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Nature of fireside deposits in a bagasse and groundnut shell fired 20 MW thermal boiler

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Abstract

The nature of deposit formation on the fireside surfaces of the boiler tubes in the various parts (water walls, platen superheater, final superheater, economizer, electrostatic precipitator etc.) of a commercial 20 MW stoker-fired boiler being fired with a mixture of 80% bagasse and 20% groundnut shell has been analyzed. The deposits in the various portions of the boiler were characterized by particle size analysis, chemical analysis, X-ray diffraction and scanning electron microscopy. The deposits were found to be mainly quartz, alkali and alkaline earth silicates and sulfates. From the phase constitution and other microscopic characteristics of the deposit, it can be inferred that the silicates in the deposit formed through inertial impaction and the sulfates formed by vapor phase deposition.

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1. Introduction

Although most of the thermal power plants in India still use coal as the fuel, recent concerns on global warming and the decreasing resources of fossil fuels have resulted in the commissioning of a few biomass fired boilers in India. Deposit formation from biomass combustion, however, is a serious problem and can be a limiting factor in the increased use of biomass in thermal boilers. Deposits that are formed on the heat transfer surfaces of the boiler tubes can lead to

reduction of the heat transfer rates (fouling) and also accelerate the rate of fireside corrosion in biomass fired boilers. Therefore, a detailed study of the nature of deposit formation in the various portions of the boiler is essential for the combustion of each type of biomass fuel used.

Deposit formation in combustion is a complex process involving various issues such as mineralogy/petrology of the fuel, fuel chemistry, combustion chemistry, particle transport, fluid dynamics, condensation, etc. The various mechanisms of ash transport/deposit formation in boilers reported in the literature [1] include (i) inertial impaction, (ii) eddy impaction, (iii) thermophoresis/diffusion, (iv) vapor

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phase condensation and (v) chemical reaction. Deposit formation by inertial impaction generally occurs on the windward side of the metal surface (i.e., in the direction of the gas flow) and for large particles ($> 10 \mu\text{m}$). Deposit formation by eddy impaction occurs in the leeward side and for particles in the size range of $5\text{--}10 \mu\text{m}$. Diffusion or thermophoresis due to a thermal gradient and vapor phase condensation in the cooler zone result in submicroscopic particles. The flue gas and metal surface temperatures as well as the location within the boiler plays a critical role in determining the nature and composition of the deposits. For biomass fuels, the form in which the alkali metal vapors are released is important in determining the nature and composition of the deposits. The release of alkali metal vapor accelerates fouling and slagging. The form of alkali vapor species depends on the type of biomass and is also a function of temperature.

The nature of deposits formed and its subsequent implication on fireside corrosion is strongly dependent on the composition and mobility of the inorganic species in the fuel. The various inorganic constituents and the forms in which they are present in biomass fuels will depend not only on the type of biomass but also on the soil chemistry as well as on the nutrients used. For example, silicon occurs in plants by absorption of silicic acid from the soil solution [2]. Potassium in plants correlates with metabolic activity and it is often found in regions where plant growth is most vigorous [2]. It is reported that silica in biomass fuels is hydrated and granular and that a major part of the alkali and alkaline earth elements in biomass fuels are atomically dispersed (non-granular) and are readily volatile on combustion [3]. Aluminum and other materials are introduced by soil contamination of the biomass crop and are therefore present predominantly in the form of clays and oxides. Dayton and Milne [4] have studied alkali metal released from gas phase during biomass combustion for several fuels using a molecular beam mass spectrometer. Their results indicate that composition of the biomass has the most pronounced effect on alkali metal released during combustion. They have identified four mechanisms of alkali metal release depending on the feed composition. Relatively low alkali metal containing fuels release through the vaporization or decomposition of alkali sulfates. Alkali metal chlorides are the primary alkali metal released during combustion of herbaceous

fuels with high alkali metal and chlorine contents. For biomass fuels with high alkali metal and low chlorine content, alkali metal hydroxides are the most abundant alkali vapor released. If high alkali content is also associated with high levels of fuel-bound nitrogen, alkali cyanates are the dominant form of alkali metal vapor. Baxter and co-workers [5–8] have studied in detail the chemistry and kinetics of deposit formation from various biomass fuels. They also observed that for straw and grass, initial deposits contain alkali chlorides, wood and almond shell produce sulfated deposits and for other fuels rich in potassium, initial deposition occurs as alkali hydroxides or carbonates.

