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Fuel Additive Technology - NOx Reduction, combustion efficiency and fly ash improvement for coal fired power stations

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Abstract

Fuel additive technology is based on the use of a solid, fuel additive (iron, aluminium, calcium and silicon based oxides), to reduce NOx emission, improve the quality of fly ash and result in 1-3% coal savings for pulverised coal combustion. The findings in this study have been mainly based on extensive experimentation on 100kWth down fired-combustion test facility (CTF) and partially on a 260tons/hr steam commercial producing water tube pf boiler. International Innovative Technologies (IIT) developed this additive based technology for the combined effect of reducing NOx from the combustion of hydrocarbon fuels (mainly coal) and more specifically to improve the combustion process of fossil fuels resulting in an ash by product with improved loss on ignition and lower carbon content. The improvement in the combustion thermal efficiency of the commercial 260tons/hr steam producing boiler has been calculated as per the direct calculation method of EN BS12952-15:2003 standard.

Keywords: Fuel, additive, NOx, fly ash, combustion efficiency, coal, boiler, BS EN12952-15 (2003).

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1. Introduction

The consumption of coal is increasing continuously on a global scale and is likely to increase in forthcoming years due to its cheaper pricing compared with other conventional fuels and further economic expansion in developing countries. However, the environmental regulations and legislation has enforced a rise in carbon floor pricing and heavy penalties towards breaching caps on emissions. In USA, the environmental protection agency has proposed to implement 1,100 pounds (499 kgs) of cap on CO_2 emissions generated for every MWh of electricity produced from June 1, 2014 [1]. Similarly clean air interstate rule (CAIR) has a total of 1,882,226 tons (170756 tonne) of NOx allowance, which is annually reconciled to check and ensure that NOx emissions reduction is strictly monitored and consequently controlled [2]. Amongst EU states, businesses are penalised if they do not have enough allowances for each calendar year to cover emissions; e.g. for 2013, penalty charges were € 100 per tonne of CO_2 (or the equivalent amount of N_2O) [3]. It is also noteworthy that the fly ash handling and disposal costs are increasing due to the higher carbon content carrying fly ash. It is of particular interest in finding systems to reduce or minimize the emissions, improve thermal efficiency, and utilise efficiently the fly ash product through catalysts or additives. The fuel improver is capable of reducing emissions, increasing thermal efficiency and produce low carbon fly ash to be used in cement industry. The technology is already patented and findings have been endorsed in UK Patent GB 2462978 and pending UK patent application No 1308472.8.

Hence it is of pivotal importance to the power plants in particular to operate and have enough allowances to cover emissions specially CO_2 and NOx. Similarly, excessive carbon remaining in the fly ash affects the optimum density and moisture content for filling application in the building industry along with less protection against freeze thaw conditions. Fly ash can be used as a replacement for a proportion of Portland cement content of concrete mixture resulting in indirect savings in CO_2 emissions since cement industry produces approximately one tonne of CO_2 / ton of Portland cement.

During recent years influences of different additives/catalysts on combustion behaviour have been investigated [4-8]. The iron-based catalyst improved pyrolysis yield and char oxidation rates at high temperatures even at high heating rates [4]. In another study when Fe^{+3}

ions were added to the demineralised coal samples via precipitation method, N_2 formation from char-N increased by two folds [5]. Similarly cluster of iron oxides are known to reduce NO to form N_2 [6]. Iron based fuel improvers because of relatively better heat transfer properties could also enhance thermal cracking of heavier hydrocarbon supported by increase in hydrocarbon intensities and Volatile-N [7]. At high temperature and water concentration, reactivity of Fe_2O_3 during reburning is increased due to oxidative ability and HCN oxidation to CO and N_2, respectively [8].

The proof of the concept to utilise IIT's fuel additive that has already been tested on smaller - bench scale reactor and has progressed through pilot scale and to commercial 260 ton/hr. The results of the pilot and full scale tests are presented here.

