Maximising solid AF firing

A TEC has been developing ways to maximise the thermal substitution rate of solid alternative fuels at the main burner. The challenge has been to combine injection in a zone with high oxygen availability, along with high control of the primary air over the particles' trajectory in a zone with high mixing effect between the particles and air for combustion. The development process has led to the design of two complimentary items of equipment: the new Flexiflame EcoPro® burner and a new A TEC ROCKET MILL® for alternative fuels, which combined are the company's MASTER System.

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Over recent decades the use of solid alternative fuels (AF) in the cement industry has increased drastically. Due to high temperatures, oxygen content and long residence times, cement pyroprocess lines are ideal for AF processing. For cement producers, the use of AFs brings reduced costs compared to the use of fossil fuels and cuts CO_2 emissions in an energy-intensive sector.

At the forefront of AF usage in the cement industry are central European countries such as Austria and Germany, which have thermal substitution rates (TSR) of 70 and 60 per cent, respectively.

Modern calciners can handle 100 per cent solid AF usage while, up to now, kiln burners were able to handle up to approximately 60 per cent, giving a total substitution rate of 84 per cent (considering a pyroprocess with 40 per cent of thermal energy input at the kiln and 60 per cent of thermal energy input at the calciner).

Going beyond a solid AF substitution rate of 60 per cent at the kiln burner has proved challenging. Achieving this rate is almost only possible when using liquid AFs with a high calorific value, such as solvents. A TEC GRECO's burners have been able to achieve an AF substitution rate of 100 per cent since 2005 under those conditions.

Flexiflame EcoPro – second prototype in operation in Austria since 2014

When trying to increase the solid AF substitution rate above 60 per cent at the main burner without the help of a high-calorific value and easy-to-burn fuels, the following issues can arise in terms of clinker quality and kiln operation:

Figure 1: solid alternative fuel pipe in the kiln hood

- Injected in a zone with higher oxygen availability
- Primary air has no control over the trajectory of particles
- Lower mixing effect between particles and air for combustion
- Easiest installation

Figure 2: solid alternative fuel pipe in the burner refractory lining

- Injected in a zone with high oxygen availability
- Primary air has low control over the trajectory of particles
- Low mixing effect between particles and air for combustion
- Easy installation in existing burner

Figure 3: solid alternative fuel pipe in the centre of the burner

- Injected in a zone with low oxygen availability
- Primary air has higher control over the trajectory of particles
- High mixing effect between particles and air for combustion
- Difficult installation – requires new burner

Figure 4: three-dimensional particle shrinking to a sphere while heated [1]

Initial shape

Shape during combustion

Figure 5: two-dimensional plastic particle shrinking to droplets when heated [1]

Initial shape

Shape during combustion

- unstable flame
- higher kiln inlet temperatures
- excessive sulphur recirculation
- ring formation
- higher CO emissions
- reduction zone near the clinker bed
- secondary flame from solid AF burning above the clinker bed
- incorrect kiln thermal profile
- negative impact on cement strength.

A new concept

With A TEC's many years of experience in supplying burners for AF usage to the cement industry, it became clear that to increase the thermal substitution rate of solid AFs at the main burner, a new design concept had to be created.

The evolution of solid AF injection at the main burner has seen many possibilities being tested: starting with simple pipes being installed in the kiln hood above the burner, to passing the pipes above the burner installed in its refractory lining, right through to the more commonly-used pipes in the centre of the burner (see Figures 1-3). Each solution has its advantages and disadvantages, but all the main advantages were not yet combined in one unique, existing design.

Therefore, a new burner concept was necessary, combining the injection of solid AF in a zone with high oxygen availability, along with a high control of the primary air over the particles' trajectory in a zone with a high mixing effect between the particles and air for combustion.

Technical background

When considering solid AF firing, there are some key aerodynamic and combustion concepts that must first be understood.

