APPLYING CFD TO OPTIMIZE FURNACES CO-FIRING BIOMASS AND THE IMPACT OF CO-FIRING ON SCR

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ABSTRACT

The international policy framework regulating the emissions of greenhouse gases from industrial and utility boilers is in flux. As such, most boiler owners are taking the opportunity to evaluate potential strategies for when, not if, more stringent reduction regulations are put into service. One of the most attractive options is the co-firing of biomass in existing pulverized coal fired boilers. This option is considered carbon neutral as the carbon released during combustion is a result of the carbon intake that the biomass stock required during its lifetime. Co-firing using existing milling, material handling, and combustion facilities, known as co-combustion, is the most cost-effective method of integrating biomass and has proven successful at heat inputs as high as 20% of total. There are significant technical difficulties regarding this approach. The risks associated with these difficulties are primarily related to the differences in the physical properties of the fuels; heating value, particle shape and size, and chemical composition, and how these properties effect combustion.

In addition, the same units that are the most amenable for biomass co-firing, large base loaded utility units, are also those that were first to adopt the NO_x reduction technology known as Selective Catalytic Reduction (SCR). The co-combustion of biomass presents particular difficulties to successful SCR operation, primary of which are plugging and poisoning. The mechanisms typically responsible for the difficulties are the alkali-metal aerosols formed during combustion of biomass in greater quantities than during the combustion of similar amounts of coal.

In both cases, the significant risks associated with blending biomass and coal can be mitigated via the use of state-of-the-art computational fluid dynamics modeling tools. This paper describes these challenges and solutions in detail.

OVERVIEW OF BIOMASS CO-FIRING

The co-combustion of biomass with coal in utility boilers has been proven an effective and cost efficient method for reducing Greenhouse Gas (GHG) emissions. This positive view of co-combustion is tempered by the knowledge that there are serious technical difficulties associated with the substitution of biomass for coal feed stocks specifically related to the material property differences of the two feedstocks given that typical system designs were assuming coal feedstock only.

As these feedstock physical properties differences can have an impact on such important furnace properties as flame profile and max temperature, it is appropriate to begin with a brief discussion of these physical properties. The most commonly discussed biomass feedstocks include corn stover, sugarcane bagasse, hard and soft woods, bamboo, switchgrass, miscanthus and animal by products. We will not discuss animal byproducts here as their application is limited to circulating fluidized bed boilers which are not included in the scope of this study. These are to be compared to the two common coal types of bituminous and sub-bituminous. In the broadest sense, one can generalize that the biomass feedstocks are higher in volatile organic matter, lower in energy density (having a lower Higher Heating Value), lower in mass density, have lower concentrations of sulfur, have higher concentrations of alkali and alkaline-earth elements (potassium, sodium, calcium, magnesium), have higher concentrations of phosphorous, chlorine and water vapor, have lower ash fusion temperatures, and cannot be as finely ground in existing coal pulverizers and thus resulting fuel particles are much larger and more irregularly shaped.

The table below attempts to summarize the fuel feedstock properties for some of the most common biolfuels.

Fuel	Bituminous	Sub-bituminous	Oil	Peat	Straw	Grass	Miscanthus	Corn Stover	Woodchips (willow)	Bark (willow)
Water (% Mass)	8	25	0.1	20.8	14.4	12.1	28.6	6.7	10.9	21.4
Volatile (% Mass)	32	32	93.9	56.3	64.4	69	56.3	72	73	56.4
Ash (% Mass)	10	5	5.5	3.9	6.4	5.3	2.6	4.9	1.7	3.1
Fixed Carbon (% Mass)	49	38	0.5	19	14.8	13.6	12.4	16.4	14.4	19
HHV (kJ/kg DAF)	31700	25,000	41875	23914	19331	19169	19768	18535	18478	19553
C (% Mass, DAF)	79	69	82.8	56.7	48.6	49.4	49.5	45.2	49.8	53.5
H (%, Mass, DAF)	5.1	4.5	11.4	6	6	6.1	5.73	5.7	6.1	5.8
O (% Mass, DAF)	13.7	24	5	35.9	43.4	44	43.9	42.8	43.1	40.4
N (% Mass, DAF)	1.48	1.02	0.36	1.70	0.92	0.61	0.53	0.91	0.60	0.33
S (% Mass, DAF)	1.66	0.25	1.29	0.20	0.23	0.08	0.08	0.15	0.06	0.06
Cl (% Mass, DAF)	0.20	0.05	0.34	0.04	0.48	0.17	0.22	0.35	0.02	0.03
As (mg/kg DAF)	6.2	6.2		0.0	1.3		1.0	0.0	1.2	0.4
Ca (mg/kg DAF)	2000	200000	149700	3250	4460		1440	3167	5417	15666
F (mg/kg DAF)	14000	16000		0	20000		20000		30000	
Hg (mg/kg DAF)	0.7	0.7		0.0	0.0		0.0		0.1	
K (mg/kg DAF)	1448		4400	432	11511	3400	91	13333	2710	1674
Na (mg/kg DAF)	1108		600	302	1417	33	307		199	899
P (mg/kg DAF)	443		160	530	1062		553	2167	699	482
Si (mg/kg DAF)	23300	23000	48600	6100	14000		8000	7750	526	922
Ash Fusion Temp (F)	2714	2160			1670	1832	1742	1750	2192	2250
Density (kg/m3)	1200	1200	1000	1000	200-500	200-500	200-500	200-500	200-500	200-500
Mean Particle Size (micron)	60	60	12	60	500-2000	500-2000	500-2000	500-2000	2000	2000