2. Experimental test facilities and methods

The pilot scale combustion test facility (CTF) comprises of a down-fired pulverised coal furnace. The furnace has eight modular sections with each having an internal diameter of 400mm (Figure 1a). The overall furnace is 4 meter in height. The input feed rate of an approximately 10-11.65 kg/hr of coal (depending upon types of coal) result in a net thermal input of about 75-85 kW to the CTF. The coal was fed in the CTF through Rospen's loss in weight feeder (Figure 1b), whereas fuel additive was blended in the vibratory tray with help of smaller vibratory feeder (Figure 1c). The down-fired quarl section of the burner expands from 66mm throat to 475mm diameter. Initially the CTF is warmed up with propane until temperature around the burner is 1000^oC for transitioning fuel from propane to coal. The coal firing continues until temperature reaches steady state. To minimise temperature creep in the system the top sections are water-jacketed and insulated.. The major flue gas species (CO_2, O_2, NOx, and CO) are measured at the outlet of furnace through water cooled stainless steel probe to the gas sampling system. The continuous emission measurements of O_2, CO_2, CO, and NO (NOx) and temperatures throughout the furnace are logged to spread sheet during each test period. The fuel additive was fed with different types of coal to the furnace in mass fractions from 1.3% to 13%. A dedicated cyclone separator collects the fly ash from flue gas path. The analysis on emissions was only performed on steady state and collected coal fly ash samples were analysed as per ASTM D7348-08 for loss on ignition (LOI).

The commercial trials have been performed on a natural circulation, front wall fired boiler with maximum continuous rating steam flow generation of about 280 tons/hr when firing coal. There are twelve burners set in 3 landings of 4 burners each. Each landing of the boiler (4 burners) is connected with vertical ball mill. Two forced draft (FD) fans supply the primary and secondary air for the boiler whereas two induced draft (ID) fans draw the exhaust gases through the air heater and an electrostatic precipitator before discharging the gases to the stack. The overall process flow diagram of the boiler is shown in Figure 2. The direct method was adopted to calculate the boiler efficiency due to the relative size of the boiler and highest accuracy in measurements. It is worth mentioning that this commercial boiler does not have steam re-heaters, steam air heater, flue gas recirculation or circulating pump arrangements.

The following were the calculations utilized for the purpose of determining the Thermal efficiency of the boiler (BS EN 12952-15:2003).

$$\eta\ (N)B = \frac{Q_N}{Q_{(N)}Ztot}$$

$$Q_{N} = m_{ST}(h_{ST} - h_{FW}) + m_{SS}\ (h_{FW} - h_{SS})$$

$$Q_{(N)\ Ztot}\ =\ m_F H_{(N)tot} +\ Q_{(N)Z}$$

Where

$$Q_{(N)Z}\ = P_M + P$$

$$H_{(N)tot} = (H_{(N)} + C_F(t_F - t_r)) / (1 - l_u) + \mu_{AS}h_{(N)AS} + \mu_A C_{pA}(t_A - t_r)$$

$$l_u = \frac{\gamma_{Ash}\,(1-v)}{1-\gamma_{Ash} - \gamma_{H2O}}\left[\frac{u_{SL}}{1-u_{SL}}\eta_{SL} + \frac{u_{FA}}{1-u_{FA}}\eta_{FA}\right] \text{(Based on estimated ash collection efficiency)}$$

The above $Q_{(N)Ztot}$ equation gets simplified into the following equation 1; when running on coal;

$$Q_{(N)}\ Ztot = m_F\left[(H_{(N)} + C_F(t_F - t_r)) \Big/ \left[1 - \frac{\gamma_{Ash}\,(1-v)}{1-\gamma_{Ash} - \gamma_{H2O}}\left(\frac{u_{SL}}{1-u_{SL}}\eta_{SL} + \frac{u_{FA}}{1-u_{FA}}\eta_{FA}\right)\right] + \mu_A C_{pA}(t_A - t_r)\right] + P_M + P$$

…………………………………………….. (1)

The measurements associated with stack emissions, coal flow, primary and secondary air flows, boiler and spray feed water flow rates, main steam flow and associated temperature and pressure were recorded during the trials. The recorded data under steady state was analysed using the following statistical techniques. Statistical average was applied on the data in order to acquire the steady state levels. The statistical analysis of the data included the standard deviation and the average. The standard deviation gave an indication of how widely values are dispersed from the average value (mean). It explains how much variation or dispersion from the average mean.

