

Article

Fouling and Slagging Investigation on Ash Derived from Sasol Coal Using ICP and XRF Analytical Techniques

Bai Kamara *, Daramy Vandi Von Kallon  and Peter Madindwa Mashinini

Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, Doornfontein Campus, Johannesburg 2028, South Africa

* Correspondence: baikamara78@gmail.com

Abstract: During coal combustion in boilers, light fly ash particles are carried away along with the hot flue gases and the heavier bottom ash particles fall to the bottom of the boiler. The fly ash particles stick on the convective heat transfer surfaces and the furnace wall, causing fouling and slagging deposition problems during the boiler operation. The fouling and slagging effect reduces the boiler's operational efficiency. This study was motivated by the decline in the operational efficiency of the installed boilers at Sasol synfuel operations in Secunda, Mpumalanga province in the Republic of South Africa. It was assumed that the drop in the boiler efficiency was caused by the coal ash deposition during the boiler operations. The rate of ash deposition and accumulation in the convective heat transfer tubes and furnace water walls during the boiler operation depends on the chemical composition of the coal ash produced during combustion. Coal fly and bottom ash samples were collected from the operational site for laboratory analysis to determine their chemical composition using induced coupled plasma optical emission spectroscopy, induced coupled plasma mass spectroscopy (ICP-OES, ICP-MS) and X-ray fluorescence (XRF) analytical methods. The major, minor and trace elements by mass (%) in the ash samples were obtained from the ICP-OES and ICP-MS, whereas the elemental composition in an oxidised atmosphere was obtained from the XRF analysis. The amount of unburnt coal particles within the ash samples was determined from the loss on ignition (LOI) test. The fouling and slagging prediction during Sasol boiler operation was evaluated using previously developed fouling and slagging indices as a guide using the analysed ash chemical composition results obtained in this study. It was concluded from the analysed results using the guided evaluated indices from the analysed coal ash chemistry that during the operations of Sasol boiler(s) there is a low to medium fouling prediction occurrence on the convective heat transfer tubes and a low slagging in the boiler furnace walls.



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1. Introduction

Ash contents obtained from laboratory analysis are determined by weighing the residue after the complete combustion of approximately 1 g of coal samples with proper equipment specifications under rigidly controlled mass, temperature, time, and atmospheric conditions [1]. Deposition problems on the heat transfer tubes during the boiler operation are mostly caused by the ash produced from coal combustion in the furnace. This reduces the operational efficiency, heat produced, and results in frequent power plant shutdown, and an increased operational downtime and failure rate of the boiler [2]. The flowing molten fly ash is then deposited and accumulated on the tube heat transfer surfaces, forming an insulating layer and creating a thermal resistance, which reduces the quantity of heat transfer from the hot flue gases to the flowing water/ steam inside the tubes. The furnace exit gas temperature (FEGT) is then increased because of the poor heat absorption in the moving fluid inside the boiler tube, causing flue gas desulphurisation and decreased output efficiency [3,4]. Under normal operating conditions, it is estimated that the ash deposition on the convective heat

transfer tube surface reduces the coal-fired boiler power plant's overall efficiency by 1% [5]. The study of monitoring ash deposition and soot accumulation during coal-fired boiler operation has become a more interesting, focused research area within the energy generating industry [6–9]. Slagging and fouling are the major effects that reduces coal-fired boilers' steam output efficiency. Slagging occurs within the boiler region, where the heat exchange surfaces are directly exposed to the flame radiation area, such as the furnace water walls [10]. Slag particles or deposits are mostly molten and are in a liquid state [10]. The deposits or particles formed on heat exchange surfaces that are not directly exposed to the radiant flame area are referred to as fouling [10]. Fouling deposits are solidified particles that are loosely bound or partially sintered; hence, they can be easily cleaned off [10]. Slagging and fouling within the boiler undergo smooth transition; the extent to which the deposits lead to slagging or fouling is dependent on the coal type, mineral inorganic chemical composition, and the operating conditions of the boiler [11].