The purpose of the present work was to study the deposition behavior in a commercial 20 MW boiler in the southern part of India (Tamilnadu) fired with a blend of 80% bagasse and 20% groundnut shell. A detailed understanding of the chemistry of deposit formation will enable ways and means to control them. Combustion of the bagasse and groundnut shell blend was carried out in a commercial 20 MW stoker-fired (grate-fired) boiler in Tamilnadu, India that was designed and commissioned by Bharat Heavy Electricals Limited, Tiruchirappalli. A sketch of the boiler is given in Fig. 1. The process conditions such as throughputs of fuel and air, flue gas inlet and outlet temperatures and metal surface temperatures in the various sections of the boiler and the specifications of the materials used in each section is given in Table 1.

2. Experimental

The commercial stoker-fired boiler fired with a blend of 80% bagasse and 20% groundnut shell was in operation continuously for more than a month prior to the collection of deposits. Deposits from the various locations (water walls, platen superheater, final superheater, economizer, electrostatic precipitator, etc.) of the boiler were collected during the boiler shutdown period. The deposits had accumulated possibly over an 8-h period, the time interval normally adopted for the soot cleaning operations. The deposits were collected mainly from the front (windward) surface of the boiler tubes, i.e., in the direction of the flue gas flow and therefore correspond to the conditions in the boiler prior to the shutdown. Proximate and detailed ultimate analyses as well as microstructural

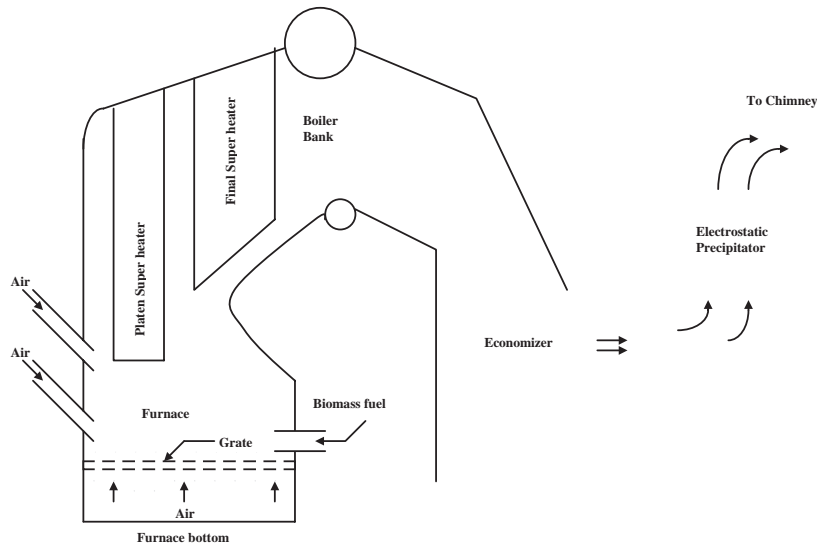


Fig. 1. A schematic representation of the commercial stoker-fired boiler used.

Table 1

Process conditions and material specification for the various components of the stoker-fired commercial boiler

Sl no.	Boiler component	Flue gas temp Inlet/Outlet (°C)	Metal temperature (°C)	Material of construction ASME specification
1	Furnace waterwalls	1150/950	290	SA210-Gr.A1 (C-0.27%, Mn-0.93%, S-0.058% max, P-0.048% max, Si-0.10%, rest Fe)
2	Platen superheater	950/860	380–402	SA213-T11 (C-0.15% max, Mn-0.3-0.6%, S-0.3% max, P-0.3% max, Si-0.5-1.0%, Cr-1.0-1.5%, Mo-0.44-0.65%, rest Fe)
3	Final superheater	860/740	438–485	SA213-T11
4	Boiler bank	740/513		SA213-T11
5	Economizer	513/265	185–255	SA210-Gr.A1 (C-0.27%, Mn-0.93%, S-0.058% max, P-0.048% max, Si-0.10%, rest Fe)
6	Electrostatic precipitator	160/150		

Input rate of 80% bagasse+20% groundnut shell blend: 34.4 ton/h.