Particle sphericity

A very important aerodynamic characteristic of a solid AF particle is its sphericity. Sphericity is defined as the ratio between the surface area of a sphere with the same volume as the real particle and the surface area of the real particle, as shown in the formula below:

$$\Psi = \frac{\mathit{Surface\ area}_{\text{sphere with same volume as real particle}}}{\mathit{Surface\ area}_{\text{real particle}}}$$

The closer the sphericity is to 1, the more sphere-like the particle. More sphere-like particles are less susceptible to the aerodynamic effects of different primary and secondary air streams, and more susceptible to gravitational forces. In other words, the particle will fall onto the clinker bed faster.

Table 1 shows the sphericity of different particles when calculated using the aforementioned formula. The results show that fluff foil is more likely to have its flight pattern influenced by primary and secondary air, while sewage sludge grains are most likely to end up on the clinker bed faster than others.

The main concern regarding the flight characteristics of a particle is not – as is commonly thought – the largest particle dimension but rather the smallest. Sewage sludge has a relatively small largest particle dimension of 2mm and has worse flight characteristics compared to a relatively large 15mm fluff particle. However, the fluff particle has a smallest dimension of 0.2mm, while the sphere has 2mm as its smallest dimension.

It is important to note that the sphericity of a particle can be influenced during solid AF preparation, as well as change during different combustion stages.

Surface area and particle shape under heating

Surface area has a significant influence on the combustion behaviour of a fuel particle. The surface area is the basic interface where the fuel meets the oxidising media throughout the different combustion stages. The larger the surface area, the greater the contact between fuel and oxidising media, therefore translating to faster combustion.

It is also important to understand how different particle shapes and materials burn, as some particles do not keep their original shape when heated. For instance a three-dimensional plastic particle forms into a sphere when heated, drastically reducing its surface area and increasing sphericity (see Figure 4).

Meanwhile, Figure 5 shows a two-dimensional plastic particle which, when heated, shrinks to small droplets. This reduces the surface area and increases the sphericity but not as much as three-dimensional plastic.

Reducing the surface area and increasing the sphericity will, throughout the flight time of a particle, gradually increase the effects of gravity and reduce the aerodynamic effects of the primary and secondary air streams. This means that the particle tends to go down faster as the time passes inside the kiln. At the

Table 1: calculation of alternative solid fuel surface area and sphericity

Material	Form	Length (mm)	Width (mm)	Height (mm)	Diameter (mm)	Surface area (mm^2)	Volume (mm^3)	Surface area of equivalent sphere (mm^2)	Ψ
Sewage sludge	Grains	-	-	-	2.0	12.6	4.2	12.6	**1.00**
Wood chips	Chips	15.0	4.0	3.0	-	234.0	180.0	154.2	**0.66**
Fluff	Foils	15.0	15.0	0.2	-	462.0	45.0	61.2	**0.13**

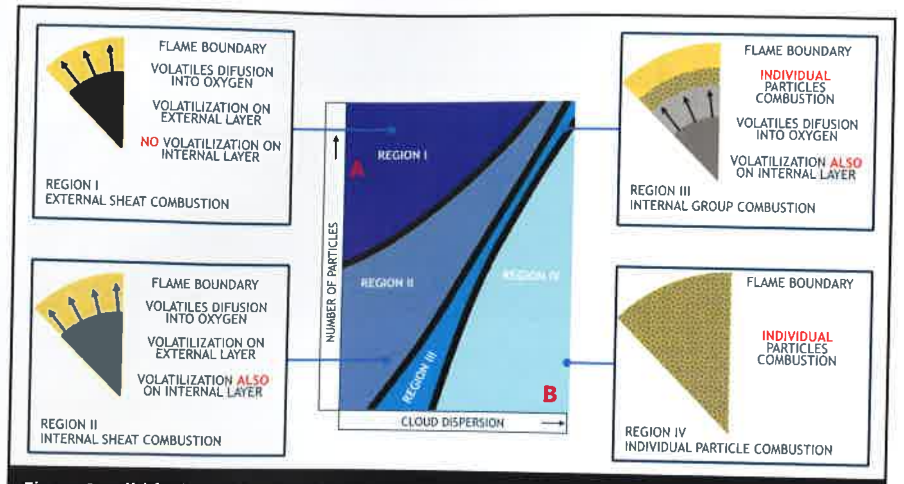

Figure 6: solid fuel particle cloud combustion mechanisms. The four diagrams show a sector of the cross-section of the flame