This study aims to address the problem of the decline in the steam output produced during the operation of the boilers installed at Sasol synfuel operations. This challenge seriously increased the company's maintenance cost and decrease its profitability. It was presumed that the decline in the boiler(s) operational efficiency was a result of the ash deposition in the boiler furnace water walls and the convective heat transferred surfaces. The severity of ash deposition and accumulation in the boiler heat transfer surfaces is assumed to depend on the chemical composition of the coal ash. In addressing this challenge, the coal fly ash and bottom ash produced during the boiler operation at Sasol synfuel were collected for detailed laboratory analysis to determine their chemical composition. The ash deposition effects, i.e., fouling and slagging during the boiler operation, were predicted from the coal ash chemistry laboratory results using published developed fouling and slagging prediction indices. The laboratory methods used to evaluate the chemical composition of the collected coal ash samples were ICP-OES, ICP-MS and XRF analysis. In this study, the boiler's deposition, i.e., fouling and slagging effects during its operation, was evaluated using previous published fouling and slagging indices as a guide with the application of the analysed chemical composition results obtained in this study.

2. Literature Review

Industrial device degradation and optimal maintenance plans are predicted using Prognostics and Health Management (PHM) [12,13]. The PHM of fouling in coal-fired boiler power plants is mainly divided into the following processes, i.e., ash fouling monitoring, ash fouling prediction, and soot blowing optimisation. Ash fouling during coal-fired boiler operations cannot be measured directly based on the complex structure of the heat transfer surfaces, it can be indirectly measured using a heat flux meter, the quantity of heat produced or through acoustic pyrometry [14–16]. Critical parameters to be considered during a coal-fired boiler construction are the furnace size and height estimation, which depend on the coal ash softening and melting temperature(s). It is estimated that the ash softening temperature must be greater than the temperature of the flue gases leaving the furnace (FEGT) [17]. Other essential factors that influence the changes within the coal constituents and ash formation on heat transfer tubes are the boiler operating conditions, fuel-air mix, soot blowing, and the gas temperature [18]. The severity of ash deposition thickness across the boiler heat transfer sections is different. This variation is dependent on the combustion environment that influences ash deposition. Strongly bonded deposit formation on heat exchanger tubes reduces soot blowing effectiveness [18]. Ash deposition growth during the boiler operation changes the flue gases flow direction and temperature within the boiler [19].

During coal combustion in the boiler furnace, molten ash above the ash fusion temperature (AFT) is then deposited on the furnace wall. Slag deposits seriously affect the performance of coal-fired boiler power plants. A major advantage of the slagging effect is reducing the unused coal ash minerals into the atmosphere [20,21]. Identifying slag flow, quantity, and position during the boiler operations can be very difficult or almost impossible, this difficulty can be overcome by the development of slag formation mathematical modelling. In recent years,

there have been multiple research attempts to develop and utilise computational analysis model in monitoring ash formation and transportation during coal combustion in pulverised coal-fired boilers [22,23]. Computational modelling enhances a better understanding of the investigation of the slagging performance during the boiler operation and provides a detailed investigation that overcomes experimental work limitations [24]. The following inorganic mineral contents SiO_2 , TiO_2 , Al_2O_3 , CaO , MgO , Na_2O , K_2O , P_2O_5 , Mn_3O_4 , SO_3 , Fe_2O_3 are contained in the coal ash deposited as slag in the boiler furnace wall [25]. A key parameter in estimating slagging and fouling potential during coal-fired boiler operations is the coal ash fusion characteristics. The ash fusion characteristics is mainly affected by the chemical composition of the ash minerals [26–29]. Higher Ca, Mg, Fe and Na contents in the coal ash lower the AFTs, whereas higher Si, Al, and Ti contents increase the AFTs [28]. The processes of slagging and fouling during the boiler operation are triggered by a higher Fe concentration in the coal ash samples in a reducing environment [30,31].