Table 1: Biomass Fuel Feedstock Properties

As these differences are embodied in the furnace of the boiler and in downstream equipment several serious issues can arise. In the following sections we will go through these issues in turn.

Effect on Combustion

The most common type of utility boiler is the pulverized coal combustion boiler, a common embodiment of which is diagrammed in the following figure. The feeding rate of coal and the amount of air available for drying and transporting the pulverized coal fuel is controlled by computers according to the boiler demand. Pieces of coal are crushed between balls or cylindrical rollers that move between two tracks or "races." The raw coal is then fed into the pulverizer along with air heated to about 650 degrees F from the boiler. As the coal gets crushed by the rolling action, the hot air dries it and blows the usable fine coal powder out to be used as fuel. The powdered coal from the pulverizer is directly blown to a burner in the furnace of the boiler. Under typical operating conditions, there is enough heat in the combustion zone to ignite all the incoming fuel.
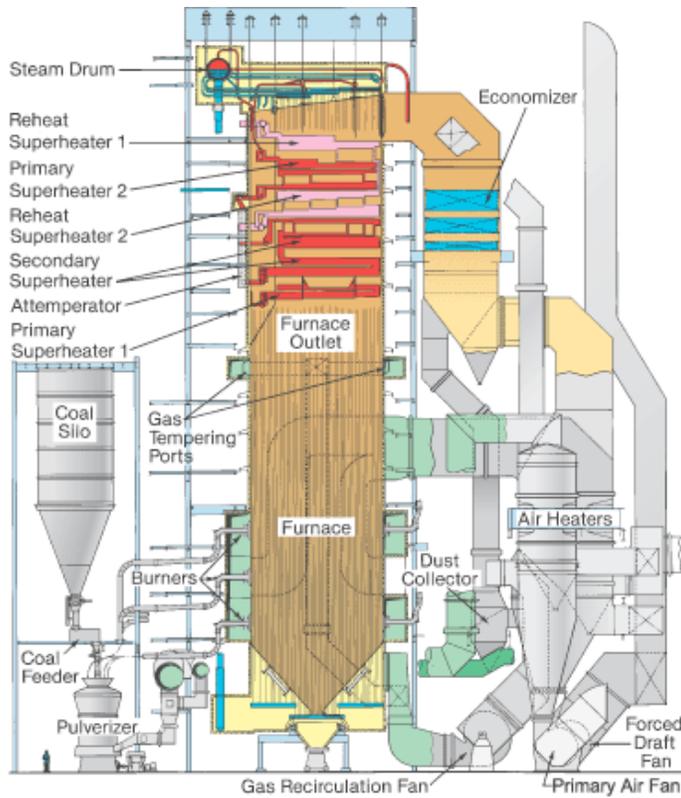
Figure 1: Typical Pulverized Coal Combustion Boiler (Courtesy of Babcock Power)

The first issue in this process arising from the substitution of biomass for coal is the result of the lower heating values of typical biomass feedstocks. As seen in Table 1, the H.H.V.s of typical biomass fuels are 10-40% lower than comparable coal heating values. This results in the need for more biomass, on a mass basis, to replace an equivalent amount of coal, on an energy basis. Combustion air demands remain relatively unchanged. The result is that individual burners must adapt to higher than design fuel mass flows.