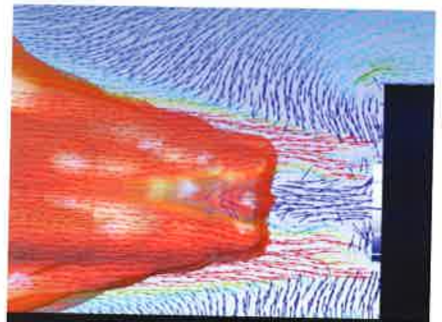

Figure 7: internal and external flame recirculation[2]

same time, the interface where the fuel meets the oxidising media decreases and delays combustion. An additional effect is that the mass of the particle decreases throughout combustion. These three effects (ie, increased sphericity, reduced surface area and decreased mass) will have a continuous influence on the combustion and aerodynamic conditions of the solid AF particle.

Cloud combustion of solid particles

Individual solid fuel particles combustion occurs in four successive stages, depending on temperature, oxidant availability and degree of decomposition.

However, the particles are not burning individually inside the kiln but in a cloud of particles. Combustion behaviour varies as the surrounding particles influence many factors, including the volatilisation rate and availability of oxygen. The combustion of a solid fuel particle cloud can be divided intp four regions or mechanisms depending on how many particles are available and how they are dispersed (see Figure 6).

- In Region I, where there is a large amount of concentrated particles, combustion only takes place outside of the solid particle cloud as only the external layer of the cloud volatilises and diffuses into the oxidant. There is no participation of the inner layers of the fuel cloud at this stage of combustion.
- In Region II, with less particles or most likely, better dispersed particles, combustion continues to only take place outside the solid particle cloud. However, the inner layers of the cloud also start to supply volatiles together with the outer layers from Region I. The combustion of the volatiles supplied by the complete cloud cause very intense combustion.
- In Region III, the solid fuel is even better dispersed. The outer layers of the cloud will have already burned the volatiles, and start to burn individually, reaching a second area with a very intense combustion. The inner layers continue to release volatile species, however there is almost no combustion as the volatiles need to reach the oxidant outside the fuel cloud.
- In Region IV, all the volatile is consumed and the complete cloud of remaining particles is burned as individual particles.
- When entering the kiln through the burner tip, the solid fuel has a large number of particles and they are concentrated in a relatively small area. This situation would be equivalent to point A in Region I (see Figure 6). At the end of the flame, the number of particles that are not completely burned is relatively small and they are relatively well dispersed into the kiln. This situation would be equivalent to point B in Region IV.

Each region has its own combustion kinetics and there are infinite ways to go from point A to B. What is important is to know how to get from point A to B, through burner design.

Flame recirculation

As shown in Figure 7, there are two important recirculation zones to give the characteristics of a flame: internal and external.

The internal recirculation is a zone where intense mixing between the fuel and oxidant from the primary air occurs, ie the zone with dark blue arrows in the centre of the flame. In this region, there is an intense reverse flow of combustion gas back to the burner tip, mainly due to the swirl components of the primary air. The return of the hot gas to the flame root, even with low oxidant availability, is important to promote the ignition of the fuel entering the kiln through the burner tip, and to maintain flame stability.

In the external recirculation zone, secondary air is inducted into the flame, ie the zone with dark blue arrows on the periphery of the flame. In this region, there is a suction of secondary air at high temperature and with high oxidant availability into the flame, mainly due to high speed axial components of the primary air. Mixing with secondary air is important to complement the combustion initiated by the internal recirculation.

Others

Many other parameters influence the combustion of solid AFs, including:

- **Density:** particles with a lower density are less likely to fall onto the clinker bed before combustion is complete
- **Particle mass:** the larger the particle mass, the longer the combustion time required
- **Chemical composition:** higher amounts of volatile species enable faster combustion
- **Lower heat value:** increased lower heat values allow higher flame temperatures
- **Water content:** lower water content enables higher flame temperatures and faster ignition.