Ash produced from coal combustion inside a coal-fired power plant contains approximately 20 wt% bottom ash and 80 wt% fly ash [32]. The fine ash particles, which are the fly ash, are transported by the hot flue gases with a particle size range of approximately 0.5 μm to 300 μm . The fly ash is made up of glassy spheres usually used as a secondary cementitious binder in Portland cement systems and as the main binder in alkali-activated systems. The bottom ash referred to as the agglomerated ash is made up of coarser particles that are too heavy to be carried along with the hot flue gases, the bottom ash particle size ranges from approximately 2 μm to 20 mm with an angular shape and a porous morphology [33,34]. The bottom ash is mostly used in the construction industry, underground mining, or as landfills in open mines and quarries [35]. The coal ash physical and chemical properties are dependent on the reactions occurring during high-temperature coal combustion in the boiler furnace and subsequent cooling of the flue gases, and the type of coal [35]. The fly ash is made up of fine, smooth, powdery particles that are predominantly spherical in shape, amorphous in nature, and either solid or hollow in form. Generally, coal ash specific gravity varies largely at an approximate range between 1.6 to 3.1 but lies mostly around 2.0 [36]. Coal ash-specific gravity variation results from several factors, including particle shape, graduation, and chemical composition [36]. Coal fly ash particles can be classified as silty sand to sandy silt containing some clay-sized fractions based on their grain size distribution [37]. Coal fly ash comprises a high specific surface area with a low bulk density [38]. Coal fly ash contains a minimum percentage of thin-walled hollow particles known as cenospheres, these are typically fine-grained silt-sized particles with a diameter range between 1 μm to 100 μm , and a median particle diameter of 20 μm to 25 μm [39]. Coal fly ash is usually dark grey or tan. The quantity of unburnt carbon and iron within the fly ash affects its colour, the colour might vary from either orange to deep red, brown, or white to yellow [40].

Coal ash chemical composition is primarily determined based on the coal chemistry during the combustion process. Ash is mainly derived from coal inorganic materials such as clays, feldspars, quartz, and metal oxides. Major coal ash elemental makeup is similar to a wider range of the composition of rocks in the earth's crust. Typical coal fly ash major mineral components comprise more than 90% of oxides of silicon, aluminium, iron, and calcium [41,42] as seen from the result obtain in this study. Elements such as magnesium, potassium, sodium, titanium, and sulphur are the minor constituents, making up approximately 8% of the fly ash mineral components. The fly ash is also made up of surface mineral constituents that comprise less than 1% of its total composition; this includes elements such as arsenic, cadmium, lead, mercury, and selenium [41–43]. Coal fly ash is recognised as the most complex material in terms of its characteristics containing 316 individual minerals amongst 188 mineral groups [44]. All fly ash is made up of substantial amounts of both amorphous and crystalline silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and calcium oxide (CaO) the main mineral compounds in coal-bearing rock strata [32]. Fly ashes are classified as acidic depending on the pH value and calcium/sulphur ratio, with a pH of 1.2 up to 7 it is acidic, a pH of 8 up to 9 is mildly alkaline ash and it is more strongly alkaline

ash with a pH 11 up to 13 [45]. Depending on the boiler combustion conditions, the fly ash might also contain some amount of unburnt carbon. Loss-on-ignition (LOI) is the laboratory test used to determine the quantity of unburnt carbon in fly ash. LOI values range from less than 1% to more than 20% [42,43]. The fly ash's fundamental chemical properties and reactivity are influenced by its relative Ca, Fe, and S contents. Ashes from Subbituminous and lignite coals relatively contain a greater concentration of Ca with an exceeding 15% (as CaO), this ash forms an alkaline solution when it contacts water (i.e., pH 11–12), whereas bituminous coal ash relatively contains a lesser Ca concentration leading to slightly acidic and alkaline solutions when contacts water (i.e., pH 5–10) [44,45].

3. Methodology

In this research, the ash investigation methods used in determining the ash chemistry, i.e., elements present (Major, Minor, and Trace) in the ash samples were ICP-OES, ICP-MS, and XRF analytical techniques. The elemental analysis for the coal sample was carried out using a CHNS (Carbon, Hydrogen, Nitrogen, and Sulphur) elemental analyser.

3.1. Samples and Sample Preparation

The samples for this research were bituminous coal fly ash (SAMPLE A), bituminous coal bottom ash (SAMPLE B), and raw bituminous coal (SAMPLE C) as shown in Figure 1. These samples were collected from the Sasol operational site in Secunda, Mpumalanga, on 6 July 2021.



