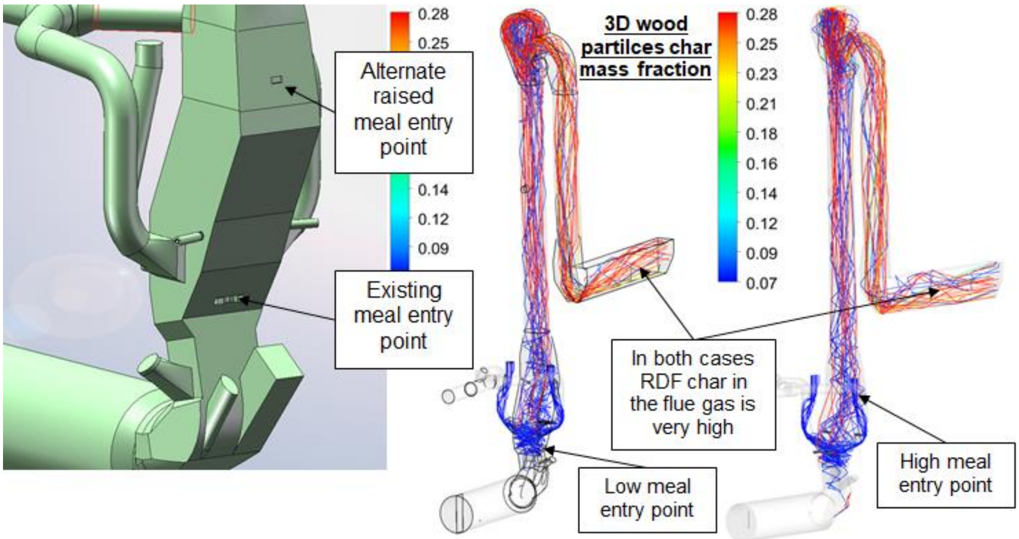


**Figure 14:** 3D wood particle char mass fraction traces for low (existing) and high meal entry points.

**Figure 15** shows the volatile and char mass fractions of a new dusty plastic AF that the plant was considering using. This dusty AF is very high in volatiles and char burnout is complete in the mixing chamber.

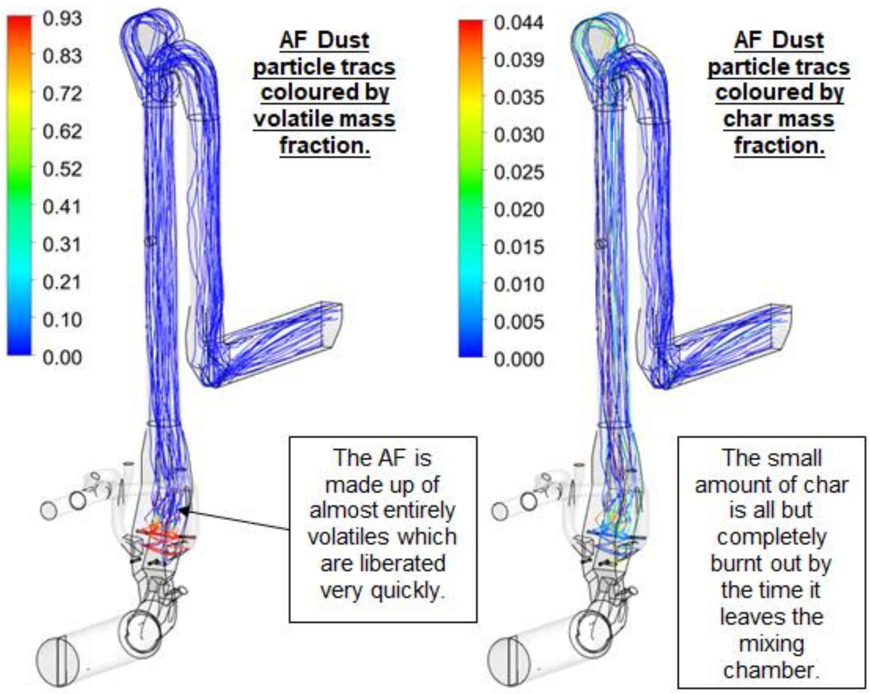


**Figure 15:** New plastic dust AF traces coloured by volatile and char mass fractions respectively.

## 5. Select the solution that best meets the customer's requirements

From the modeling examples shown, the following conclusions and recommendations were made.

*Re-location of the Coal Burners to the low velocity region on level 3 will provide a marked improvement in coal combustion in the calciner.*

There is also improved combustion from smaller 2-D particles of the various alternative fuels used.

