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**Paper:**

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Combustion of Pakistani Lignite (Tharparkar coal) in a pilot scale pulverised fuel down fired combustion test facility

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Abstract

In this study, Pakistan’s first and foremost pilot scale combustion test results of Tharparkar Lignite Block-8 have been reported. The reported data will be an addition to the existing literature on lignite firing testing. In this paper NO, CO and CO\textsubscript{2} measurements were recorded at different axial locations in a down-fired combustion test facility for 2s, 2.3s and 2.6s of primary combustion zone residence times in a 4 meter long down-fired pulverised fuel furnace. The overall NO\textsubscript{x} and SO\textsubscript{2} emissions have also been reported for un-staged and air-staged combustion conditions. The reported data (emissions and carbon burnouts) is for fuel to air stoichiometric ratios of 0.9, 1.01 and 1.16 near the burner zone. The fly ash sample were analysed and the percentage of iron oxide was found in the range of 18-21% whereas the percentage of alumina concentration was in the range of 14-16% for varying stoichiometric ratios. Furthermore, slagging and fouling analysis has also been carried out on the collected ash samples during testing.

Key Words: Pakistani Lignite Coal; Emissions; Residence time; Stoichiometric ratios; Carbon burnout; Slagging and fouling indices

1. Introduction

Both developed and developing countries have been exploiting vital lignite coal resources for power generation. In recent years, countries such as Germany, Poland, Turkey, Serbia, Czech
Republic and Greece have increased their lignite production to about 440 million tonnes. Global lignite coal production has reached 1.0 billion tonnes and still has massive potential for growth. Pakistan's lignite coal reserve of 176 billion tonnes has an electrical potential equivalent of 100,000MW. This would enable the mitigation of the present electricity shortfall and also enable the country to meet any electricity demand in the future. In order to attract investment in coal fired power plant the GOP drafted a new set of incentives which, offer attraction to investors as well as keep consumer prices within affordable limits. Keeping in view these objectives, the Policy for Power Generation 2002 was formulated so as to offer maximum incentives and assurance to investors. In the Power Policy 2002, the main emphasis was on the development of power projects based on indigenous fuel resources, especially coal and renewables.

Co-firing of firewood and lignite has been proven to exhibit acceptable temperatures, combustion efficiency and low emissions at low (50kW) to high (150kW) thermal outputs. Similarly, lignite combustion resulted in stable operation with remarkably low NO emission levels with stoichiometric conditions around 0.9. The concept of ignite co-firing at a 10% biomass Cynara cardunculus (cardoon) thermal share for a 330 MWe pulverized fuel plant in Northern Greece is investigated. In most co-firing cases, CFD results indicated that the substitution of lignite with biomass has minimal impact on the plant operational parameters as well as has the potential for NOx reductions. It is also worth mentioning that before practical use, lignite coal has to be dried to reduce inherent moisture. Out of available technologies WTA (waste heat utilization) technology developed by RWE Power can technically and economically is suitable for lignite-based electricity generation.

In Pakistan there are discussions and plans for co-firing of indigenous coal specially Thar lignite with imported or locally sourced biomass. Keeping in view the future need of power plants in Pakistan a series of tests have been performed on a 50kWth combustion test facility (CTF) in order to understand the combustion characterization of Pakistani Thar lignite.

The present study expands the main combustion product concentrations (CO, O2, NOx, SO2, LOI) data bank for lignite coals; especially in terms of scarcely reported pilot scale combustion trials.
on Pakistan’s Tharparkar lignite coal. This reported data would support the research and development phase for establishing new lignite based power plants to overcome the energy crises in Pakistan.