Figure 1. (A) Bituminous coal fly ash, (B) bottom ash, and (C) raw coal samples.

For the ICP-OES and ICP-MS for both bituminous coal ash samples.

A 0.3 g bituminous coal ash sample was weighed and added to a 10 mL HNO_3 solution. The samples were then heated at a temperature of 180 °C for 25 min and kept at this temperature for a further 10 min for complete digestion of the samples in the solution. The samples were then quantitatively diluted with 50 mL ultrapure water. The samples were filtered using 0.22 μm acrodisc syringe filters, and an additional two dilutions ($2\times$) were prepared by diluting 0.5 mL to 10 mL. The samples were calibrated and analysed following the prescribed certified reference material (CRM) standards. The samples were filtered using the 0.22 μm acrodisc syringe to remove the undissolved quartz and clay minerals in the HNO_3 ash solution.

For the XRF analysis, both bituminous coal ash samples (A and B) were heated separately at a temperature of 105 °C in open air. The samples were then placed in a glazed porcelain crucible and heated from room temperature to 930 °C for 30 min to determine the samples loss on ignition (LOI). A mass of 0.7 g of the heated volatilised ash samples was fused in a borate fusion disk. After the borate fusion disk preparation, the XRF analysis was carried out to determine the major element mixtures of pure chemicals (essential oxides)

with certified reference materials used as a fundamental parameter model. This allows the detection of all the elements presents within the calibrations range.

3.2. Instrumentation and Experimental Procedures

For the ICP analysis, the instruments used were Spectro Arcos ICP-OES and Perkin Elmer NexION 300 ICP-MS, whereas for the XRF the instruments used were an electric fusion machine (TheOx from Claisse) and a wavelength-dispersive XRF spectrometer (MagiX PRO from Malvern Panalytical). The CHNS analysis was carried out using a Flash 2000 CHNS Elemental analyser from Thermofisher Scientific.

The ICP-MS, ICP-OES, and XRF tests were done at the Spectra analytical facility, University of Johannesburg, at the C-LES lab. The CHNS test was done in the chemical sciences department.

The tests carried out in this study were induced coupled plasma optical emission spectroscopy (ICP-OES), induced coupled plasma mass spectroscopy (ICP-MS), X-ray Fluorescence spectroscopy (XRF), and Carbon Hydrogen, Nitrogen, and Sulphur (CHNS) analysis. The ICP-OES test was carried out for both ash samples (A and B) to determine the element presents within the ash samples using an emission spectroscopy technique whereas the ICP-MS was also used to determine the ash elements present based on their overall percentage mass in the coal ash samples.

The XRF test was carried out for both coal ash samples (A and B) to determine the chemical composition by mass of the elements present within the ash samples in an oxidised atmosphere using a non-destructive bombardment X-ray emission technique by directing emitted X-ray beam through a boron fusion disc.

The CHNS analytical test was used to determine the major elements present [carbon (C), hydrogen (H), Nitrogen (N), Sulphur (S)] by mass percentage within the raw mine bituminous coal. An approximate mass of about 1.75–1.85 g of coal sample (C) was placed into a universal soft tin cup, the cup folded using tweezers to a barrel shape, and then placed into an autosampler. Using a Flash 2000 CHNS Elemental analyser from Thermofisher Scientific, the folded sample was fed by pushing it into a quartz reactor in the instrument furnace at a temperature of 950 °C for flash combustion with the aid of oxygen. The gaseous combustion products N_2 , NO, H_2O , SO_2 , O_2 , and CO_2 were carried away by the helium gas through a column filled with copper oxide (CuO) to a Copper (Cu) column where the nitrogen oxides are reduced to elementary nitrogen and oxygen to copper oxide (CuO). Water is then absorbed in another column. The remaining gasses are then introduced into a TPD (Temperature Programmed Desorption) column where the nitrogen gas enters right through, and the other gases are bound to the column. With a programmed temperature rise in the column, the gases are released separately flowing along a thermal conductivity detector (TCD) which produces an electrical signal proportional to the concentration (in %) of Nitrogen, Carbon, Hydrogen, and Sulphur present within the coal sample.