However, the 3-D particle combustion is not improved significantly by a re-location of the burners – the particle size/shape is the problem

*For improved combustion of the 3-D particles, either the calciner residence time must be increased, the AF particles must be limited to 1mm max in any dimension or some other novel design be considered that allows more time for particle burnout (mixing chamber design or complete calciner design for example).*

*Main burner is not efficiently purging sulphur from the system and should be replaced.*

Due to the relatively large size of the alternative fuels its burn out time is much longer than the residence time of the calciner.

The calciner is designed for coal combustion and does not have a sufficiently high residence time ratio for combustion of the alternative fuels within the calciner.

In addition, the calciner design does not provide a high temperature zone for combustion of difficult to burn fuels.

As a result, unburnt volatiles and char exit the calciner and continue to burn giving off CO which is then detected by the gas analysis system limiting the fuel firing rate.

In addition, unburnt char is collected in the bottom stage cyclone and enters the kiln with the hot meal causing reducing conditions.

Chloride bypass is too small for current input of chloride.

## Flexible kiln burner for alternative fuels

Combustion performance in the rotary kiln revolves around the burner. Just like with the car on the racing track, you must start with a high-performance burner. In designing a burner there are many parameters involved. Normally these parameters are fixed with a small deviation. These parameters include (but are not limited to):

- Kiln diameter
- Cooler and firing hood geometry
- Kiln firing rate
- Secondary air temperature
- Secondary air velocity and aerodynamics
- Raw materials
- and … **Fuel**

Therefore, burners can be designed to optimize around a set of parameters with impulse and swirl number (or axial and swirl momentum) adjustment for control of flame shape.

Burner impulse is one of many parameters that can be interpreted as a measure of turbulent mixing between the different species in the flame. It is linked with flame ignition and length. FCT Combustion uses a modified Craya-Curtet parameter (which can be interpreted as the ratio between burner and secondary air momentum) as a measure of the burner capability to promote the entrainment of secondary air in the flame. It is like a target for burner impulse but considers secondary air momentum.

The swirl number represents the capability of fuel dispersion in the flame, and it is linked to flame diameter.

It is well established that axial and swirl momentum from primary air are the main controls of the flame radiation profile to the clinker. Different burner manufacturers take different approaches to achieve axial/swirl control through air nozzle designs, air pressures and adjustment mechanisms.

FCT Combustion's philosophy is not to have moving parts in the burner – to ensure trouble-free operation without jamming and avoid repeatability problems in a hot and dusty kiln environment. The situation at the burner tip is always known precisely. This is achieved with the easiest possible controls, a single valve coupled with blower speed. Blower speed is used to control impulse while the valve is set to control the swirl number. **Figure 16** shows the single primary air inlet to an FCT Combustion Turbu-Jet™ burner and the single valve used to control the proportion of swirl momentum.

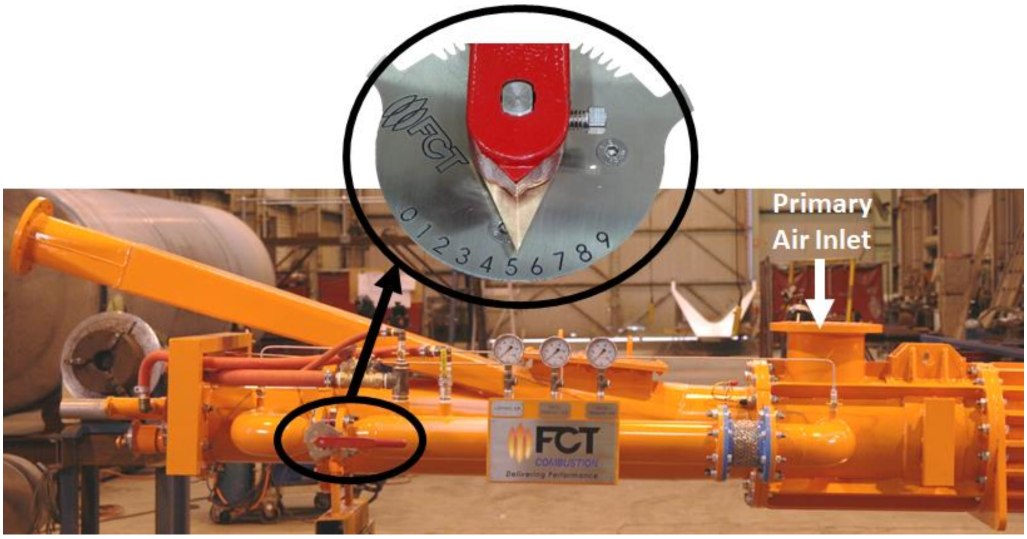


**Figure 16:** Turbu-Jet$^{TM}$ primary air swirl valve and inlet.

Other important parameters in the burner design are the number and arrangement of axial primary air holes.