Figure 8: the first prototype of A TEC GRECO 's Flexiflame EcoPro®

Conceptual solution

The idea proposed by A TEC GRECO to combine the injection of solid AF in a zone with high oxygen availability, along with a high level of control of the primary air over the particles' trajectory in a zone with a high mixing effect between the particles and air for combustion, was to place the solid AF into an annular channel in the periphery of a burner designed for 100 per cent solid AF injection. This way, being inside the burner would allow a high level of control over the particles trajectory, intense mixing between fuel and oxidant performed by primary air and high oxygen availability from primary and secondary air.

First prototype

The first prototype was developed in 2013 for installation in a German cement plant. The specification for the solid AF (delivered and prepared by a third party), was two-dimensional material with a maximum size of 15mm.

Prior to the manufacturing of the burner, several injection tests were undertaken on site to establish the likelihood of blockages in the channel and to evaluate the distribution of the solid AF around the annular channel. Those tests were made using the existing transport line for solid AFs, redirecting it to the inlet of a 1:1 scale annular channel. In this way, the real solid AF would be blown with the real transport air, through a real annular channel with the tip connected to one end of a container with a dust collecting system at the other end. During the tests, different geometries and airflows were used.

The burner was designed to have maximum operational flexibility, allowing different tests with the following channels (from periphery to centre):

- external air channel with axial speed components
- annular channel for solid AFs
- tangential air channel with tangential speed components
- annular channel for coal
- dispersion air channel with tangential speed components
- central plate with cooling air with axial speed components, fuel oil lance, igniter, flame sensor and, as a back-up, a central pipe for solid AF up to 60 per cent of burner thermal power.

During the operation, as a result of problems in the solid AF preparation and/or contamination during the solid AF supply chain, there were constant blockages at the burner inlet caused by some material that did not meet specifications. Figure 9 shows some of the materials found in the inspection door at the burner inlet for solid AFs. Some materials were as large as 30 times the maximum specified size.

Following unsuccessful efforts to prevent the 15mm shredded solid AF being contaminated by the oversized particles, the plant decided to stop the trials.

The main learnings of the first prototype were:

- The installation of an additional back-up pipe for solid AFs in the centre of the burner, as well as a second channel with swirl air, increased the burner diameter. This required an excessive amount of transport air for solid AF to keep the annular channel gap above a certain value, jeopardising combustion and control. Reducing the burner diameter to a minimum and removing those channels would have been beneficial to burner operation.
- The geometry of the solid AF inlet at the burner could be optimised for a smoother connection to the burner body, enhancing the distribution of solid AF over the circumference and reducing the possibility of blockages.
- Excessive moisture in the solid AF had a negative influence on flame behaviour.

Figure 9: oversided material found in the solid alternative fuel that did not meet specifications during a trial project at a German cement plant

Austrian case study

A second step in the quest for maximising solid AF injection at the main burner was made in 2014, when an Austrian plant wanted to increase the substitution rate of its main burner from 40 to 100 per cent. This would not only reduce fossil fuel usage (and in turn costs) but would also make production at the plant CO_2 neutral.

Drawing on previous experience the following steps were taken:

- The solid AF would need to be ground finer than the previous two-dimensional particle being used, with no oversized material
- Moisture in the solid AF had to be reduced as it would help increase the relative calorific value and flame temperature
- A new main burner was necessary.

At that point in time, while A TEC GRECO was developing the burner for maximising AFs, the A TEC Rocket Mill® was being developed for solid AFs.

The burner and the mill are the main components of A TEC's Maximum Alternative Substitution To Environment

Figure 10: A TEC's Rocket mill® installed at a cement plant in Austria

Recovery (MASTER) system. The system suited the plant's targets, because it combines all the necessary steps into a single end-to-end integrated system.

The A TEC Rocket Mill combines drying and grinding in one step and consists of a robust crushing chamber equipped with four interchangeable horizontally-rotating chains and interchangeable perforated screens.