The ash samples were prepared and analysed using a precision form of instrument repeatability for the ICP-OES and ICP-MS. The common instrumental error estimation for the ICP-OES and ICP-MS analysis is less than 5% in the equipment's analytical region and a 10% error at the detection limit.

The estimated lower limit of detection for the ICP-OES analysed data is 0.05 mg/kg. The estimated assumed safe limit of detection for the ICP-MS analysis is 0.1 ug/L (0.0001 mg/Kg) for most elements and 0.01 ug/L (0.00001 mg/Kg) for Hg and Cd.

For the XRF chemical composition analysis, the standard error estimation for the concentrated analysed major elemental composition (i.e., Al_2O_3 and SiO_2) is 2%. The error/uncertainty tends to be higher for minor elements concentration (i.e., CaO, TiO_2 , Fe_2O_3 , MgO etc.).

The limit of detection for the analysed XRF results is approximately 0.05 mass (%) (500 mg/Kg).

3.3. Fouling and Slagging Prediction Indices

The application of successfully published ash deposition indices in predicting the severity of fouling and slagging deposits formed during the boiler operation would increase the boiler's operational efficiency [31]. The base acid ratio index expresses the relationship between the basic oxides (Fe_2O_3 , MgO , K_2O , Na_2O , CaO) and the acidic oxides (SiO_2 , Al_2O_3 and TiO_2) constituents in the ash samples. It is used to predict the slagging and fouling occurrence during the boiler operation, which can be evaluated using Equation (1) [46]. Higher acidic oxides indicate a higher melting point of the coal ash samples with a minimum fouling and slagging prediction during the boiler operation [45].

$$\frac{B}{A} = \frac{(\text{Fe}_2\text{O}_3 + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO})\%}{(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2)\%} \quad (1)$$

The base acid ratio indices for samples A and B from the analysed results are 0.16 and 0.19, respectively. The base acid ratio of the coal ash sample with values between 0.4–0.7 indicates a low ash fusibility and a higher slagging potential during the boiler operation [21]. However, the base acid ratio of both ash samples in this study is less than 0.2 indicating high ash fusibility with a corresponding lower slagging potential prediction during Sasol boiler(s) operation. Ash deposition in the boiler furnace wall and heat transfer surfaces during the boiler operations is mainly caused by condensed alkaline vapours, thermophoretic aerosols/fume particles and the slagging/sintered passage formed by the molten basic components reacting with clay and quartz [47–49].

The fouling potential (f_u) during the boiler operations can be predicted based on the base acid ratio and the alkali (Na_2O and K_2O) chemical composition in the coal ash samples as expressed in Equation (2) [50].

$$f_u = \frac{B}{A}(\text{Na}_2\text{O} + \text{K}_2\text{O}) \quad (2)$$

An increase in the surface stickiness on the heat transfer tubes is caused by the condensation of potassium (K) in the fly ash particles. The major constituents that cause ash deposition problems on the boiler superheater tubes are K_2O , SO_3 and CaO [20].

Brayers (1996) proposed that the fouling potential during the boiler operation can also be predicted using an index based on the number of sodium oxides (Na_2O) present within the coal ash samples within the low-grade bituminous coal [47].

Attig and Duzy developed a slagging prediction index (R_s) on the furnace wall during the boiler operation, this method is the product of the coal ash base acid ratio and the percentage of sulphur (S) contained within the raw coal samples as expressed in the Equation (3). This index is applicable for all types of coals [51].

$$R_s = \frac{B}{A} \times S \quad (3)$$

A predicted fouling tendency index during the boiler operation was also developed by evaluating the product of the base acid ratio and the number of sodium oxides (Na_2O) present within the coal ash samples, as shown in Equation (4) [47,51].

$$R_F = \frac{B}{A} \times \text{Na}_2\text{O} \quad (4)$$

Fouling during coal-fired boiler operation can also be evaluated using the alkali metals (K_2O , Na_2O) and silicate (SiO_2) compounds present in the coal ash samples. The slag viscosity index (S_r) in Equation (5) is used to predict the slagging tendency in the boiler

furnace wall, since the furnace wall deposits are similar to the coal ash constituents that are made up of mostly silicate materials [52].

$$S_r = \left(\frac{SiO_2}{SiO_2 + CaO + MgO + Fe_2O_3} \right) \times 100 \quad (5)$$

A higher slag viscosity index represents a high viscosity of the silica constituents inside the boiler furnace with a corresponding low slagging potential [34].