Biomass particles vary quite dramatically in size, shape and density, but are typically larger, more irregularly shaped, and less dense than comparable coal particles. In addition, they have high volatile matter and water contents, as can also be seen in Table 1. To understand what effect these properties have on combustion we should provide a brief summary of solid fuel combustion. The following figure from *Kurose et al.* neatly summarizes the sequential steps in this type of combustion.
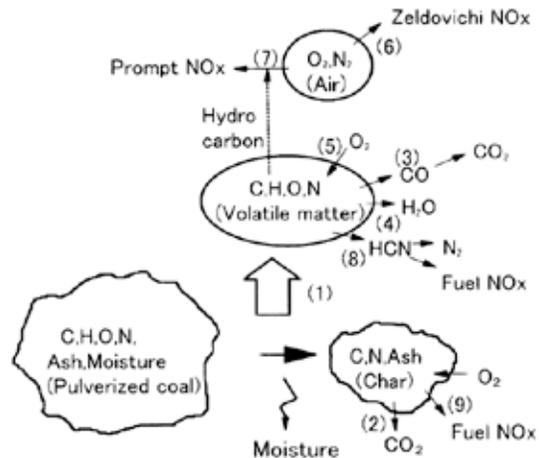

Figure 2: The Steps of Solid Fuel Combustion (Courtesy of *Kurose et al.*)

The first step required is the driving off, via evaporation, of the moisture within the fuel particle. After this occurs, the volatile matter at the particle's surface begins to undergo pyrolysis (devolatilize or degas) as further heat is absorbed. The volatile matter is quickly consumed via an oxidation (combustion) reaction with available O_2. After the last of the volatile matter is driven off, the remaining fixed carbon content is free to oxidize similarly. The solid particle that remains after complete combustion is known as ash.

There are many competing dynamics at play that influence differences in coal and biomass combustion dynamics, the most obvious of which is that higher moisture contents will delay devolatilization and combustion. In the most extreme cases, this separation may cause flame separation from the wall, which can negatively affect NOx production and flames stability.

In contrast and competition with this delay are the properties of larger particles size and greater volatile matter percentages. These properties increase the rate of devolatilization, as a function of available surface area, and rate of heat release, as a function of volatile matter oxidation being the faster oxidation reaction, as compared with coal.

Lastly, if particles become prohibitively large (>1000 microns) their ability to remain entrained in the flow can become an issue and they may fall into the bottom of the boiler. At intermediate sizes particles may carry further into the boiler than the design coal, impinging on boiler tube walls or exiting unburned in some cases.

The fuels lower heating values, coupled with the properties described above, do create changes in flame shapes and temperature profiles within the boiler where significant quantities of biomass are being integrated. The generic result of most of the above is a cooler, more detached flame that does not stretch as far up into the convective section of the boiler as for 100% coal. With respect to nitrogen oxides production, and all things being the same, this combustion dynamic would result in higher values of NO_x, but in this case any increase is offset by lower fuel bound nitrogen concentrations, the overall net effect being neutral to slightly NO_x reducing.

Additional complications cluster around the various chemical constituents that are present at considerable levels not seen in coal, including the alkali and alkaline-earth metals (potassium, sodium, calcium, magnesium), and phosphorous and chlorine. Chlorine is particularly harmful due to its known propensity to enhance fine ash formation and produces a dangerous mechanism for transportation of potassium and other constituents which can be harmful to downstream equipment, as will be discussed in the sequel.

Secondly, the increased concentrations of the alkali and alkaline-earth metals, especially potassium and calcium, act to lower the ash fusion, or melting, temperature. This typically results in a greater amount of boiler slagging (boiler tubes becoming covered with liquid ash which is not easily displaced) and reduced boiler efficiencies.