The rotating chains accelerate the material inside the mill, which is crushed against other material particles, the walls and the screens. The openings in the interchangeable screens are selected depending on the size and production of the final product required by the customer's pyroprocess. In the case of the Austrian plant, a 15mm screen was used, meaning that the maximum particle size at the burner would be 15mm. The prototype installed in Austria, with a motor of 250kW and single chamber, was able to produce up to 3tph with continuous operation of fine and dry material. Since the A TEC Rocket Mill can accept a particle size of up to 250mm, usually only one preshredding stage is needed.

The solid AF treated in the A TEC Rocket Mill has three main advantages compared to conventional shredders:

- **Product size and specific surface**

Due to the mill operation principle, using a 15mm screen opening means that approximately 50 per cent of the produced solid AF is <5mm. The crushing process, (as opposed to cutting) creates particles with a higher specific surface which improves ignition and combustion characteristics (see Figures 11 and 12).

- **Drying while crushing**

A drying effect occurs during the grinding process of approximately 10 per cent of the total moisture content. For example, if the input material's moisture content is 25 per cent, the drying effect will reduce the amount of moisture to 15 per cent after it passes through the mill. This drying is achieved with the heat generated during the crushing process. Additionally, hot gas from the pyroprocess can be injected into the mill, which promotes additional drying of the solid AF. Drying the material is beneficial to the ignition of the solid AF in the kiln, as well as in the flame temperature, as the lower heat value of the solid AF is increased.

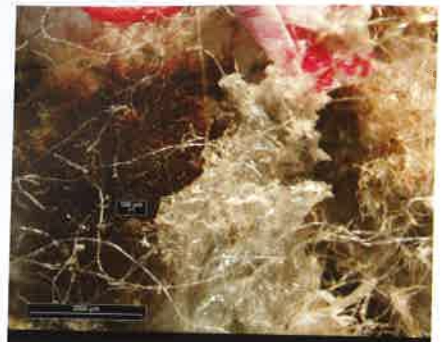
Figure 11: solid alternative fuel produced by A TEC's Rocket Mill®


Figure 12: solid alternative fuel produced by a conventional cutting shredder

- **Robust design**

Clean non-ferrous metal is recovered separately from the crushing chamber during operation via slide gates (see Figure 14). Due to the operating principle of the mill, with its moveable metallic chains, the mill can withstand foreign metallic particles, which the cutting shredder cannot.

Second prototype

A second prototype was developed for the Austrian plant and as an A TEC Rocket Mill was installed, particles above the required material size specification were eliminated. The A TEC Rocket Mill also reduced the moisture and therefore increased the lower heat value, thereby improving flame temperature. Due to the crushing process undertaken inside the A TEC Rocket Mill, the surface area of the solid AF increased which enhanced its ignition and combustion.

The other weak point of the first prototype was also corrected. The second channel with swirl components and the spare central pipe for solid AFs were removed. This allowed an overall smaller burner diameter, and a wider solid AF annular channel, without the need for an excessive amount of conveying air. This improved the flame adjustability and reduced the amount of cold air injected into the flame.

Different configurations have been tested on the second prototype, but the latest and current configuration is (from periphery to centre):

- external air channel with axial speed components
- annular channel for solid AFs
- annular channel for coal
- dispersion air channel with tangential speed components
- central plate with cooling air with axial speed components, natural gas lance, igniter and flame sensor.

Improvements were made at the solid AF inlet and in the annular channel at the burner, completely eliminating blockages experienced during the previous prototype.