4. Results and Discussion

The main objective of this study is to investigate the decline in the overall efficiency and steam output pressure of the boiler(s) operated by Sasol synfuel limited; this challenge might be a result of the coal ash accumulation on the boiler heat transfer tubes. In meeting the research objective, an investigation on the coal ash produced from the coal combustion was carried out to determine the coal ash chemical concentration. The fouling and slagging potential during the boiler operation was predicted using the analysed laboratory results in this study. Fouling and slagging prediction indices developed from previous research work based on the coal ash chemical composition were used as guidelines or evaluation reference point to evaluate the slagging and fouling prediction of the operated Sasol boiler(s).

This section entails the presentation and discussion of the analysed laboratory results obtained during the coal ash analysis.

Table 1 is a representation of the elemental composition detected from the coal ash samples from the ICP-OES analyser, it shows the major (Ca) and minor (Na, Mg, K, S) elements present within the coal ash.

Table 1. ICP-OES elemental analysis.

Element Present	Sample A mg/Kg	Sample B mg/kg	Sample A Mass (%)	Sample B Mass (%)
Na	2066.6	2804.9	0.21	0.28
Mg	3843.3	3600.6	0.38	0.36
K	774.2	894	0.08	0.09
Ca	45,971.6	58749.6	4.60	5.87
S	1412.7	669.7	0.14	0.07

Table 2 is a representation of the elements detected in the coal ash samples from the ICP-MS analyser. these elements make up the trace elements (As, Se, Cd, Hg, Pb) within the coal ash sample.

Table 2. ICP-MS elemental analysis.

Element Present	Sample A mg/Kg	Sample B mg/Kg	Sample A Mass (%)	Sample B Mass (%)
As	7.58	1.88	0.00076	0.00019
Se	5.78	3.19	0.00059	0.00032
Cd	0.09	0.019	0.000009	0.000009
Hg	0.10	0.018	0.00005	0.0000018
Pb	19.3	3.55	0.0019	0.00036

Table 3 represents the detected concentrated elements present in the coal ash samples from the XRF analyser. The major elements presents are Al_2O_3 and SiO_2 . The chemical composition results for the bituminous coal ash in this study agreed with previous research results discussed in Section 2 in this article.

Table 3. XRF chemical composition analysis.

Chemical Composition	Sample A (Mass %)	Sample B (Mass %)
Al ₂ O ₃	32.66	32.53
BaO	0.16	0.15
CaO	6.93	9.31
Cr ₂ O ₃	0.04	0.05
Fe ₂ O ₃	2.81	3.75
K ₂ O	0.67	0.61
MgO	0.97	1.04
Na ₂ O	0.91	0.75
P ₂ O ₅	0.35	0.28
SiO ₂	44.73	47.57
SO ₃	0.14	0.04
TiO ₂	1.76	1.71
LOI	7.32	2.43

Table 4 is a representation of the elemental composition of the raw bituminous coal used for firing the installed boilers at the Sasol synfuel operation.

Table 4. Raw bituminous coal ultimate analysis on as received basis.

Element Present	Raw Coal (% wt.)
N _{ar}	1.57
C _{ar}	52.11
H _{ar}	2.99
S _{ar}	0.19
O _{ar}	43.14

ar represents the coal on as received basis.

The published developed fouling and slagging prediction indices based on the ash chemical constituents are summarised in Table 5, indicating the predicting factor, evaluated index (formula), and the predicted fouling and slagging type (i.e., low, medium, high, and severe) based on analysed coal ash chemical constituents.