2. Experimental Setup

The schematic combustion test facility (CTF) comprising a down-fired pulverised coal fired furnace 4min length with an internal diameter of 400mm is shown in Figure 1. The burner was operated at an input feed rate of approximately 10.5 kg/hr of Pakistani lignite resulting in a net thermal input of about 50 kWth. The actual combustion test facility is designed to be operated at 100kWth but due to the limited availability of the coal (especially sourced via bore drilling after travelling nearly 960 miles) resulted experiments to be performed at lesser heat input rate of 50kWth. Hence lesser coal sufficient to give 50kWth input was fed in a 100kWth combustion test facility. The major flue gas species CO₂, O₂, NOₓ, and CO were measured at the furnace exit. Gas samples were constantly drawn through water cooled stainless-steel probe to the gas sampling system so that the correct combustion conditions could be set in the furnace. The extracted flue gas from the probe was transferred via Poly Tetra Fluoro Ethylene (PTFE) tubing through a series of filters and water traps for cleaning and drying purposes. The flue gas was then cooled to 20°C (which is a requirement for safe operation of the gas analysers) by passing it through a chiller. The filters were frequently replaced and the water traps were regularly cleaned to prevent any blockage in the gas sampling system. The flue gas was passed through a manifold that directed the sample gas to different gas analysers. To prevent any blockages during operation, the gas sampling probe was regularly purged using a compressed nitrogen supply which was connected to the sampling probe (utilized for drawing in flue gas from the furnace). O₂, CO₂, CO, NO (NOₓ) and SO₂ emissions were monitored in real-time by gas analysers and temperatures down the furnace were monitored and all data was logged on a PC in real-time as all the tests were carried out.

Fly ash solids were collected in a fly ash catchpot connected to a cyclone separator. The samples and emissions were collected and measured, respectively, after attaining steady state conditions for each test. Fly ash samples were analysed for loss on ignition (LOI) in a muffle
furnace by firstly, drying them at a temperature of 105°C for one hour and secondly, further heating the samples to 850°C and then holding that temperature for 2 hours.

![Combustion Test Facility (CTF)](image)

**Figure1.** 50 kW_{in} combustion test facility (CTF).

3. **Results and Discussion**

The ultimate and proximate analysis, evaluation of gross calorific value and particle size distribution of Thar coal are shown in **Table 1**. To compare the properties of the Thar lignite, two other brown coals are also reported in this table. In **Table 2**, we can observe the positions of the thermocouples and their axial distances from the burner. An ultimate and proximate analysis was performed using a CE Instruments Flash EA1112 Series Analyzer and Shimadzu TGA-50 Thermogravimetric Analyzer, respectively. The calorific values were determined by using a Parr 6200 Oxygen Bomb Calorimeter. The particle size distribution of the sample was analysis using laser diffraction in a Malvern Mastersizer-2000. In **Table 1** the average particle sizes are expressed as the volume mean diameter, \(D_{[4,3]}\); whereas \(d_{[0.1]}\), \(d_{[0.5]}\) and \(d_{[0.9]}\) are the diameters determined at the 10\(^{th}\), 50\(^{th}\) and 90\(^{th}\) percentile of the undersized particles. The
particle size analysis shows that the 90% of the coal sample is less than 250 µm, which fulfil the design requirement of the CTF.

Table 1. An ultimate, proximate analysis and particle size distribution of Tharparkar lignite coal along with some reference values of brown coal.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ultimate Analysisa</th>
<th>Proximate Analysisa</th>
<th>GOVa</th>
<th>Moisturea (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C (%)</td>
<td>H (%)</td>
<td>O (%)</td>
<td>N (%)</td>
</tr>
<tr>
<td>Thar Lignite</td>
<td>36.39</td>
<td>4.21</td>
<td>7.76</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>9.53</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greek lignite</td>
<td>61.95</td>
<td>4.3</td>
<td>31.2</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>8.06c</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhenish lignite</td>
<td>67.6</td>
<td>4.96</td>
<td>26.3</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>8.171c</td>
<td>58.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a as received basis except as denoted in table; b calculated by difference; FC= fixed carbon; VM= volatile matter; GOV= gross calorific value; D[4,3]=volume mean diameter; d[0.1], d[0.5] and d[0.9] are the percentile diameters determined at the 10th, 50th and 90th percentile of the undersized particles, c Net Calorific value (the values for ultimate analysis are dry ash free basis.