Input rate of air: 154.5 ton/h.

characterization of both bagasse and groundnut shell was carried out. As suggested by Miles et al [5], ashing of the fuels for chemical analysis were carried out at 450–500°C to eliminate vaporization of the volatile alkali compounds during the standard ashing and calcining process. The X-ray diffraction patterns of the ash samples derived from the bagasse and groundnut shell were recorded. The microscopic study of the bagasse and groundnut shell samples was carried out

using a Leitz Orthoplan Microscope. The deposits collected from the various locations of the boiler were subjected to particle size analysis, wet chemical analysis, X-ray diffraction, scanning electron microscopy and EDAX to determine the nature and composition of the deposits, phases present in the deposits and their morphology. Particle size analysis was carried out on wet mode in a CILAS (Model No. 1180) laser particle size analyzer. Chemical analyses were based

Table 2
Proximate and ultimate analysis of bagasse and groundnut shell

	Bagasse	Groundnut shell
Proximate analysis	Wt(%)	Wt(%)
Moisture	49.90	10.12
Volatile matter	42.50	62.20
Ash	1.50	5.40
Fixed carbon	6.20	22.40
Ultimate elemental analysis		
Carbon	23.70	45.28
Hydrogen	3.00	4.63
Sulfur	0.0	0.42
Nitrogen	0.0	0.51
Oxygen (by difference)	22.58	35.34
Silicon	0.4925	0.4463
Aluminum	0.0154	0.1149
Iron	0.0121	0.0551
Calcium	0.0734	0.6854
Magnesium	0.0684	0.3817
Sodium	0.0145	0.1995
Potassium	0.1022	1.6586
Phosphorous	0.0279	0.1431
Chlorine	0.01	0.01
Moisture	49.90	10.12

mainly on atomic absorption spectrophotometry and complemented by EDAX attached to a scanning electron microscope. X-ray diffraction analysis was carried out with a Siemens D-500 diffractometer using Co- K_{α} radiation ($K_{\alpha} = 1.79026 \text{ \AA}$). Micro-structural

analysis of the deposits was carried out using a JEOL JSM 840A scanning electron microscope in the back-scatter electron imaging mode.

3. Results and discussion

3.1. Characterization of the biomass fuels

The proximate and ultimate analysis of the air-dried bagasse and groundnut shell as used in the commercial stoker-fired boiler is given in Table 2. It is seen that the ash content and the alkali and alkaline earth constituents is much higher in the groundnut shell than in bagasse. Sulfur and fuel bound nitrogen are virtually absent in the bagasse whereas they are present in significant amounts in the groundnut shell sample. Although agricultural residues in general contain high alkali and chlorine contents, bagasse is an exception. The cane processing for sugar production removes much of the alkali from bagasse. The groundnut shell sample also contained moderately low levels of chlorine. The optical micrographs of pure bagasse and groundnut shell samples depicting the petrological features are shown in Fig. 2. The presence of micro-crystals of inorganic quartz ($\alpha\text{-SiO}_2$), diopside $\{\text{CaMg}(\text{SiO}_3)_2\}$ and apatite $\{\text{Ca}_5(\text{PO}_4)_3\}$ in bagasse and quartz, orthoclase (KAlSi_3O_8), magnesium–silicate ($\beta\text{-Mg}_2\text{SiO}_4$) and opaques (sulfates/sulfides) in groundnut shell could be identified in the optical micrographs.