The indices in Table 5 were used as a guide for evaluating the fouling and slagging prediction for the installed Sasol coal-fired boiler(s) using the data set from the analysed laboratory coal ash chemical constituents in Tables 3 and 4.

Table 6 is the evaluated fouling and slagging potential prediction of the boiler installed at Sasol synfuel operation in Secunda based on the analysed coal ash chemical composition obtained from the laboratory analysis. Using the evaluated indices and the predicted fouling and slagging types in Table 5 as a guide. The results obtained predict a low to medium fouling potential and a low slagging potential during the operation of the installed boilers at Sasol synfuel limited. However, the accumulation of the ash in the boiler furnace wall and convective tube surfaces over long operational period, would result in the formation of thick insulated layer reducing the amount of heat transfer to the moving fluid inside the tubes resulting to a decline in the overall efficiency. The installation of smart soot blowers for ash removal on the boiler tubes is therefore recommended as to achieve an optimal operational efficiency.

Table 5. Summarised published developed fouling and slagging prediction indices.

Predicting Factor	Evaluating Index	Low	Medium	High	Severe
Fouling tendency prediction (Rf) [47,51]	$\frac{B}{A} \times Na_2O$	<0.2	0.2–0.5	0.5–1.0	>1.0
Fouling potential prediction (fu) [18,50]	$\frac{B}{A} (Na_2O + K_2O)$	<0.6		0.7–40	Above 40
Fouling potential prediction on Na ₂ O presence [47]	Quantity of Na ₂ O in the ash sample	<0.5	0.5–1.0	1.0–2.5	>2.5
Slagging type prediction (Rs) [51]	$\frac{B}{A} \times S$	<0.6	0.6–2.0	2.0–2.6	>2.6
Slag Viscosity prediction (Sr) [52]	$\left(\frac{SiO_2}{SiO_2 + CaO + MgO + Fe_2O_3} \right) \times 100$	Above 72	65–72	Below 65	
Acid Based ratio slagging prediction [45,53]	$\frac{B}{A}$	<0.5	0.5–0.9	1.0–1.74	Above 1.75

Table 6. Evaluated fouling and slagging prediction for Sasol coal-fired boiler(s).

	Predicting Factor	Evaluating Index	Quantity/Unit		
			Sample A	Sample B	Index/Type
a	Fouling tendency prediction (Rf)	$\frac{B}{A} \times Na_2O$	0.15	0.14	Low
b	Fouling potential prediction (fu)	$\frac{B}{A} (Na_2O + K_2O)$	0.25	0.26	Low
c	Fouling potential prediction on Na ₂ O presence	Quantity of Na ₂ O in the ash sample	0.91	0.75	Medium
d	Slagging type prediction (Rs)	$\frac{B}{A} \times S$	0.03	0.04	Low
e	Slag viscosity prediction (Sr)	$\left(\frac{SiO_2}{SiO_2 + CaO + MgO + Fe_2O_3} \right) \times 100$	80.68	77.14	Low
f	Acid Based ratio slagging prediction	$\frac{B}{A}$	0.15	0.19	Low

5. Conclusions

This article is an investigation into predicting fouling and slagging occurrences during the operation of the installed boilers operated by Sasol synfuel limited. The investigation involved analysing the coal fly ash and bottom ash residue collected from Sasol operational site in Secunda using ICP-MS, ICP-OES and XRF laboratory analytical techniques. Previously published fouling and slagging indices based on the coal ash chemical composition were used as a guide to evaluate the fouling and slagging potential of the installed boilers operated by Sasol synfuel limited. The prediction results obtained using the analysed chemical composition of the coal ash samples in this study indicate or predict a low to medium fouling potential in the boiler convective heat transfer surfaces, and a low slagging potential in the boiler furnace wall. Hence, we can eliminate the ash as the source of the decline in the boiler operational efficiency.

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Data Availability Statement: Data for this study can be obtained from the Department of Mechanical and Industrial Engineering Technology, and the Department of chemical Sciences, University of Johannesburg, South Africa. www.uj.ac.za, accessed on 2 October 2022.

Conflicts of Interest: The authors declare that there is no conflict of interest.

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