A large number (say 36) of axial primary air holes results in an almost annular flow of axial air restricting/delaying the entrainment of secondary air to the coal inside the primary air. As a result, the peak temperature of the flame and therefore NOx is supressed. (See**Figure 17A**)

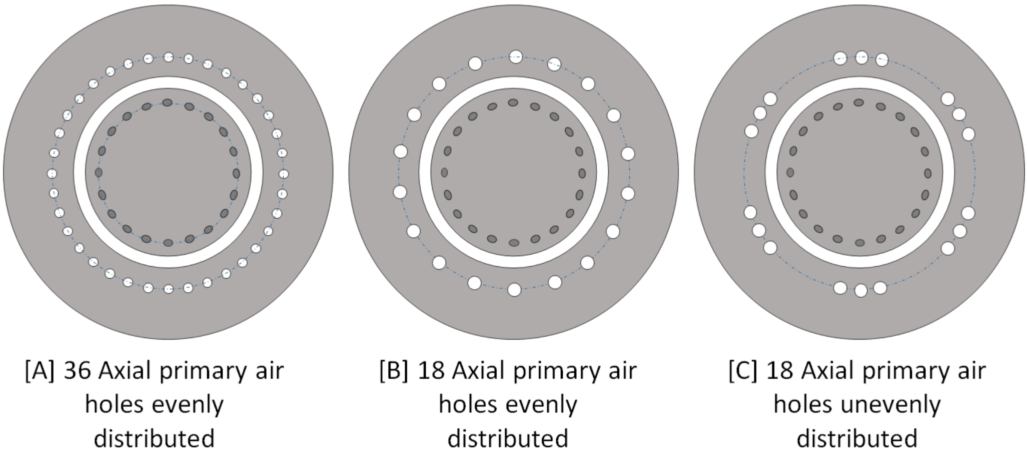


**Figure 17:** Axial primary air hole arrangement

A small number (say 18) of axial holes (with the same area, air flow and momentum) results in higher secondary air entrainment rate and therefore higher peak temp and higher NOx. (See **Figure 17B**)

Grouping the axial air holes such that there are large gaps between the axial air flows results in even higher secondary air entrainment, flame temperature and NOx. (See **Figure 17C**)

As can be seen in **Figure 18**, for coal firing in a rotary cement kiln, reducing the number of axial holes and then grouping them can increase the flame temperature and the peak heat transfer from the flame to the clinker.

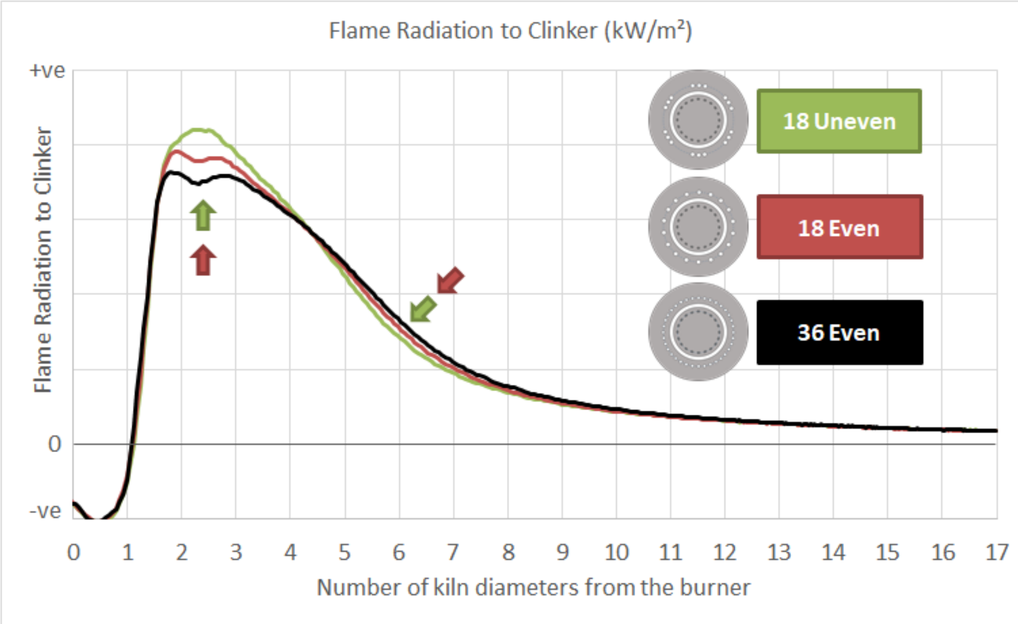


**Figure 18:** Flame Radiation to Clinker for three different primary air axial hole arrangements for the same specific momentum.

As shown in **Figure 19**, it is possible to define the heat transferred from the flame to the clinker as the area under the curve. The area under the curve closest to the burner (say the first 5 kiln diameters from the burner "5ø Radiation") has a significant influence on achieving a rapid rise and drop in clinker temperature.