Table 2. Vertical positions of thermocouples and sampling ports.

<table>
<thead>
<tr>
<th>Thermocouple location</th>
<th>Axial position from the burner (mm)</th>
<th>Port location</th>
<th>Axial position from the burner (mm)</th>
<th>Experimental studied stoichiometric ratios (λ) or staging levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>804</td>
<td>Port 1</td>
<td>1685</td>
<td>Un-staged 16% overall excess air</td>
</tr>
<tr>
<td>T2</td>
<td>1307</td>
<td>Port 2 (staged air)</td>
<td>1810</td>
<td>11% level of staging near combustion zone, λ = 1.01</td>
</tr>
<tr>
<td>T3</td>
<td>1810</td>
<td>Port 3</td>
<td>2691</td>
<td>22% level of staging near combustion zone, λ = 0.9</td>
</tr>
</tbody>
</table>
3.1 NO\textsubscript{x}, CO, O\textsubscript{2} and SO\textsubscript{2} measurements

The changes of experimental conditions during trial always influence in-furnace conditions, therefore, in order to remove any dilution of the pollutants in the process, the values of NO and SO\textsubscript{2} are standardised at 6%\textsubscript{O\textsubscript{2}} in the flue gas using the following equations.

$$\text{NO} @ 6\%\text{O}_2 = \text{NO} \left[ \frac{20.9\% - 6\%}{20.9\% - \text{O}_2\%} \right] \quad (1)$$

$$\text{SO}_2 @ 6\%\text{O}_2 = \text{SO}_2 \left[ \frac{20.9\% - 6\%}{20.9\% - \text{O}_2\%} \right] \quad (2)$$

where NO and SO\textsubscript{2} are the measured concentrations in flue gas (ppmv) and O\textsubscript{2} is the measured concentration in flue gas corresponding to the set condition. NO and SO\textsubscript{2} reduction (%) was evaluated by using Eq. (3) and (4) in which coal baseline was used as a reference for comparison.

$$\text{NO red } \% = \left( \frac{\text{NO}_{\text{coal baseline}} - \text{NO}_{\text{biomass-coal blends}}}{\text{NO}_{\text{coal baseline}}} \right) \quad (3)$$

$$\text{SO}_2^{\text{red } } \% = \left( \frac{\text{SO}_2^{\text{coal baseline}} - \text{SO}_2^{\text{biomass-coal blends}}}{\text{SO}_2^{\text{coal baseline}}} \right) \quad (4)$$

Both bituminous and sub-bituminous coals produce volatile-N during volatilization mainly in the form of tarry compounds which further decay into HCN and soot-nitrogen. In contrast low rank coals such as lignite due to lower fixed carbon and higher volatile matter directly liberate the
lighter nitrogen species such as NH$_3$. In a recent publication on 3-D CFD modelling of a 1.2 MW$_{th}$ CFB it is reported that for lignite the HCN released is negligible particularly during char combustion. In order to examine the difference in the combustion performance of Thar coal, the average concentration of O$_2$, CO and NO$_x$ was recorded along the vertical axis of the CTF for stoichiometric ratios of 0.9, 1.01 and 1.16.