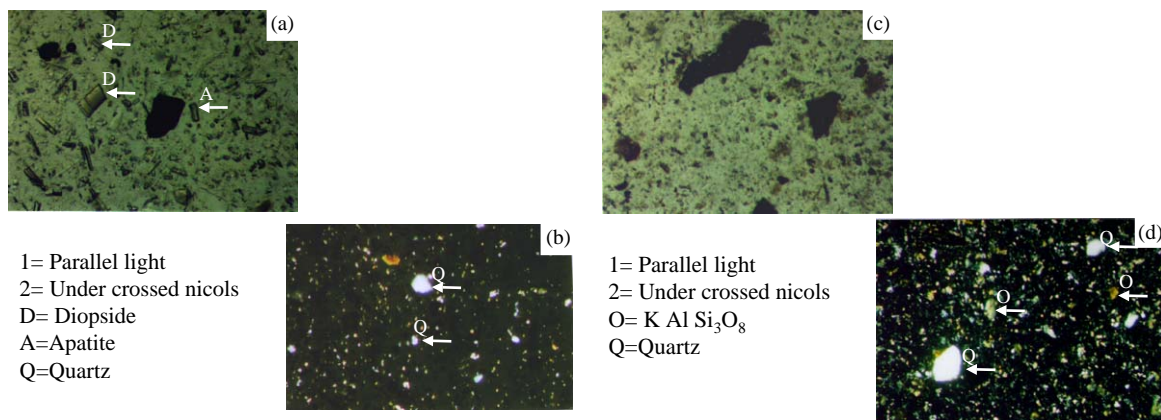


Fig. 2. General morphological features of bagasse (a, b) and groundnut shell (c, d), magnification $\times 100$. Figs. (a) and (b) are under parallel light while (c) and (d) are under crossed nicols.