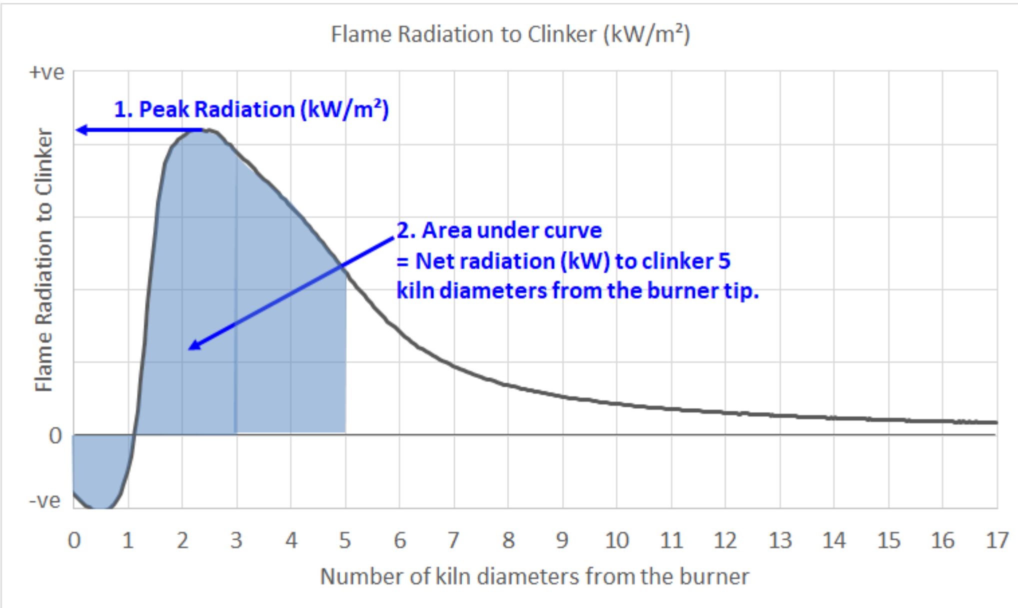


**Figure 19:** Flame radiation to clinker - Peak (kW/m$^2$) and Total (kW) in first 5 kiln diameters.

In **Figure 20** the Peak Radiation, NOx and Total Radiation to clinker in the first 5 kiln diameters (Radiation 5ø) are compared. As can be seen, there is ~7% increase in Peak Radiation and NOx and ~3% increase in Radiation 5ø when halving the number of axial holes and a further ~7% (Peak Radiation & NOx) and ~4% (Radiation 5 ø) increase when the holes are grouped together.

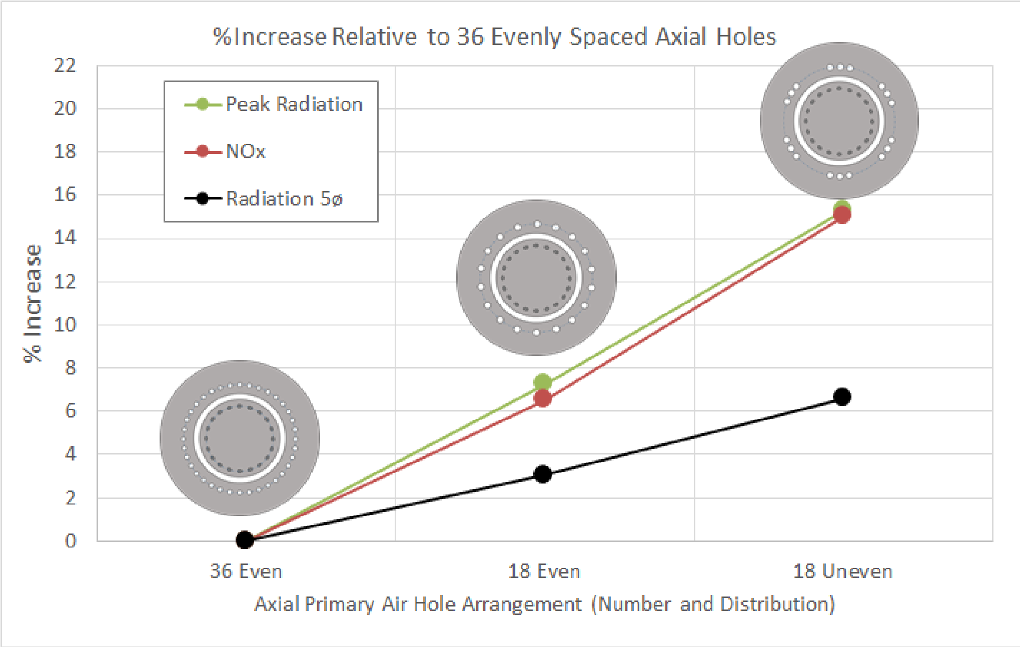


**Figure 20:** %Increase in NOx and radiation heat transfer to clinker for different axial primary air hole arrangements relative to 36 Evenly Spaced Axial Holes.