2.1.<u>Material</u>

Additive is mainly a mixture of iron, aluminium, calcium and silicon oxides. It is low cost synthetic mineral with a strongly bonded matrix structure of different elements. Two of the types of additives can be produced; a: Air Cooled Additive, b: Water Cooled Additive. The XRF/XRD composition of the both these types are tabled below (Table 1).

Table 2 shows the particle size distribution of both types of Additive milled in IIT M600 patent mills (GB 2451299, GB 2460505, and GB 2471934). It is recommended to have the processed Additive milled at 90th percentile equal or less than 32 µm [d (0.9) ≤ 32], this would benefit in minimum impact towards rate of abrasion in normally basalt lined Pf lines. It has been suggested in literature [9-10] that generally the erosive wear increases with the cube of particle size, hence by keeping the milled particle size distribution less than 25 microns the rate of erosion can be negligible. Preferably the average particle size of fuel additive and carbon based fuel (coal) is reduced by pulverisation. The additive comprises of oxides or other compounds of chemical elements from periods 3 and 4 (groups II-V) of the periodic table. The fuel additive can be injected into the combustion chamber alongside the fuel (preferably in the pulverised fuel carrying lines) or mixed within the coal based fuel feed. The additive can also replace a proportion of the carbon based fuel in the amount ranging from 1% to 5% by weight depending upon the acceptability of the improvement in loss on ignition (LOI) in overall performance assessment. The coal firing boilers can either produce same steam load by burning less fuel or increase steam load by burning the same fuel input, depending upon the amount of additive and improvement in LOI. The fuels used during the experiments included commercially available coals having low, medium and high ash contents. The Russian sub bituminous medium ash coal, Columbian low ash coal and UK Kellingley high ash coal (Table 3) were used in the additive tests.

3. Results and Discussion

3.1 Effect on NO emissions

Fuel bound nitrogen contributes to about 80% - 95% towards the NO_x formation in pulverized coal combustion while the balance is associated with the thermal and prompt NO_x. Fuel bound nitrogen during coal combustion is generally split into volatile-N and char-N [11]. This division preferentially depends upon nitrogen content and volatility of coal along with the combustion conditions such as temperature, residence time, and heating rates [11]. In the case of sub bituminous coals, the volatile-N comprising of tarry compounds decay rapidly to hydrogen cyanide (HCN) or soot-nitrogen [12-13]. Whereas In contrast the low rank coals would preferentially release the light nitrogen species such as NH_3. Combustion of nitrogenous species (NH_3 and HCN) present in the released volatiles and oxidation of the char-nitrogen results in the formation of oxides of nitrogen. However, the HCN or NH_3 may also be reduced to N_2 after reacting with the available NO. This depends upon the available stoichiometric ratio near the burner, mixing of the evolved species in the furnace and fuel-N concentration [11-15]. Generally in-furnace control technologies, air staged combustion and reburning result in less emissions of NO_x but at the cost of higher levels of loss on ignition. The oxygen enriched combustion can facilitate to offset the compromise on loss on ignition [16-19] however, the developed additive is capable of benefitting not only lower NO_x emissions, lower loss on ignition, improved thermal efficiency and utilise efficiently the fly ash product.