A highest concentration of about 19% for CO was observed at an axial distance of 1685 mm from the burner at a stoichiometric ratio of 0.9, whereas CO concentrations of 8% and 2.5% were observed for 1.01 and 1.16 stoichiometric ratios, respectively (Figure 2A). These CO concentrations signify the existence of a fuel-rich zone close to the burner at lower O$_2$(oxidant) concentration. This is in agreement with a recent study where it is reported that during devolatilization, hydrocarbon species (C$_x$H$_y$), hydrogen (H$_2$), water vapor (H$_2$O), carbon monoxide, carbon dioxide (CO, CO$_2$) and tars are released. In another study it is observed that generally, peak CO concentrations are high in the regions where temperature peaks are also predicted. These values also indicate poor combustion conditions near the burner at lower stoichiometric ratios. However, the decreased concentration in the measured CO and increased oxygen concentration (measured) demonstrate better fuel-lean combustion conditions at stoichiometric ratio of 1.16. It can be observed in Figure 2A that the CO axial profile exhibits a sharp drop after the injection of overfire air. This indicated stable and complete combustion. Similarly, the oxygen concentrations were observed to increase from less than 1% to about 3.4% for changing stoichiometric ratios in fuel-rich zone.

An increase in the stoichiometric ratio near the burner converts the fuel-rich conditions to fuel-lean and this partly delays the mixing of Pakistani lignite with air resulting in a reduction in NO emissions (Figure 2B). The calculated value of residence times for the fuel-rich zone increased by 23% from 1.16 to 0.9 stoichiometric ratios. This is indicative of the delayed mixing of fuel with oxidant, resulting in controlled in-furnace reduction of NO emissions via air-staging. The lignite coal combustion is deemed to produce higher concentrations of NH$_3$ in the flame-rich zone due to its poor grade, thus resulting in N$_2$ production pathway instead of NO. This leads to an in combustion reduction via selective non-catalytic reduction phenomena for reduction of
NO to N$_2$. It can however be seen that discrepancy on part of the oxygen measurement is only
for staging experiment believed to be due to poor mixing especially in the post over fire
injection zone i.e. fuel lean zone. This poor mixing between the remaining combustibles in the
fuel lean zone i.e. post over fire injection zone resulted in laminar regions at the exit of the
furnace resulting in variation of about 1% in oxygen. This also suggests the combustion would
still be taking place even close to the furnace exit because of poor mixing. This is also indicative
in the variation of carbon in ash results. This can be confirmed by the variation in carbon
burnouts. It was also witnessed that the flame during the staged experiments was extending
deep into fuel lean zone (i.e. about 1000mm further down from 1810mm (over fire air injection
port). However the reasons for stable CO emissions are unexplainable.

Pakistani lignite despite being high in ash and low in fixed carbon content exhibited complete
combustion. It is evident from experimentation that the Pakistani lignite coal produced overall
NO emission levels below 190 ppmv @ 6% O$_2$ for 16% excess air levels. This corresponds to
being substantially lower than other bituminous and low ranks fuels reported in literature$^{6,16,17}$. Figure 3 demonstrates the overall NO and SO$_2$ emissions and corresponding reductions
corrected at 6% O$_2$ levels for 0.9, 1.01 and 1.16 stoichiometric ratios. The reported residence
times are calculated for gases, it is also found that residence time increases with decrease in
the stoichiometric ratio. To avoid any confusion and to simplify the measurements thus making
them more understandable, the results are reported on concentration basis (i.e. ppmv or
mg/Nm$^3$ @ 6%O$_2$) rather than energy specific basis (i.e. mg/kWth). It is worth noting that due to
the presence of high amount of inherent sulphur, the SO$_2$ emissions were in the range of
1380ppmv to 1550ppmv (@ 6%O$_2$) for 0.9 to 1.16 stoichiometric ratios, whereas the overall NO
emissions were in the range of 65 ppmv to 165 ppmv (@ 6% O$_2$), respectively. An overall
reduction of about 10% in SO$_2$ and 60% in NO can be achieved with a simple in-furnace air-
staging combustion technique, i.e. 22% level of air-staging. There is a possibility that in air-
staged combustion system the inherent sulphur of the Pakistani lignite reacted with CaO
present in the ash to form CaS especially in the fuel-rich zone later being converted to CaSO$_4$ in
the burnout zone$^{18}$. This has resulted in a reduction in SO$_2$ emissions during air-staged
combustion.
Figure 2. Axial concentration (CO, O₂, NOₓ) profiles for 0.9, 1.01 and 1.16 stoichiometric ratios (λ).
3.2 Effect on temperature and carbon burnout