The high secondary air entrainment from a small number of holes grouped together, is ideal when co-firing RDF with coal. High secondary air entrainment rate improves the RDF combustion and heat radiated to the clinker, while the high moisture content and low calorific value inherent in burning RDF supresses NOx.

The high number of axial holes is a benefit when burning only coal or petcoke as it helps to suppress NOx formation, while still giving good radiation profile to the clinker, resulting in higher clinker quality.

Maximizing the firing capability by changing the air supply and without the use of moving parts

We could design a burner that is optimum for an easy to burn fuel like coal (with many axial primary air holes) or we could design for co-firing of coal and a difficult to burn fuel such as RDF (with a small number of holes grouped together).

But what if we want to change between coal only and co-firing of coal and RDF?

FCT Combustion's solution is the Turbu-Flex™ burner (or Flexible Turbulent Jet Burner) in which the axial holes are in two groups each with a separate air supply shown in **Figure 21**. With the turn of a single valve the burner changes from operating with many evenly distributed holes (say 36) all at the same pressure to operating with a small number of holes (say 18) at high pressure grouped together.

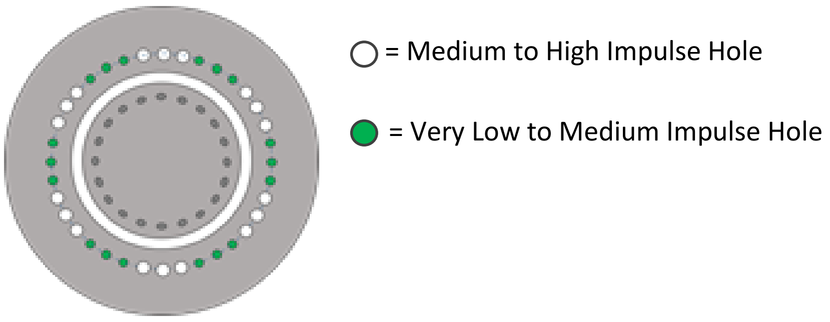


**Figure 21:** Axial hole grouping by air supply.

In other words, the burner changes from AF mode to Low NOx mode of operation simply by opening a valve, the Low NOx valve.

**Figure 22** shows how the coal flame radiation profile, for the same impulse and swirl number, can be changed significantly from high AF mode with high peak radiation to Low NOx mode with one valve. So, when AF firing is off or at low proportions and the burner is firing predominantly pulverized solid fuel the Low NOx mode can be selected. As the proportion of AF is increased, the Low NOx valve can be closed, increasing the secondary air entrainment rate and the peak temperature.

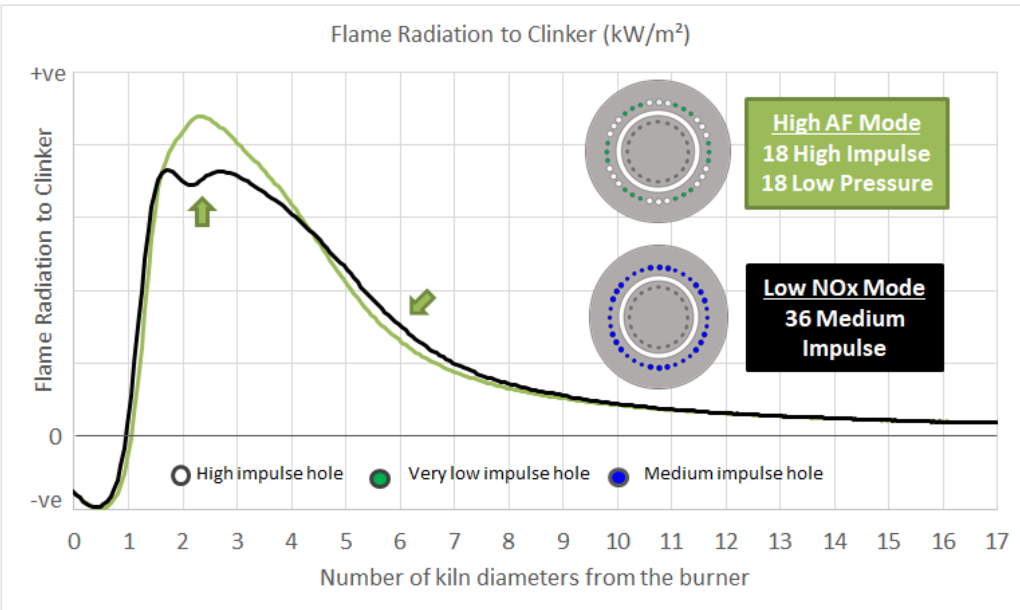


**Figure 22:** Burner performance: Flame Radiation to Clinker (kW/m²) for the Turbu-Flex$^{TM}$ burning coal.

**Figure 23** shows the increase in radiation and NOx when firing coal in the Turbu-Flex$^{TM}$ burner. It is important to note that the increase in NOx with the same pulverized fuel means a more intense flame which allows more RDF. RDF inherently reduces NOx emissions due to its high moisture content.