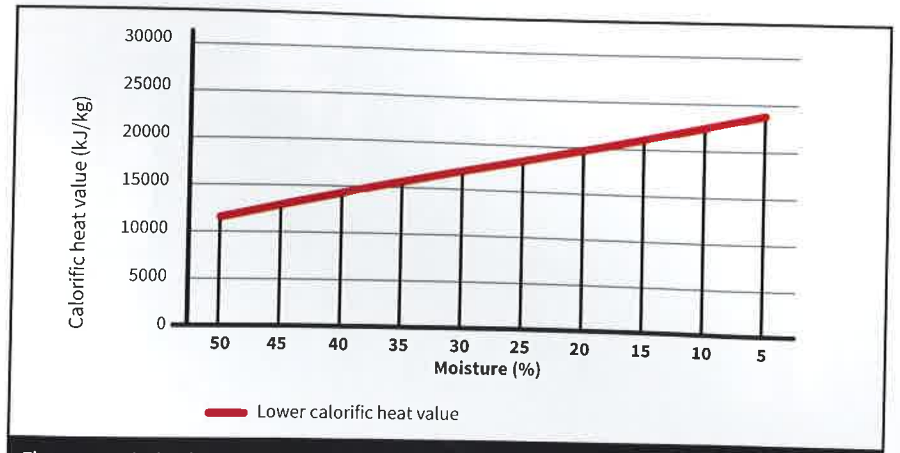

Figure 13: relation between lower heat value and moisture


Figure 14: inorganic material collected at the Rocket Mill's slide gates during operation

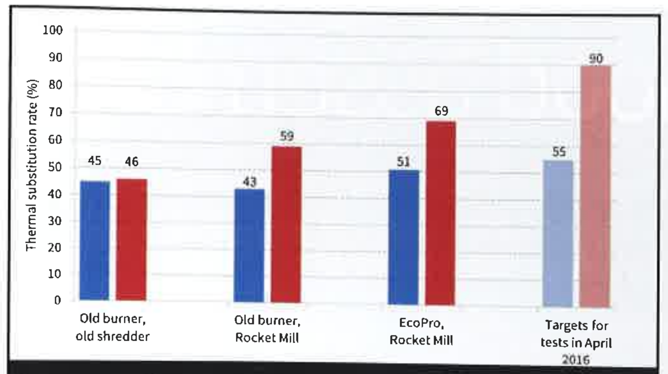

Figure 15: evolution of thermal substitution rate at the main burner in the Austrian plant

Results so far

To find out the benefits of the new system installed in the plant in Austria, it is necessary to split the data in two scenarios: the average values and the maximum achieved values.

Such differentiation is necessary because the chlorine bypass in this plant is at the limit, as the calciner operates with 100 per cent solid AFs. Therefore, it is not possible to operate the plant with a higher thermal substitution rate at the main burner in a constant basis above 50-55 per cent, due to chlorine limitations. Another reason is that the A TEC Rocket Mill installed in this plant has reduced dimensions and a production limited to approximately an equivalent of 60 per cent of the main burner thermal power.

With this in mind, it is possible to see in Figure 15 that, when compared to the previous condition (ie, the old burner and previous shredder), the average amount of solid AF injected at the main burner was kept the same. However, due to the better quality of the solid AF produced by the A TEC Rocket Mill when compared to the previous shredder (lower moisture and higher surface area), the maximum could also be increased by almost one third, from 46 to 59 per cent.

When the Flexiflame EcoPro was installed, the kiln immediately achieved its limited average of main burner thermal substitution rate (due to chlorines and the A TEC Rocket Mill production rate) with a value of 51 per cent. The maximum increased up to around 70 per cent. Being able to achieve this substitution rate at main burner means 50 per cent more than previously, a considerable increase. In this process, only the main burner and the mill for solid AFs were replaced. An absolute comparison to other kilns cannot be carried out, as every kiln reacts differently to AF injection.

In the data presented in Figure 15 only daily averages were used, taking into consideration the days in which the kiln was in operation with production above 70 per cent of daily capacity.

A new set of modifications was performed to the daily capacity. Of course, for shorter periods of 12h for instance, the thermal substitution rate achieved by the new system was higher. An Flexiflame EcoPro burner during the winter stoppage to achieve higher thermal substitution rates at the main burner and a new test battery is scheduled for April 2016. The results are to be shared soon on A TEC's website. ■

REFERENCES
[1] Courtesy of LEAT, Ruhr-Universität Bochum
[2] Courtesy of aixergee process optimization