Almost exclusively and except in the rare case where pilot tests can be performed, the only way to investigate the expected quantitative effects of co-firing biomass is through computational modeling of the combustion process. The following figures correspond to a Computational Fluid Dynamics (CFD) model study of a 32-MW wall fired PC unit and demonstrate the comparison of flame conditions from baseline to a modified case where 20% wood chips are being co-fired. CFD can be used to provide quantitative comparisons of many critical parameters including maximum wall surface temperatures, levels of unburned carbon, and concentrations of emissions.
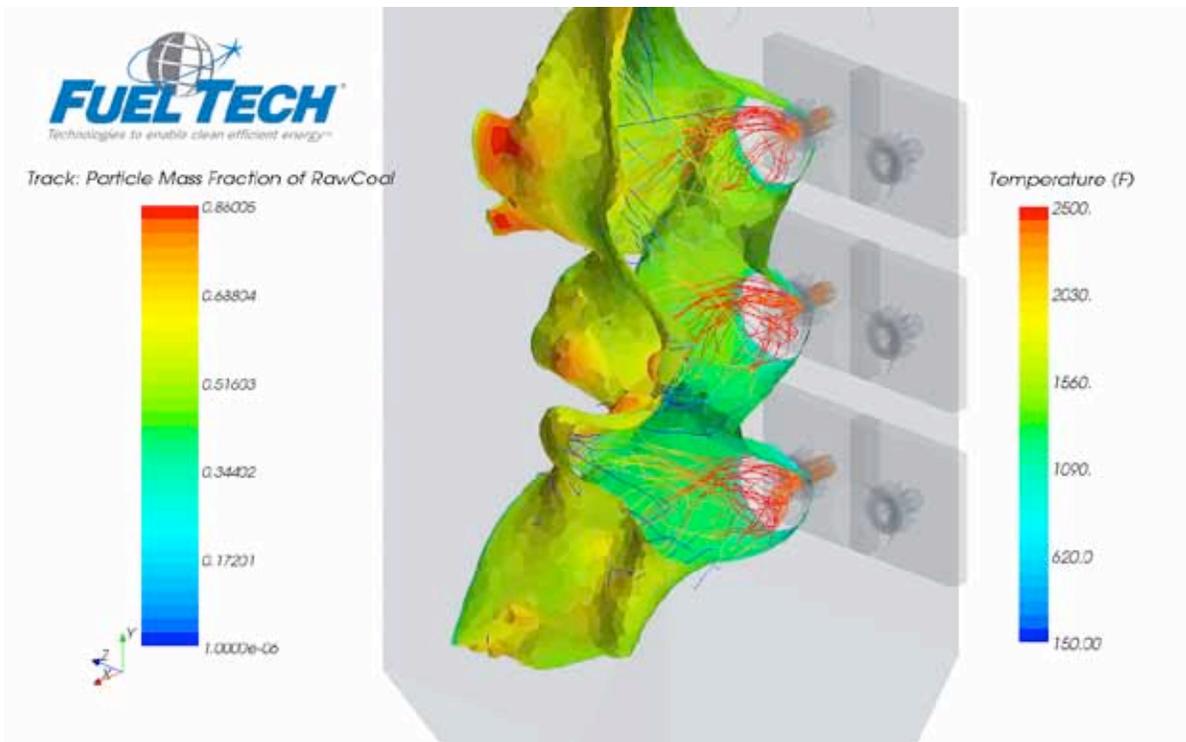
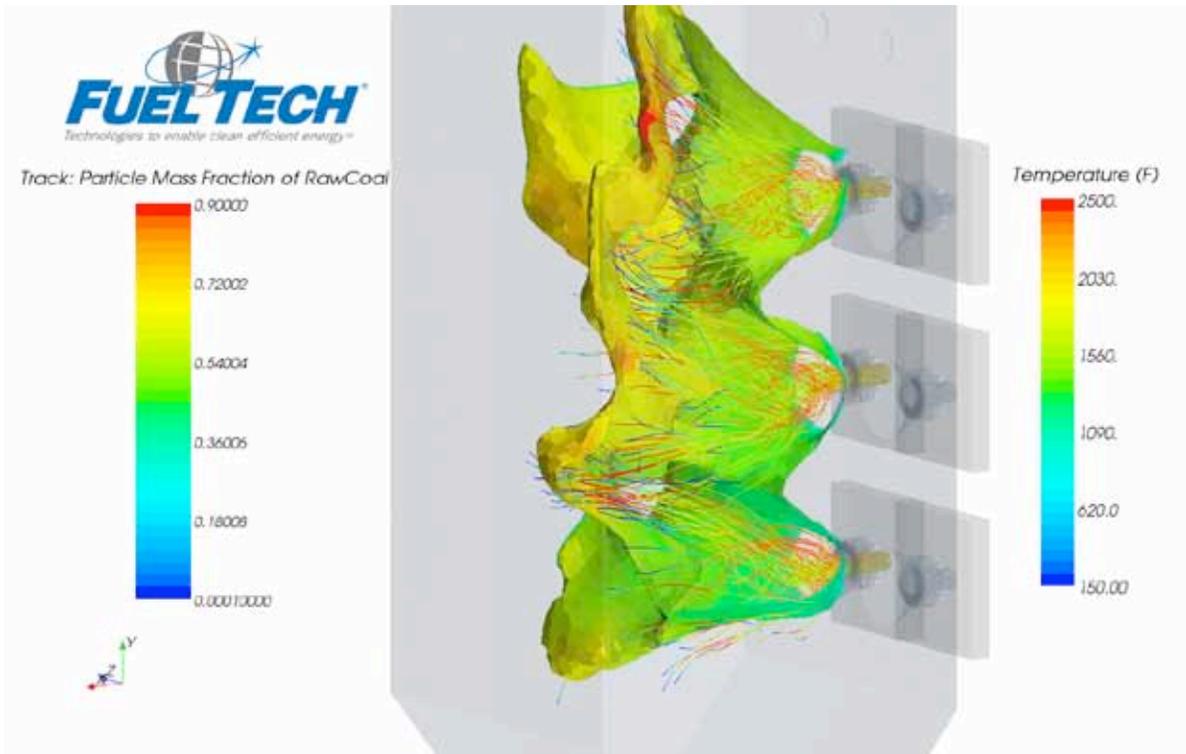Figure 3: Baseline CFD Model Result for 32-MW Wall Fired PC Unit