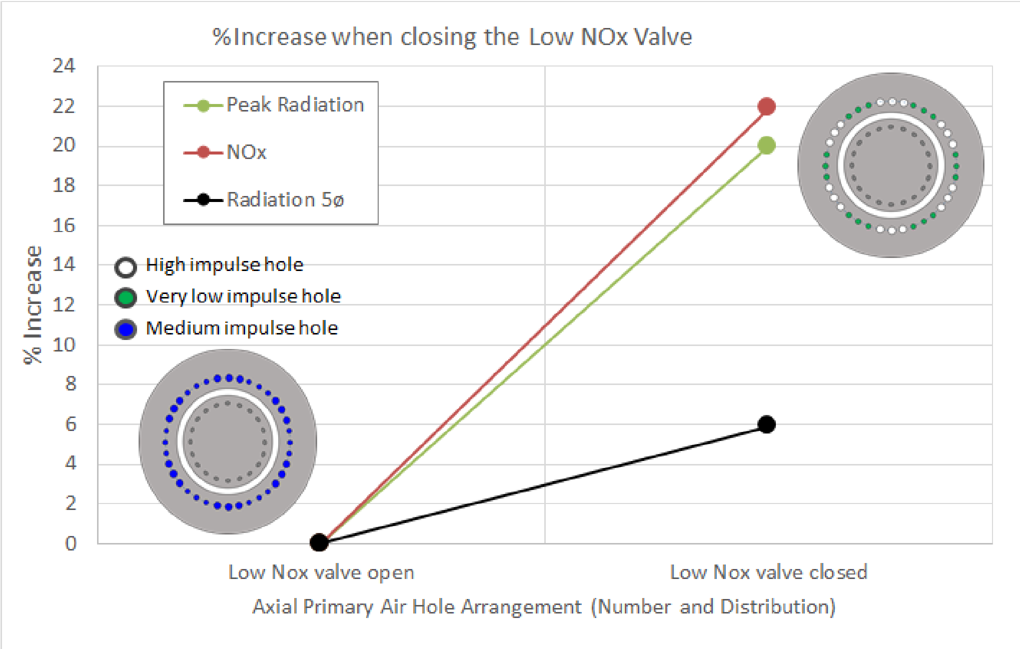


**Figure 23:** Burner performance: %Increase when closing the Low NOx Valve.

**Figure 22 and Figure 23** show the burner performance with coal only, but what is the impact on AF/RDF?

**Figure 24** shows the impact of firing 50% RDF on the radiation to clinker in the kiln and the impact of closing the Low NOx valve. The solid black line shows 100% coal firing with the Low NOx valve open. The dashed-black line shows 50% RDF co-firing with the Low NOx valve left open. The radiation to the clinker is significantly reduced (10% reduction in the radiation to the clinker in the first 5ø). If the Low NOx valve is subsequently closed, as represented by the dashed-green line, then the radiation to the clinker is recovered significantly (5% increase in 5ø Radiation compared to the dashed-black line, still 5% less than the solid black line).