Figure 3 shows the effect of addition of both types of Additive towards NO_x emissions. The process of NO_x reduction under un-staged combustion observed during additive addition is associated partly with the interaction of additive fine particles with coal matrix and volatiles as they are released from coal particles, resulting in cracking of the heavier hydrocarbons favouring the split of fuel-N into volatile-N (Figure 4). This favours the NO_x reduction pathway towards N_2 formation rather than NO formation by oxidation, since this form of fuel-N is easier to control in the fuel -rich zones of the flame. This was evident from the fundamental laboratory tests done (Table 4) on a two stage fixed bed reactor (comprising of two chambers of which one is loaded with 2-4gms of coal sample pyrolysed with inert gas and the derived gases were reformed in a second reactor where fuel additive is placed. Products after the second-stage reaction were condensed by air and dry-ice. The non-condensed gases were collected by the gas sample bag and further analysed by gas chromatograph). It has been found that an increase of 33-41% in the gas yield and 18-47% reduction in tar yield has been established. In literature it has been reported that tar (of which naphthalene is the main constituent) reduction is controlled by catalytic decomposition on iron or its oxides. Similarly in case of volatile aromatic hydrocarbons; benzene, an important intermediate of complex tar reduction mechanism, has been found to undergo enhanced reduction over iron based catalysts (equation 2) [20-22].

$$C_6H_6 \overset{slow}{\underset{}{\xLeftrightarrow{H_2\,,\;\; Fe\ Catalyst}}} C_6H_6\,(activated) \xrightarrow{fast} C_6H_{12} \overset{\Delta}{\rightarrow} C_nH_m, CH_4, \dots\dots\dots\dots \quad (2)$$

Fe-Al catalysts with increase content of iron, increased pore structure and surface area enhanced the steam reforming of naphthalene. However, the crystalline phase and oxidative states of the active sites are more influential chemical properties than physical influences [22]. Similarly in a separate study related to pyrolytic cracking of coal tar, the initial heavy tar in the liquid product decreased by 88% over iron oxide catalyst [23]. However, as part of this study a range of about 18% to 47% reduction in tar yield was observed compared to RC baseline. This increase in the gas yield supports the hydrocarbon cracking and release producing more of volatile which in turn facilitates the NO reduction into N_2 (Figure 4). Moreover, the presence of iron oxide in the fuel additive would also interact with coal to result in additional NO reduction reactions supplementing the existing pathway towards N_2 formation. The suggested mechanism also revolves around the reactions proposed by researchers [24-25]; showing that Fe_2O_3 can be reduced to Fe in presence of CO, and later on NO can oxidize iron to reproduce Fe_2O_3. In a separate comprehensive study it has been reported that primarily CO/NO adsorbed on the Fe_2O_3 weakens one of the O-Fe bonds by creating a loosely attached O site which further oxidizes CO to form Fe_2O_2. This Fe_2O_2 now reduces NO via redox (oxidation and reduction steps) reactions to produce oxidized Fe_2O_3 [26]. The interaction amongst CO, NO with additive in the flame envelope and surrounding region (fuel-rich and fuel-lean pockets) can be summarized as follows;

$$3CO + Fe_2O_3 \rightarrow 3CO_2 + 2Fe \ldots\ldots\ldots\ldots \tag{3}$$

$$2Fe + 3\,NO \rightarrow \frac{3}{2}N_2 + Fe_2O_3 \ldots\ldots\ldots\ldots \tag{4}$$

The net algebraic addition of reactions yield

$$CO + NO \rightarrow CO_2 + \frac{1}{2}N_2 \ldots\ldots\ldots\ldots \tag{5}$$

Three different types of coals investigated for the study with a view to observe any variation in the behaviour of additive on NO_x reduction. The medium ash Russian Coal (RC) and high ash Kellingley Coal (KC) resulted in slightly higher reduction in NO_x as compared to Columbian Coal (CC) because of relatively higher volatile matter and lower fixed carbon compared to CC. The air to fuel ratio in the combustion test facility (CTF) was set at 20% excess air levels (stoichiometric ratio of 1.20) for un-staged flame firing condition. The optimum range up to 13% by weight of that of coal input was observed for both types of Additive. NO_x reduction of 15% & 16% for 13% & 12% mass fractions of WC and AC Additive were observed for RC, respectively. Whereas, 11% & 10% NO_x reduction was achieved for 11% and 13% mass fraction of WC and AC Additive with CC, respectively. KC with WC and AC Additive co-firing resulted in 14% & 15% reduction in NO_x for 10% and 13% added mass fractions, respectively. In recent publication it has been found that increasing the water concentration and temperature of furnace enhances Fe_2O_3 activity during reburning. It associates with water vapour being an oxidant enhances HCN oxidation to CO and N_2 along with Fe_2O_3 oxidative ability at high temperature [8].