The process of coal combustion (i.e. combustible matter such as volatiles/hydrocarbon species) releases major amounts of heat in close proximity to the primary combustion zone. Hence, the temperature in the primary combustion zone is higher than the rest of the furnace at fixed values of stoichiometric ratios. However, since air-staged combustion delays the fuel so that excess oxidant mixing occurs, this results in marginal differences between the air-staged and unstaged primary combustion zone temperatures. The temperatures of the primary combustion zone under air-staged combustion are less than the unstaged fuel baseline. Similarly, it has also been reported that under air-staged coal combustion marginal temperature differences near the exit of the furnace are produced when compared to un-staged
coal combustion. This is partly due to the combustion of residual combustibles entering from the fuel-rich to fuel-lean zone\textsuperscript{18-19}. In this study, a noticeable 40-50\degree C temperature difference is observed amongst tested stoichiometric ratios in the main primary combustion zone. However, this difference is almost minimized to about 5\degree C near the furnace exit. This indicates that the existing 16\% overall excess air level (both for staged and unstaged air levels) is enough for a high degree of complete combustion of Pakistani lignite. It is also known that with the control of local peak flame temperatures and increasing residence times of the primary combustion zones, the NO formation (mainly thermal NO\textsubscript{x} and fuel-NO\textsubscript{x}) can be controlled (Figure\textsuperscript{3-4})\textsuperscript{19}.

![Temperature measurement for 0.9, 1.01 and 1.16 stoichiometric ratios.](image)

The ash samples for the lignite coal collected under different air-staged combustion conditions were analyzed to determine carbon burnout using the following ash tracer method:
\[ Carbon\ burnout = \frac{\left( 1 - \frac{z_k}{z_x} \right)}{\left( 1 - \frac{z_k}{z_k} \right)} \] (5)

Where: \( z \): dry ash mass fraction, \( k \): ash content in the input solid fuel and \( x \): ash content in the char sample.

Figure 5 demonstrates the impacts of the variation of residence time of the primary combustion zone on carbon burnout. Lengthened residence time in the primary combustion zone causes marginally poor overall combustion efficiency due to the shorter burnout zone which is further compounded by lower temperatures within the primary combustion zone\(^{20}\).

However, in the existing pilot-scale combustion tests the primary combustion zone temperature difference between 20 un-staged and 22\% level of air-staged combustion is 40\(^\circ\)C-50\(^\circ\)C; this is effectively reduced to 5\(^\circ\)C up to the flue section of the furnace. At 16\% excess air un-staged firing condition an overall carbon burnout level of 99.92\% was obtained as compared to 90.56\% carbon burnout obtained at 22\% level of air-staging. This suggests that an overall NO\(_x\) reduction of 60\% with a corresponding carbon burnout of 92.56\% at 22\% level of air-staged combustion condition is a feasible condition for Pakistani lignite combustion at a larger scale.

Hence, 92.56\% of carbon burnout result for 0.9 stoichiometric ratios or 22\% level of air-staging are not the only advantages in terms of reduced NO emissions but are also accompanied by a lesser impact on the overall combustion performance.
3.3 Effect on slagging and fouling propensities

Pakistani lignite coal ash samples collected from the pilot-scale combustion tests have been analysed using XRF technique (Table 3). The reported oxides of main heavy metals are utilized to establish slagging and fouling characteristics of the deposits which collect on the radiant and heat recovery section of boilers, respectively. In previous work\textsuperscript{21-22}, the slagging and fouling indices have been used to assess the propensity of fuel ash which generally causes heat transfer and corrosion related issues.