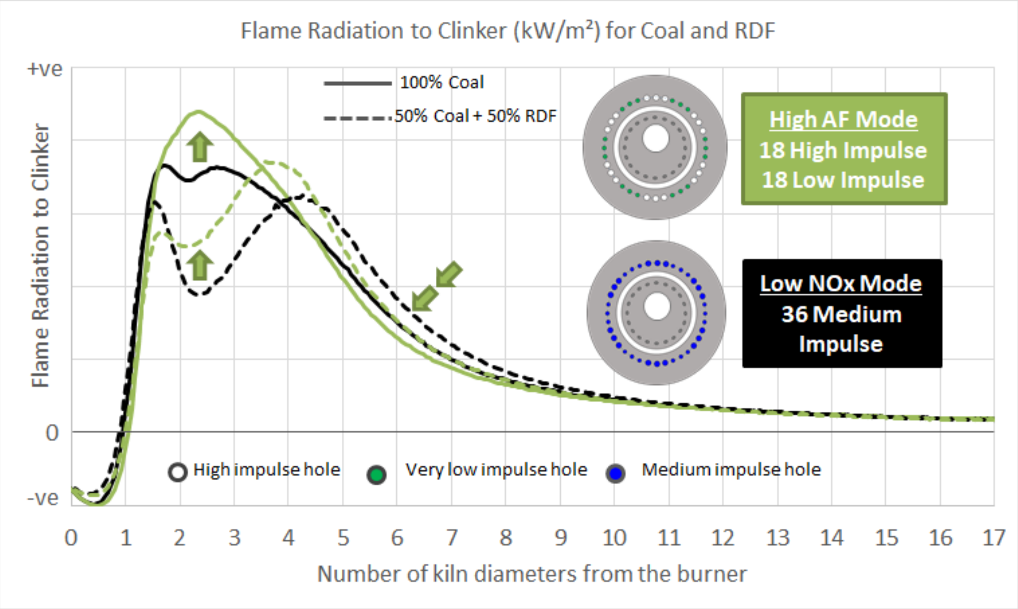


**Figure 24:** Flame radiation to clinker (kW/m²) for 100% coal and Co-firing of 50% coal and 50% RDF.

The reason for the improved flame radiation from RDF with the Turbu-Flex$^{AF}$ burner can be seen in **Figure 25**. Below the radiation profiles in **Figure 25** are plots of the rate of combustion of volatiles originating from coal and RDF. The staggered release of volatiles for coal and RDF explain the twin peaks. With the Turbu-Flex$^{TM}$ burner in AF Mode the rate of combustion of RDF volatiles is higher and finishes closer to the burner explaining the earlier drop in the tail of the radiation profile.

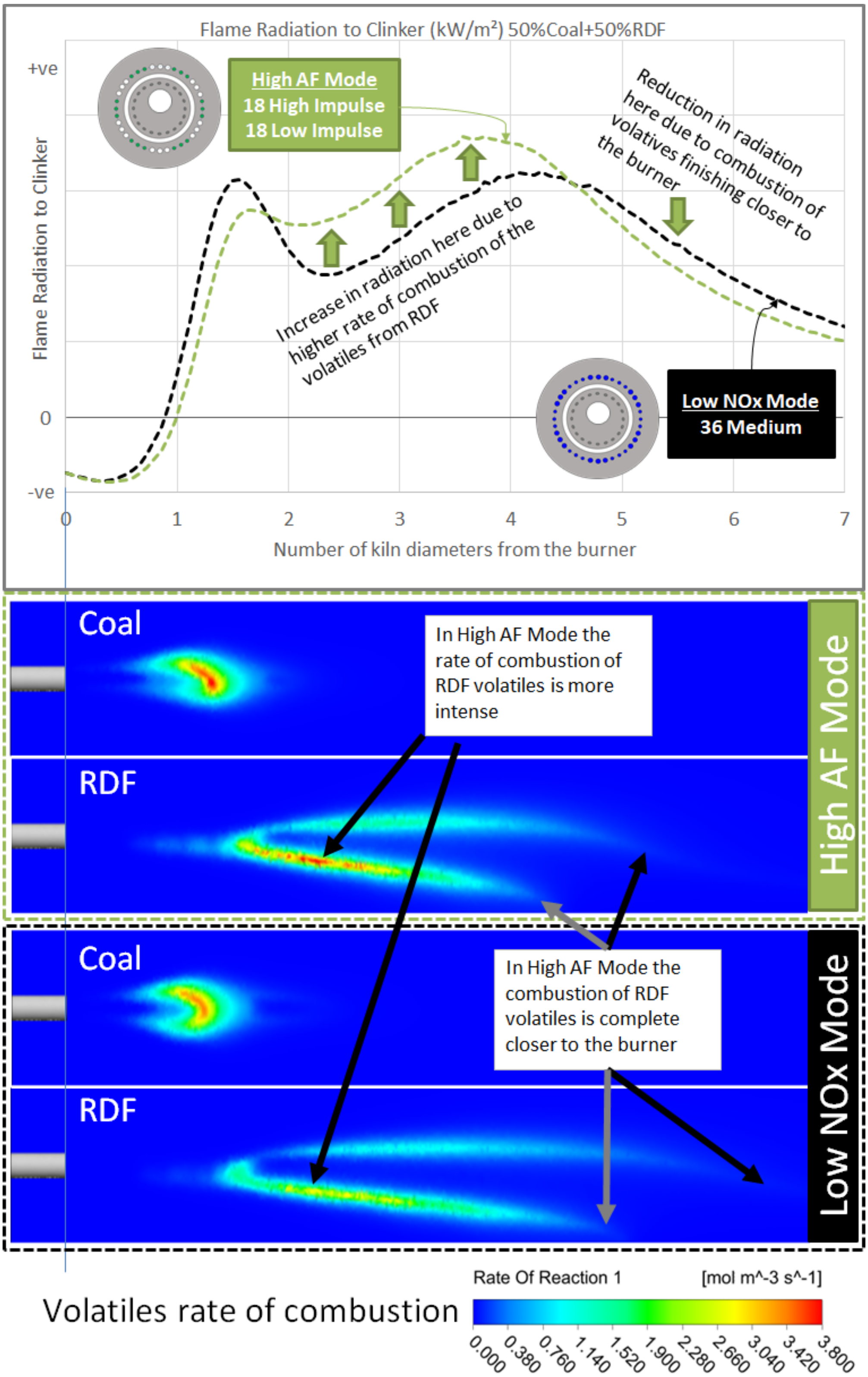


**Figure 25:** Lining up radiation to clinker profiles with plots of rate of combustion of volatiles for co-firing of 50%coal and 50% RDF with Turbu-Flex™ in High AF and Low NOx modes.