In general the following mechanisms can be summarised towards reduction of NO_x emissions using both types of Additive.

- It is associated partly with the interaction of Additive particles and coal matrix, resulting in cracking of the heavier hydrocarbons favouring the split of fuel-N into volatile-N. The increase in the gas yield (Table 4) supported by the higher concentration of CO and hydrocarbon would favour the NO_x reduction pathway towards N_2 formation rather than NO by oxidation, since volatile part of N is easier to control in the fuel -rich zones of the flame.
- Additive having higher surface area because of finer particle size distribution compared to coal, would facilitate the thermal degradation of heavier hydrocarbon into lighter hydrocarbons and these lighter hydrocarbon are less likely to form Char-N.
- The presence of iron oxide in the fuel additive would also interact with coal to result in additional NO_x reduction reactions supplementing the existing pathway towards N_2 formation.

Figure 5 represents the effect of change of stoichiometric ratio near the combustion zone on different co-firing blends of Additive with RC, CC and KC. The in-furnace air staged combustion creates fuel rich zones due to the delayed mixing of fuel particles with air resulting in the abatement of NO. The reduced stoichiometric ratios i.e. 0.8, 0.9 in primary combustion zone restrain coal combustion, and a large amount of unburned char enters the burnout zone resulting in poor carbon burnout. The addition of Additive resulted in an additional impact on increase in NO reduction with decreasing air to fuel ratio. WC Additive with RC resulted in a range of 4.6% to 25.8% reduction in NO for range of 0.9 to 1.20 stoichiometric ratio. Whereas, a range of 4.7% to 23.9% was observed for WC/AC Additive with CC for 0.8 to 1.16 changing air to fuel ratios. AC/WC Additive with KC for 0.9 to 1.30 stoichiometric ratio resulted in 7.3% to 31.1% reduction in NO with respect to coal staged flame base lines.

3.2 Effect on temperature measurements

The various feed rates of the additive have resulted in increased temperature measurements close to the burner section; this increase in temperature is due to enhanced and intensified combustion taking place in the presence of Additive. Figure 6 represents the temperature differences measured at axial distances downward from the burner with T1 being close to the burner and T7 near the flue section. The values were calculated for different mass fractions of additive for all the studied coals against the corresponding coal baseline temperature measurements. As indicated from the general trend found in Figure 6, the different mass fraction of Additive produced a broad range of 12-30 ^{o}C change in temperatures at T1. These changes in T1 values are categorically dependent upon the added mass fraction of Additive. The increase in the temperature also supports the improved values of loss on ignition. The addition of Additive resulted in generation of extra temperature due to the burning of the additional carbon of the coal feed, favouring the split of carbon more into light volatiles rather than remaining in the char.

3.3 Effect on Loss on ignition (LOI)

The United States of America, India, China and Australia are the major producers of fly ash, USA alone produced 57.2 Million metric ton (Mton) of fly ash of which only 22.4 Mton was used in concrete / cement manufacturing [27]. Fly ash mainly comprising of oxides of silicon, aluminium and iron principally consists of glassy spheres together with unburnt carbon and some crystalline matter. The introduction of low NOx burners led to a gradual rise in loss on ignition. The unburnt carbon is significant in air-entrained concrete mixtures because of its tendency of adsorbing air-entrained surfactant rendering less protection against freeze-thaw conditions. Similarly excessive carbon affects the optimum density and moisture content for filling applications.