Figure 4: 20% Wood Co-firing CFD Model Result for 32-MW Wall Fired PC Unit

Effects on Selective Catalytic Reduction (SCR)

SCR is the most efficient NO_x reducing post combustion technology and entails injection of NH_3 into the flue gas downstream of the boiler and reaction with NO_x upon a catalytic substrate at temperatures generally within the range of 550 to 750 F. In general, the following reactions are responsible for NO_x reduction.

$$2NH_3 + 2NO + \frac{1}{2}O_2 \rightarrow 3H_2O + 2N_2$$

$$4NH_3 + 2NO_2 + O_2 \rightarrow 6H_2O + 3N_2$$
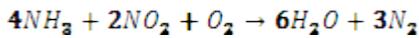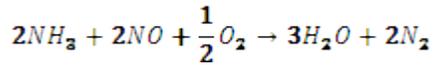
NO_x reduction efficiencies as high as 95% have been achieved in the most favorable cases.

Perhaps even more so than the boiler function, SCR function is challenged by co-combustion of biomass. There are many technical challenges, mainly relating to the chemical constituents present in biomass not present in coal. The first of these challenges is the chemical deactivation of the catalyst caused by chemicals attack on the active sites of the catalyst. The second is the small scale plugging of catalyst micropores caused by the agglomeration and inefficient flow through of very fine scale ash and other particulates. These two types of "poisoning" are diagrammed in the following figure, as shown originally in the work of *Baxter*.
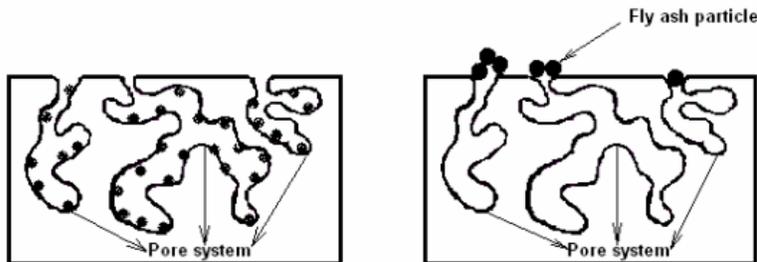

Figure 5: Two Pathways to Deactivation, Chemical Attack of Catalyst Active Sites and Physical Blinding/Plugging of Catalyst Micro-Pores.

Perhaps the most important aspect of biomass co-combustion as it relates to the operation of SCR is the increased hygroscopic, or hydrophilic, nature of the fly ash produced coupled with the higher levels of water vapor and catalyst poisons in the flue gas. This being the case, it cannot be stressed enough that the catalyst should be kept warm and dry under all circumstances as to not let this ash become moist and saturate the catalyst's pore system, as it will contain poisons such as potassium, phosphorous, sodium, etc. that will chemically blind the active sites. This can be accomplished through the dual use of preheated air flow through the catalyst for a predetermined time period before flue gas is introduced and the filling of the reactor with hot dry air during layup periods.