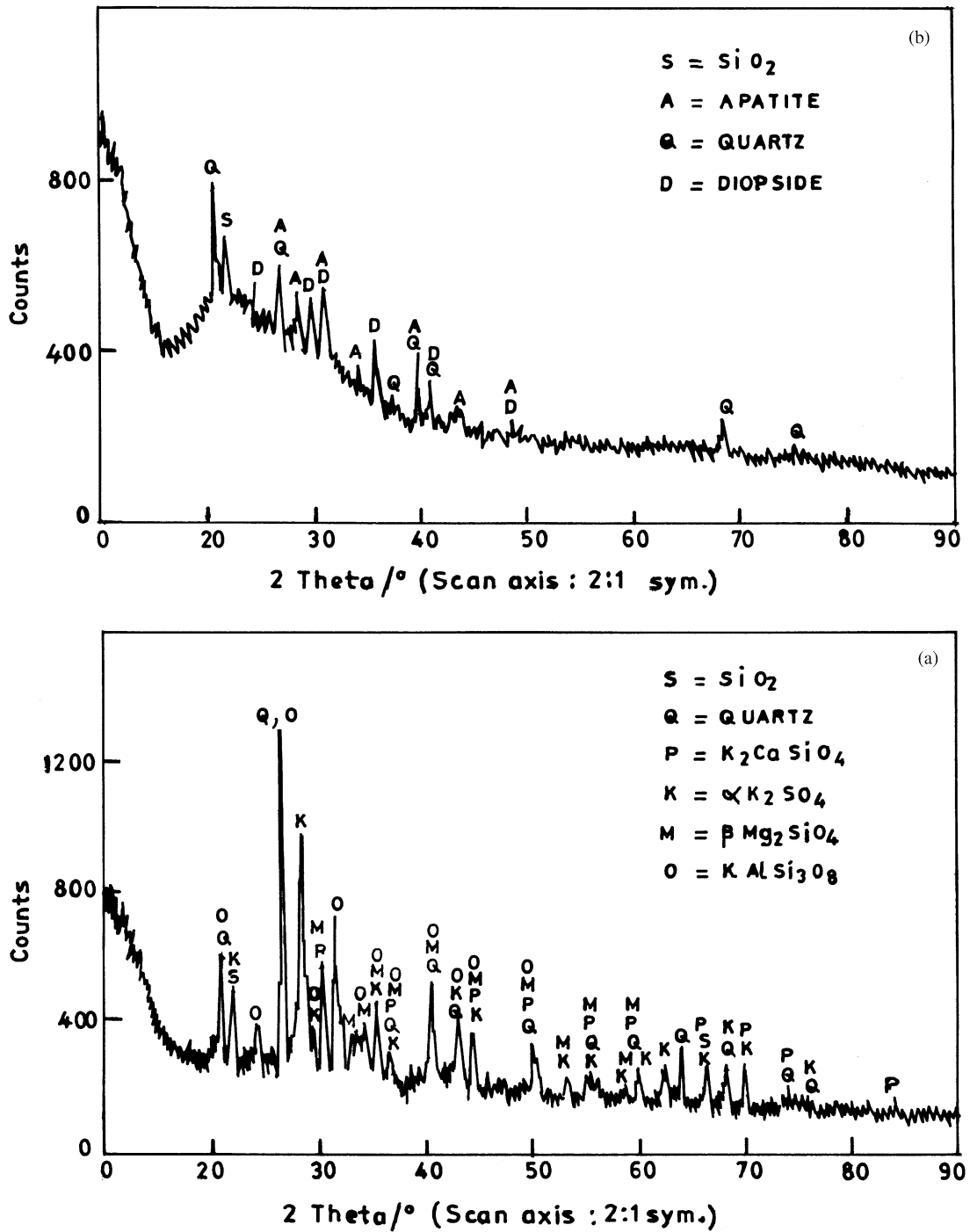


Fig. 3. (a) X-ray diffraction pattern of the ash sample derived from ashing of pure bagasse at 450°C. (b) X-ray diffraction pattern of the ash sample derived from ashing of pure groundnut shell at 450°C.

Table 3

Chemical compositions of the deposits for the firing of 80% bagasse+20% groundnut shell blend in the various parts of the boiler

Location in the boiler	Experimental (AAS & EDS) chemical composition-weight percent										
	SiO ₂	K ₂ O	CaO	MgO	Al ₂ O ₃	Na ₂ O	Fe ₂ O ₃	SO ₃	P ₂ O ₅	Cl ppm	H ₂ O
Furnace waterwalls	39.63	13.04	9.12	2.20	13.72	1.00	2.95	11.72	2.32	80	1.70
Platten superheater	43.07	19.18	9.17	3.25	1.83	1.68	3.12	13.82	3.94	180	0.42
Final superheater	38.83	21.40	4.47	2.49	2.65	1.43	0.13	17.37	1.79	115	4.66
Boiler main bank	43.36	15.50	6.57	3.53	2.82	1.13	1.58	16.25	3.88	100	6.50
Economizer	41.75	13.50	6.63	4.11	3.50	1.03	1.47	17.01	3.43	115	5.20
Electrostatic precipitator	59.37	4.16	4.64	2.18	3.22	0.85	2.40	7.53	1.48	115	13.68

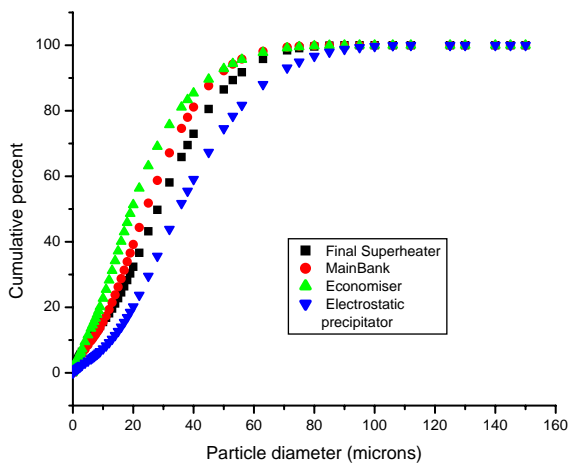


Fig. 4. Particle size distributions in the deposits collected from the various locations in the boiler.

The X-ray diffraction patterns of the ash sample derived from the ashing of pure bagasse and pure groundnut shell at 450°C are shown in Figs. 3(a) and (b), respectively. The bagasse ash sample shows good crystallinity and the phases detected were the same as the inorganic phases detected microscopically in pure bagasse and comprises of quartz, SiO₂, diopside, and apatite. The ash generated from pure groundnut shell at low temperature (450°C) also shows a crystalline behavior and the phase constitution of the ash is: quartz, SiO₂, α -K₂SO₄, orthoclase, K₂CaSiO₄ and β -Mg₂SiO₄. In the case of groundnut shell also, the silica and silicates in the ash correspond to the original phases present in pure groundnut shell. However,

it is difficult to ascertain whether the presence of crystalline potassium sulfate in the ash sample is derived directly from groundnut shell or formed during the combustion process.