Additive addition results in a substantial improvement in LOI as evident from Figure 7. The presence of additive has increased the hydrocarbon intensity and gas yield conversion from coal, which in turn intensifies the combustion and results in improved LOI. In case of RC, an overall net reduction for the LOI in the range of 19% to 63% for 1.3% to 13% mass fraction of added Additive was achieved. Similarly, a range of 20% to 70%; 64% to 70% reductions in LOI were found for 2.5% to 11%; 5% to 13% mass fractions of added Additive for CC and KC, respectively. The optimum mass fraction of Additive ranges from 5% to 12% in order to be used as cement substitute having less than 7% LOI for cement manufacturing. The particle size distribution (PSD) of resultant coal fly ash can potentially fluctuate depending upon the operation of the power station. Typically power stations are operated under a steady load to compensate for variation of the resulting fly ash. General purpose cement utilizes finer ash because finer the ash the greater the reactivity. Moreover, the variability in the fineness of the fly ash dictates the strength and water content of resulting concrete. Figure 8 represents overlay of RC - 4.2% additive resulting fly ash and KC - 4.8% additive fly ash along with RC, KC and a typical UK fly ash PSD. It can be seen from the graph that with addition of additive (4.2% to 4.8%) the fineness of resulting fly ash increased by about 36% to 85% in addition to that of RC and KC fly ash baselines, respectively. This would benefit in terms of improving the fineness of the resultant fly ash. The addition of additive results in fly ash which falls under PFA BS EN 450 standard where by 40% or less of product fly ash is retained on 45 micron sieve, as well as PFA BS 3892 ($\leq$ 60% retained on 45 microns sieve). Similarly 56 Day cube strength tests on the fly ash of both RC and RC- 4.2% additive mixture were performed by a major cement manufacturer of the UK. It can be seen from the Table 5 that the cube strength results are reasonably close to each other without any major variation in the strength characteristics of the cement mixture. Similarly to comply with Portland cement requirements, SiO_2+Al_2O_3+Fe_2O_3 must be above 70% which is true for additive. The addition of additive has resulted in equally comparable strengthen mortar when prepared by mixing 30% of coal plus additive fly ash blend with Portland cement.

3.4 Effect on Slagging and Fouling

Slagging and Fouling characterizes the deposits on the radiant section of the boiler and heat recovery section, respectively. These deposits are formed through a series of complex mechanism, forming a variety of compounds causing corrosion and reduction in heat transfer rates. Slagging and fouling indices are used for the assessment of the propensity of fuel ashes to form these deposits. These indices have been specifically developed for the assessment of coal ashes only, but these indices are widely used in literature for co-fired fuels as well. Most commonly used traditional indices used to calculate the fuel ash deposition tendency are shown in Table 6. The predicted composition is calculated as mass average of the metal oxides present in the known feed rate of coal and fuel additive. Whereas the actual ash samples collected during these combustion tests were used to measure the ash components and were reported as measured values in Table 6. The predicted values of metal oxides are in close proximity to the actual measured concentration of metal oxides. The existing difference between the values is expected due to the ± 1-2% combined variation in the actual feed rates of coal and fuel additive. However, irrespective of the predicted and calculated indices, there is an insignificant increasing trend in both the predicted and measured values of fouling and slagging indices, when compared with the metal oxide concentration of individual coal fly ash samples. The reported chemical composition of the fly ash samples show a narrow range of variety of alkali oxides between coal fly ash and coal fly ash plus fuel additive samples. A dominance of SiO_2, Al_2O_3 and Fe_2O_3 was found in all the fly ash samples. This is partly due to the inherited concentration of these oxides in the actual coal and fuel additive. The percentage of oxides of iron was found increased in the fly ash mix, whereas the percentage of alumina concentration decreased, slightly. Generally substantial increase in the percentage concentration of Na_2O and K_2O results in higher fouling propensity in commercial boiler. The % of K_2O is relatively higher in RC and KC fly ash as compared to Additive; hence addition of Additive delivers an overall positive impact towards lowering fouling propensities. Moreover, the tabulated overall measured concentrations show an insignificant variation concluding trivial effect on the actual boiler furnace wall. Moreover, the measured values of $R*\left(\frac{B}{A}\right)$ were less than 0.75 indicating that ash flow temperature will be higher resulting in a decrease of slagging tendency. The addition of Additive delivers an overall positive impact towards lowering fouling propensities for the fuels which have relatively higher % of Na_2O and K_2O. It can also result in increasing the ash flow temperature resulting in decrease of slagging tendency depending on the type of fuel (coal).