It is observed in Table 3 that the reported chemical composition of the fly ash samples indicates very high levels of Na\textsubscript{2}O, K\textsubscript{2}O and CaO resulting in higher values of basic to acidic ratios of oxides. This has a direct influence on the slagging and fouling tendency of the resultant ash formations. The overall values for both fouling and slagging propensities were in the high to
extremely high range indicating the necessity of boilers capable of compensating for higher levels of corrosion and lower heat transfer in the super heater and heat recovery sections of the boiler. During some combustion trials on a pilot FBC it is reported that Polish coal presents higher tendency for slagging and fouling than the Colombian coal\textsuperscript{23}. It is suggested that a detailed analysis on the slagging and fouling tendency should be performed to understand the interactions of co-firing Thar lignite and other fuels for power generation. Slagging and fouling deposits from a pulverized lignite fired power plant at West Macedonia, Greece was investigated. The major chemical constituents found were Fe\textsubscript{2}O\textsubscript{3}, CaO and SO\textsubscript{3}, while considerable contents of SiO\textsubscript{2} and Al\textsubscript{2}O\textsubscript{3} were also detected\textsuperscript{24}. In another study twenty samples from a main seam of Panian coalfield in Semirara Island, Antique Province, Philippines, were collected. Chemical analysis of the ash revealed high contents of Na, Mg, Fe, Ca, Ba and Sr. The strongly negative correlation of these elements with the ash content indicates an organic affinity of the chemical elements of the seam. Owing to enrichment in alkali and alkali-earth elements, slagging and fouling indices indicate that the seam has medium to high propensity for slagging and a severe tendency for fouling\textsuperscript{25}.

In this study the percentage of iron oxide was found in the range of 18-21% whereas the percentage of alumina concentration was in the range of 14-16% for varying stoichiometric ratios. The concentrations of Na\textsubscript{2}O and K\textsubscript{2}O are generally dominating factors towards the fouling propensity in commercial boilers. The percentage of K\textsubscript{2}O is in the range of 0.5-0.8% whereas Na\textsubscript{2}O is found in the range of 13-15%. The study also reported that the composition of these metallic oxides present in Tharparkar Lignite coal fly ash falls within the range of general lignite coal fly ash samples except iron oxide. Moreover, the combined percentage of oxides of Al, Fe and Si is about 67% close to 70% recommended for Portland cement blending. These percentages would have a direct non-trivial impact on the actual boiler furnace wall. It is important to mention that aside from the concentration of iron, sodium and potassium elements in oxide form, it is also important to know that what phases these oxides are present in product fly ash. The presence of iron oxide in resultant coal fly ash is mostly either in fayalite or magnetite phases. If present in magnetite form would be beneficial towards fire side tube passivation. Hence presence of iron oxide in magnetite form would help to mitigate the fire side
corrosion. Similarly the presence of aluminosilicate phases helps towards mitigating the basic to acidic ratio which then compensates the higher slagging and fouling propensities.