3.2. Nature and composition of deposits

The chemical composition of the deposits collected from the various portions of the boiler corresponding to the firing of a blend of 80% bagasse and 20% groundnut shell is given in Table 3. As mentioned earlier, chemical analysis was mainly by atomic absorption spectrophotometry and complemented by EDAX analysis. The deposits consist mainly of SiO₂, K₂O, CaO, SO₃ and some amount of moisture at lower temperatures. The water wall deposit composition to some extent resembles the fuel ash composition. However, the superheater, main bank tube and economizer deposits are more enriched in potassium and sulfur. The particle size distribution of some of the deposits is depicted in Fig. 4. The particle size range and distribution for the deposits collected from the various locations after the platen superheater were similar and was between 0 and 80 μ m. The X-ray diffractograms of all the deposits are shown in Fig. 5. The corresponding SEM photomicrographs seen in the back scattered electron imaging mode depicting the morphology of the deposits collected from the various portions of the boiler are shown in Figs. 6(a–f). Atomic number contrast can be seen in the back-scattered images (higher atomic number elements appear brighter and lower atomic number elements appears darker). The elemental analysis at specific regions determined using EDAX is also summarized in Table 4. The X-ray

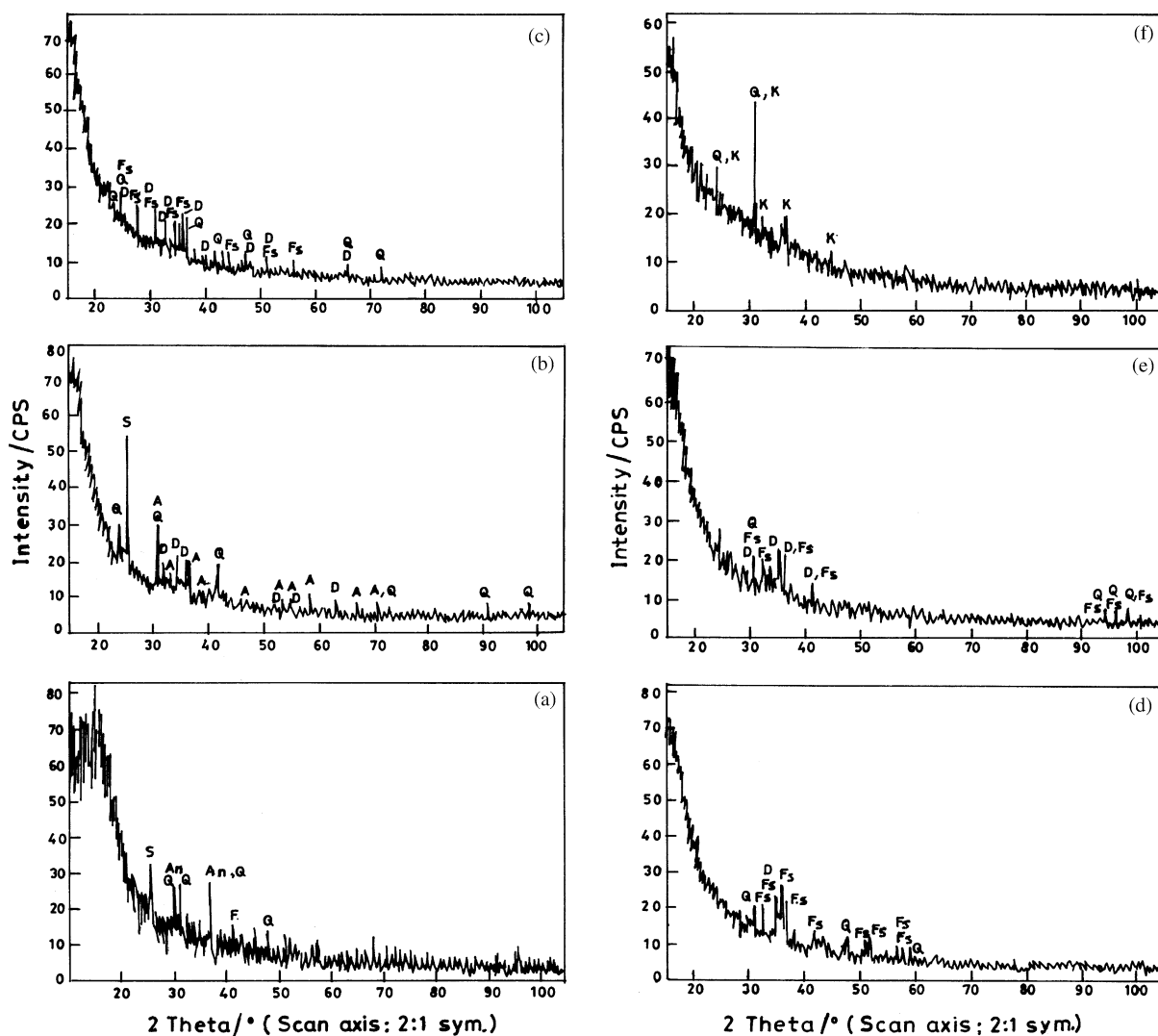


Fig. 5. X-ray diffractograms of the deposits from (a) furnace waterwalls, (b) platen superheater, (c) final superheater, (d) boiler bank, (e) economizer and (f) electrostatic precipitator.

diffractograms of all the deposits showed features characteristic of low crystallinity. From the XRD, SEM and EDAX results, the water wall deposit can be inferred to contain crystalline quartz, silica, anhydride and fayalite along with some glassy phases. The crystalline quartz and silica in the water wall deposit are derived directly from the fuel ash. The formation of the glass phase, fayalite and anhydride in the water wall deposit can be attributed to the high temperature combustion reaction in this region. The XRD and

SEM results of the platen superheater deposit indicate the presence of crystalline quartz, silica, diopside, apatite and amorphous alkali and alkaline earth sulfates. The crystalline phases and their size range detected in the platen superheater are the same as that present in the original fuel prior to combustion whereas the sulfate phase shows characteristics of having formed by gas phase reaction and subsequent condensation. The deposits in the final superheater, boiler main bank and economizer show similar features in terms