It is also believed that the use of Additive would cause the passivation of the boiler tubes (fire side) due to the silicon content of the fuel additive. Albeit, magnetite formed as part of the passivation process also protects the tube surfaces from further corrosion and it is evident from the Table 1 that both WC and AC Additives contain magnetite forms. It is also noticeable that the XRD analysis of the KC coal when injected with 10% AC Additive resulted in 37% of magnetite present in the resultant ash, which again would help with fire side tube passivation of the boiler. It is also worth mentioning that the XRD analysis also revealed disappearance of fayalite structure into magnetite which is due to the well-known interaction of fayalite with generated CO_2 [30].

Hence the fuel additive can help on mitigating not only corrosion but also slagging and fouling issues.

3.5 260 tons/hr MCR commercial boiler results

The burner nozzles of the boiler are positioned to support the tangential projection of stream of coal plus additive with air to intensify the rapid combustion. Additionally the cavities of the furnace are up drafted to support carry over the produced fly ash towards electrostatic precipitators. The installed electrostatic precipitators were able to separate out the product fly ash along with additive simply because of presence of fayalite and / or magnetite structures, conducive for conductive properties. Moreover the performance of the precipitators would also increase due to relatively less unburned carbon present in the product fly ash.

The additive was injected via weight in loss feeders (feeding at 2.5tons/hr) in to the coal mills set at a total coal load of 27.5tons/hr feeding RC. The coal mills load, downstream high pressure steam manifold and intermediate steam turbine load were all maintained at steady levels during the overall 6 hours of recorded data. Efficiency improvement though being expressed in different formats; reported either as absolute or relative change in overall efficiency. The method adopted to report the results for the aforementioned commercial trial is relative change in overall efficiency adopted from BS EN 12952-15:2003. The calculations based on the measurements taken from steam, spray water, feed water, coal mass flows at corresponding temperature and pressure delivered a net 2% improvement in combustion thermal efficiency with added benefit of 9% reduction in NOx, 2% increase in steam pressure (Figure 9) with less than 7% unburned combustible left in fly ash for 9% of added additive. The measured unburned combustibles in coal fly ash before addition of additive was 12% which reduced down to 7% after additive injection.

The statistical analysis applied to the recorded data produced average, average plus standard deviation and average minus standard deviation limits. These limits are also highlighted (red and blue lines) in the Figure 9 for coal and coal plus Additive. The overall induced fluctuations of steam flow, pressure and NOx emissions were found to be with permissible fluctuations of BS EN 12952-15:2003. Table 7 entails the supporting information regards to the measured parameter and subsequent calculation employed as per the BS EN 12952-15: 2003. It is evident that with 2% improvement in combustion efficiency of a 2000 MWe power plant could result in about £8 Million worth of coal savings with added potential revenue from sales of high quality fly ash. Hence, the overall viability of this technology is based on return on investment from fuel savings, NOx reduction incentives, and fly ash sales compared to some of the other alternative technologies (i.e. SNCR, SCR) which partly offer solution for only emission reductions.

4 Conclusions

It is evident from the extensive studies performed on lab, pilot and commercial scale that IIT's commercial Additive is capable of improving combustion thermal efficiency of a full scale boiler, reducing NOx emissions and unburnt carbon in fly ash. The fuel additive is capable of enhancing the volatile hydrocarbon cracking to facilitate both NO reduction and improved combustion of coal fired burners as shown in bench scale tests. The overall benefits of the Additive deliver up to 25% NO reduction, up to 12 ^{o}C -30 ^{o}C measured increase in the flame combustion temperatures along with 1%-5% gains in the combustion efficiency depending upon its injection rates. The optimum range for addition of the fuel additive is within 1% to 12%. The process also produced fine fly ash with reduced carbon content to levels sufficient for use as pozzolan. The fuel additive does not adversely affect the slagging and fouling indices by keeping it below the extremely high range and preferably $\leq$ 0.6 (medium range). The presence of magnetite and conversion of fayalite to magnetite would also help towards tube side passivation of the boiler. Hence the Additive addition can help on mitigating not only corrosion but also slagging and fouling issues.