### Table 3. Metal oxides present in Pakistani lignite coal ash samples at 1.16, 1.01 and 0.9 stoichiometric ratios.

<table>
<thead>
<tr>
<th>Metal Oxides</th>
<th>Unstaged Pakistani lignite coal ash (SR=1.16)</th>
<th>11% air-staged Pakistani lignite coal ash (SR=1.01)</th>
<th>22% air-staged Pakistani lignite coal ash (SR=0.9)</th>
<th>Typical Lignite coal metal oxide present in fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>31.82</td>
<td>35.22</td>
<td>31.22</td>
<td>15-45</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.43</td>
<td>2.06</td>
<td>2.43</td>
<td>-</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.21</td>
<td>14.43</td>
<td>16.19</td>
<td>10-25</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>17.95</td>
<td>21.27</td>
<td>18.34</td>
<td>4-15</td>
</tr>
<tr>
<td>MnO</td>
<td>0.12</td>
<td>0.93</td>
<td>0.12</td>
<td>-</td>
</tr>
<tr>
<td>MgO</td>
<td>0.60</td>
<td>0.30</td>
<td>0.50</td>
<td>3-10</td>
</tr>
<tr>
<td>CaO</td>
<td>15.49</td>
<td>12.10</td>
<td>16.48</td>
<td>15-40</td>
</tr>
<tr>
<td>Na₂O</td>
<td>15.40</td>
<td>13.00</td>
<td>14.30</td>
<td>0-6</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.56</td>
<td>0.87</td>
<td>0.53</td>
<td>0-4</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.1090</td>
<td>0.1020</td>
<td>0.11</td>
<td>-</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.10</td>
<td>0.08</td>
<td>0.09</td>
<td>0-10</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.0006</td>
<td>0.0016</td>
<td>0.0006</td>
<td>-</td>
</tr>
<tr>
<td>CuO</td>
<td>0.0010</td>
<td>0.0020</td>
<td>0.0009</td>
<td>-</td>
</tr>
<tr>
<td>PbO</td>
<td>0.0001</td>
<td>0.0003</td>
<td>0.0001</td>
<td>-</td>
</tr>
</tbody>
</table>

\[
\left( \frac{B}{A} \right)_{14-15, 21} = \left( \frac{Fe₂O₃ + CaO + MgO + Na₂O + K₂O}{SiO₂ + Al₂O₃ + TiO₂} \right)_{14-15, 21}^{14-15} = 0.99 \quad 0.92 \quad 1.01
\]

Simplified:

\[
\left( \frac{B}{A} \right)_{14-15} = \frac{Fe₂O₃ + CaO + MgO}{SiO₂ + Al₂O₃}_{14-15, 21} = 0.71 \quad 0.74 \quad 0.68
\]

\[
R_s = Fe₂O₃ + CaO + MgO + Na₂O + K₂O \quad 14-15^{14-15} = 50.00 \quad 50.15 \quad 47.54
\]

\[
F_u = \left( \frac{B}{A} \right)_{14-15}^{14-15} \quad 15.81 \quad 14.92 \quad 12.75
\]

\[
R_s = \left( \frac{B}{A} \right)_{14-15}^{14-15} \quad \text{where } S_b = \% \text{ of } S_in \quad 3.04 \quad 3.09 \quad 2.82
\]

- If \( F_u < 0.6 \) low fouling inclination; \( F_u = 0.6-40 \) high; \( F_u > 40 \) extremely high
- \( R_s < 0.6 \) low slagging inclination; \( R_s = 0.6-2.0 \) medium; \( R_s = 2.0-2.6 \) high; \( R_s > 2.6 \) extremely high
- \( B/A = \) Basic to acidic ratio; \( R_s = \) Sagging Index; \( F_u = \) Fouling Index

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4. Conclusions

Lignite coal obtained from Pakistan’s largest coal reserve in Tharparkar, Sindh (Block-VIII) was combusted in a 50kWth pilot-scale combustion furnace test facility. It was found that under a normal fuel to air ratio of 1.16 maximum NOx emissions of 165 ppmv at 6% O2 levels were observed. However, at 22% level of air-staging a maximum NOx reduction of 60% was achieved to lower the NOx emissions to 65ppmv at 6% O2. A noticeably higher level of inherent sulphur resulted in SO2 emissions in the range of 1380ppmv to 1550ppmv (@ 6% O2) for 0.9 to 1.16 stoichiometric ratios. An overall carbon burnout of 99.92% was obtained for 1.16 stoichiometric ratio near the burner as compared to a carbon burnout of 99.56% for 0.9 stoichiometric ratio in the burner zone. The overall values for both fouling and slagging propensities were in the range of high to extremely high further indicating a dire need of either injection of specialized chemicals in the boilers to compensate for higher levels of corrosion and lower heat transfer in the boiler super heater and heat recovery sections or blending of lignite coal with relatively better quality coal.

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