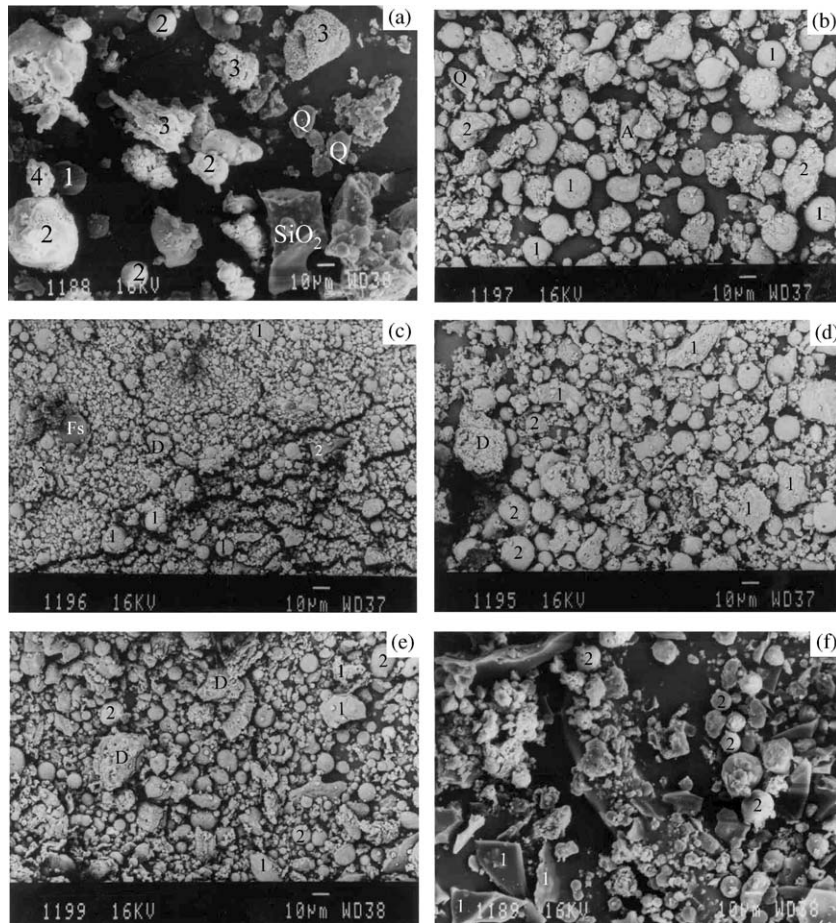


Fig. 6. SEM photographs in the backscattered electron imaging mode giving the morphology of the deposits from: (a) furnace waterwalls, (b) platten superheater, (c) final superheater, (d) boiler bank, (e) economizer and (f) electrostatic precipitator.

of phase constitution and particle size distribution. They comprise of crystalline quartz, diopside and ferrosillite in addition to the amorphous sulphate phases. The phase ferrosillite probably forms by chemical reaction and the absence of the apatite phase in the low-temperature deposits signifies its decomposition at the lower temperatures. The deposit collected from the electrostatic precipitator shows the presence of only crystalline quartz, potassium–calcium–sulfate [$K_2Ca_2(SO_4)_3$] and some glassy phases. It is interesting to note that the potassium–calcium–sulfate that was present in amorphous form in the superheater and economizer deposits has crystallized. Further, the absence of the crystalline diopside and ferrosillite phases

in the XRD pattern of the ESP deposit is difficult to explain.

4. Conclusions

The deposition behavior in the various parts of a 20 MW commercial thermal boiler fired with a blend of bagasse and groundnut shell was analyzed. The phase constitution and microstructural features of the deposits show that many of the original minerals present in the fuel blend such as crystalline quartz, silica, diopside and apatite are retained in the deposits. However, the alkali and alkaline earth sulfates

Table 4
EDAX analysis for elemental composition (wt%) of the deposits in selected particles (see Fig. 6 for more details)

Location of deposit	Mg	Al	Si	P	S	K	Ca	Fe
Furnace water wall								
Bulk	1.07	7.86	34.04	1.86	9.46	19.90	17.63	6.96
Ph-1	0.14	0.49	5.40	Nil	0.8	12.27	4.14	74.99
Ph-2	0.71	33.37	9.79	0.62	14.67	21.20	12.74	3.53
Ph-3	2.55	0.82	44.11	2.79	0.40	36.83	7.48	4.84
Ph-4	0.11	23.56	11.90	0.18	5.66	0.98	49.69	4.62
Platen superheater								
Bulk	1.37	0.63	36.63	3.13	10.07	28.97	11.93	7.28
Ph-1	Nil	Nil	21.77	1.30	18.80	54.19	3.22	0.72
Ph-2	Nil	1.04	62.48	0.76	8.98	22.76	2.61	1.37
Final superheater								
Bulk	0.44	0.89	43.25	1.58	15.39	28.95	6.55	3.03
Ph-1	5.22	2.10	29.61	3.87	18.08	19.65	15.36	6.12
Ph-2	0.76	0.41	86.55	1.77	2.76	5.53	1.33	0.86
Boiler main bank								
Bulk	2.33	0.82	32.14	3.44	17.52	29.80	11.06	2.87
Ph-1	Nil	0.22	88.21	0.54	3.29	5.92	1.16	0.65
Ph-2	0.30	Nil	9.23	0.39	30.37	23.37	34.61	1.73
Economiser								
Bulk	0.77	0.33	36.78	3.06	18.30	29.51	8.71	2.54
Ph-1	0.19	0.54	82.20	1.54	4.17	10.16	0.33	0.86
Ph-2	2.67	0.64	30.72	6.01	16.16	27.29	9.71	6.80
Electrostatic precipitator								
Bulk	0.48	0.48	64.66	1.51	9.03	12.79	8.57	2.48
Ph-1	0.93	3.18	10.16	9.94	18.75	17.42	33.27	5.84
Ph-2	1.44	3.18	10.16	9.94	18.75	17.42	33.27	5.84

such as anhydride and potassium–calcium–sulfate [$K_2Ca_2(SO_4)_3$] forming during the combustion process are transported through the vapor phase and deposit by condensation.

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