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Figure Captions

1. a: Experimental set up of 100kW combustion test facility, b: Solid state pulverised additive feeder with vibratory tray, c: Rospen’s coal feeder with hopper, screw feeder, vibratory tray, d: Coal burner with primary air /coal, secondary air, gas flame detector.
2. Process flow diagram of the commercial boiler (Maximum continuous rating- MCR $\underset{\sim}{}$ 270 tons/hr).
3. Effect of mass fraction of both types of additives on NO emissions from various commercial coals under un-staged flame conditions of stoichiometric ratio= 1.20; A: WC Additive with RCl; A': AC Additive with RC; B: WC Additive with CC; B': AC Additive with CC; C: WC Additive with KC; C': AC Additive with KC.
4. A: Proposed schematic mechanism for the interaction of the additive with coal [31], B: NO_x reduction chemistry pathway [15] in presence of additive, C: Carbon split pathway in presence of additive.
5. Effect of stoichiometric ratio on NO emissions from various commercial coals with varying mass fraction of both types of additives; A-C: 6.4%, 8.8% and 13% mass fraction of WC Additive with RC; D-F: 5.45%, 6.2% and 7.8% mass fraction of WC, AC and WC Additive with CC, respectively; G-I: 8.9%, 9.1% and 10.3% mass fraction of AC, WC and AC with KC, respectively.
6. Temperature measurements for different mass fraction of Additive A: RC with additive; B: CC with additive; C: KC with additive.
7. LOI versus mass fraction of additive A: Russian coal; B: Columbian coal; C: Kellingley coal.
8. PSD comparison between coal fly ash with and without additive.
9. Recorded parameters during the trial on 260 tons/hr boiler (NOx, Steam pressure, Steam flow).

Table captions

1. XRF / XRD composition of Water and Air Cooled Additive Overall oxygen concentration in the combustion air.
2. Particle size distribution, physical and chemical properties of the Additive.
3. Chemical composition of tested coals.
4. Gas / Oil yields and concentration of gases.
5. Compressive strength tests on Russian coal fly ash with and without additive
6. Calculated and predicted slagging and fouling indices
7. Boiler efficiency calculations with and without additive

Nomenclature:

Description	Symbols and corresponding units
Main steam flow	m_{ST}, kg/s
Specific enthalpy of main steam	h_{ST}, kJ/kg
Spray water flow rate to the main steam attemperature	m_{SS}, kg/s
Specific enthalpy of spray water	h_{SS}, kJ/kg
Boiler feed water flow rate	m_{FW}, kg/s
Specific enthalpy of spray water	h_{FW}, kJ/kg
Total coal flow to the boiler-6	m_{F}, kg/s
NCV of the coal	$H_{(N)}$, kJ/kg
Specific heat of the fuel	C_{F}, kJ/kg- ^{o}C
Average temperature of the coal supply (fuel)	t_{F}, ^{o}C
Reference temperature	t_{r}, 25 ^{o}C
Specific heat of the air	C_{PA}, kJ/kg- ^{o}C
Combustion air to mass fuel ratio	μ_{A}, kg/kg
Ratio of unburned to supplied fuel mass flows	l_{u}
Ash content in the fuel	γ_{Ash} , kg/kg
Moisture content in the fuel	γ_{H2O}, kg/kg
Volatile matter content of ash	v, kg/kg
Unburned combustible content of slag	u_{SL}, kg/kg
Ratio of collected furnace bottom-ash mass to mass of ash in fuel minus its volatile fraction	η_{SL}= 0.05
Unburned combustible content of fly ash	u_{FA}, kg/kg
Fly ash retention efficiency	η_{FA}= 0.95

Coal Pulveriser power	P_M, kW
Any other power required on motors	P, kW
Average temperature of the flue gas	t_G, °C
Useful heat output	Q_N , kW
Total heat input	$Q_{(N)Ztot}$, kW
Thermal efficiency by Direct method	$\eta\ (N)B$