In addition, these same poisons (potassium, phosphorous, sodium, etc.) that are not absorbed onto ash particles will readily oxidize during the combustion process and form aerosols that also allow for the chemical attack of the pore system. Alkali-metal aerosols formed during combustion of biomaterial are well known to be able to severely impact the performance of SCR catalysts physically blinding the catalyst pores through formation of sulfates where both are present in significant concentrations. These sub-micron particles adhere to the surface of the catalyst and are readily transported to the active sites by surface diffusion. Spectroscopic studies suggest that the poisoning mechanism occurs via chemical bonding of the alkali metal to the crucial –V-OH sites, the so-called Brønsted-acid sites which also adsorb and "activate" the ammonia, forming –V-OM (M being K or Na) and thereby blocking the catalytic cycle.

If potassium levels are extreme, the ash fusion temperature can approach SCR operating temperatures and such a condition will quickly lead to complete deactivation of the catalyst. The use of a particular variety of straw at one unit resulted in significantly accelerated catalyst deactivation with 45 percent activity loss in 10,000 operating hours. All of these conditions are best accounted for in the process design of the SCR.

Co-firing of biomass will change the nature of the flyash. Fines will become smaller, predominantly in the sub 10 micron range, and can become stickier as they form sulfates on the catalyst. These changes make it more difficult for the ash to flow efficiently through the reactor. If the flyash does not flow through the catalyst it will be subject to the 2nd pathway to deactivation, fly ash pluggage. It cannot be understated that proper flow design, through CFD and experimental fluid dynamics modeling, is a relatively low cost tool to ensuring that ash flows through the reactor efficiently. If a current SCR reactor experiences ash pluggage issues one should expect that the co-firing of biomass will exacerbate this situation. Fuel Tech has developed specific technology for ensuring proper flow conditions through the catalyst, including the above reactor flow distribution device known as the Graduated Straightening Grid (GSG), as shown in scale model testing below. In addition, the use of either soot blowers or sonic horns (preferred) are a necessity in keeping the ash fines excited as they move through the catalyst layers.

Figure 6: Experimental Scale Modeling of Flow Through GSG and SCR Catalyst

Lastly, co-firing biomass has shown the tendency to increase the prevalence of what is commonly referred to as Large Particle Ash (LPA). These particles are typically highly porous, agglomerations or fusions of ash particles, which can range in size from microns to over 10 millimeters. Due to their low density they remain primarily entrained in the flue gas flow and can reach the catalyst if nothing is done to prevent this. There they will quickly plug the catalyst channels disrupting the flow to the remainder of the reactor and quickly causing major problems. The solution to this problem is the intelligent design of LPA capturing devices, including LPA screens that are optimized via fluid dynamics modeling. A picture of such an installation is shown in the following figure, as well as a typical sample of LPA.

Figure 7: LPA Screen Installation

A cost evaluation by EPRI has shown that for modest cases of catalyst deactivation – typifying 10-20 percent biomass firing – the impact during a 15-year period for additional catalyst replacement could be 20-60 percent of the baseline case.

SUMMARY

The following observations have been made during the course of the author's experience with co-fired biomass applications, modeling, and SCR evaluations, and have been reported on herein.

- The physical properties of the specific biomass fuel feedstock can have significant effects on both combustion and downstream pollution equipment, especially SCR.
- The specific embodiments in the boiler are flame shape, temperature profile, boiler efficiency, and boiler maintenance, and are typically due to the non-design biomass properties such as lower energy content, higher moisture content, chemical constituents, and particle size and shape.
- Computational Fluid Dynamics is the foremost tool to investigate the predicted quantitative behavior of test scenarios with various combinations of fuels.
- The specific embodiments in the SCR are pr(Baxter, 2005)imarily poisoning due to chemical attack on active catalyst sites via poisons such as potassium, phosphorous and sodium, and physical blinding due to the increase in flyash fines due to the increased calcium content of the fuel and its proclivity to form sulfates on the catalyst.
- Also of concern is the hygroscopic nature of the fly ash due to the increased alkaline-earth metals in the fly ash, causing increased risk of flyash condensation and leaching of poisons into the catalyst, and requiring strict operating procedures ensuring the catalyst remains warm and dry.
- Also of concern are the increased risk of pluggage due to modification of ash properties and an increase in LPA production. Both are mitigated via CFD and experimental modeling and flow distribution devices such as Fuel Tech's GSG.
- Overall, catalyst deactivation can increase at rates from 20 to 60%, and can be minimized through proper design and engineering.

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Kurose, R. M. (2004). Numerical analysis of pulverized coal combustion characteristics using advanced low-NOx burner. *Fuel* , 693-703.