The new FCT Turbu-Flex™ burner has now moved from concept to deployment. Building upon the proven, industry-leading technologies of an existing turbulent jet burner, it is a world first in flexible burner design containing no moving parts.

The image below shows the first Turbu-Flex™ burner that has been in operation since August 2017. The outer axial holes are grouped in 5 groups of 3 larger holes and 5 groups of 3 smaller holes.  The larger holes always have the full flow of axial primary air.  The smaller holes can have their air supply restricted to give a very low velocity and essentially no momentum providing little more than cooling of the face plate.

The burner is fired with RDF, Liquid AF and Petcoke.  The burner has been operating successfully with over 80% RDF and the face plate and channel design has proven reliable with no moving parts in the burner.

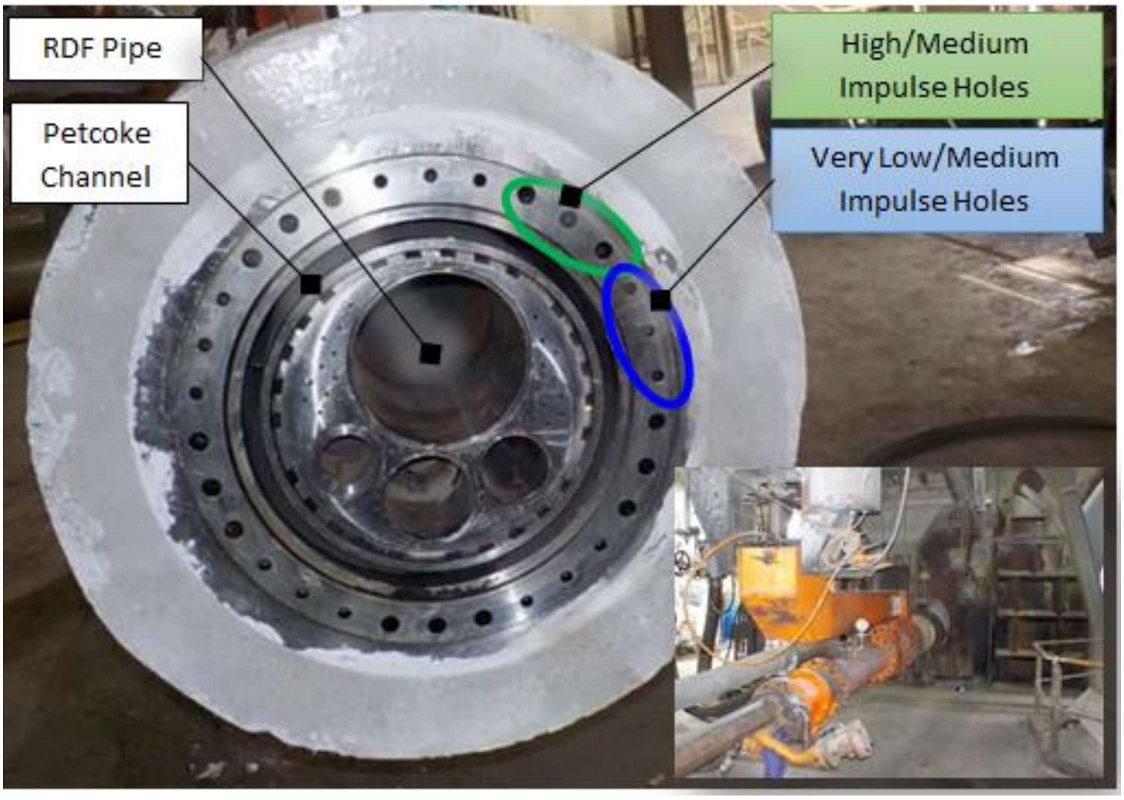


**Figure 26:** First Turbu-Flex$^{TM}$ burner firing 80% RDF in operation since August 2017.

FCT Combustion's modeling can help solve AF location challenges in your calciner increasing AF use, production and fuel efficiency.  The new Turbu-Flex$^{TM}$ burner will help to maximize AF rates whilst minimizing the negative effects of AF's on clinker quality, production rates and NOx emissions.  The Turbu-Flex$^{TM}$ burner has the flexibility to switch between fuels and provide trouble free operation with no moving parts in the burner