Characterising Fuels For Biomass – Coal Fired Cogeneration
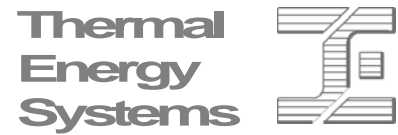
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Thermal
Energy
Systems

Abstract

Coal is commonly used as an auxiliary fuel in biomass fired co-generation power stations. Design of the boilers for these stations therefore requires a detailed knowledge of the properties of the biomass, the coal and any interaction between the two.

A continuous ash discharge (CAD) stoker is normally used for this combination of fuels. In assessing an acceptable grate rating for biomass fuel firing, the effective moisture of the biomass is the key parameter required whilst the grate rating for coal is a function of its reactivity.

The GCV of biomass fuels has been characterised as a formula involving their moisture and ash contents. In the case of bagasse, the values of the constants have been sufficiently defined to avoid the need to measure its GCV empirically. To size the grate for biomass fuel firing the concept of 'effective' moisture has to be introduced to overcome the distortion caused by any variation in ash content.

There are sophisticated methods of analysing coal to establish reactivity but the methods are time consuming and only a few laboratories are equipped to use them. A new approach is proposed to use the petrographic composition of the coal to predict reactivity, microscopically examining the coal to determine the make-up of its organic constituents [the 'macerals'] and hence determine its characteristics. The technique is fast and relatively inexpensive and where it has been used recently has yielded commercially viable results.

The techniques described allow the grate to be designed for optimum combustion but do not predict how the ash chemistry of the fuels may adversely affect the anticipated results. Furthermore they do not predict any interaction between the fuels which may preclude combination firing. An appropriately designed grate will help resolve differing primary air and ash discharge requirements. The characteristics of the two ashes, however, must be brought to account by means of specialist phase diagrams in order to determine whether the grate and/or furnace will need to be de-rated to prevent clinker and slag formation and boiler fouling.

Introduction

Coal is often used as an auxiliary fuel in biomass fired co-generation power stations such as those installed in the cane sugar industry. These stations typically employ 10 to 75 MW turbo-alternators coupled to 75 t/h to 250 t/h boilers. Dual fuel boilers are usually equipped with continuous ash discharge [CAD] stokers, as shown in Figure 1 (over the page) :
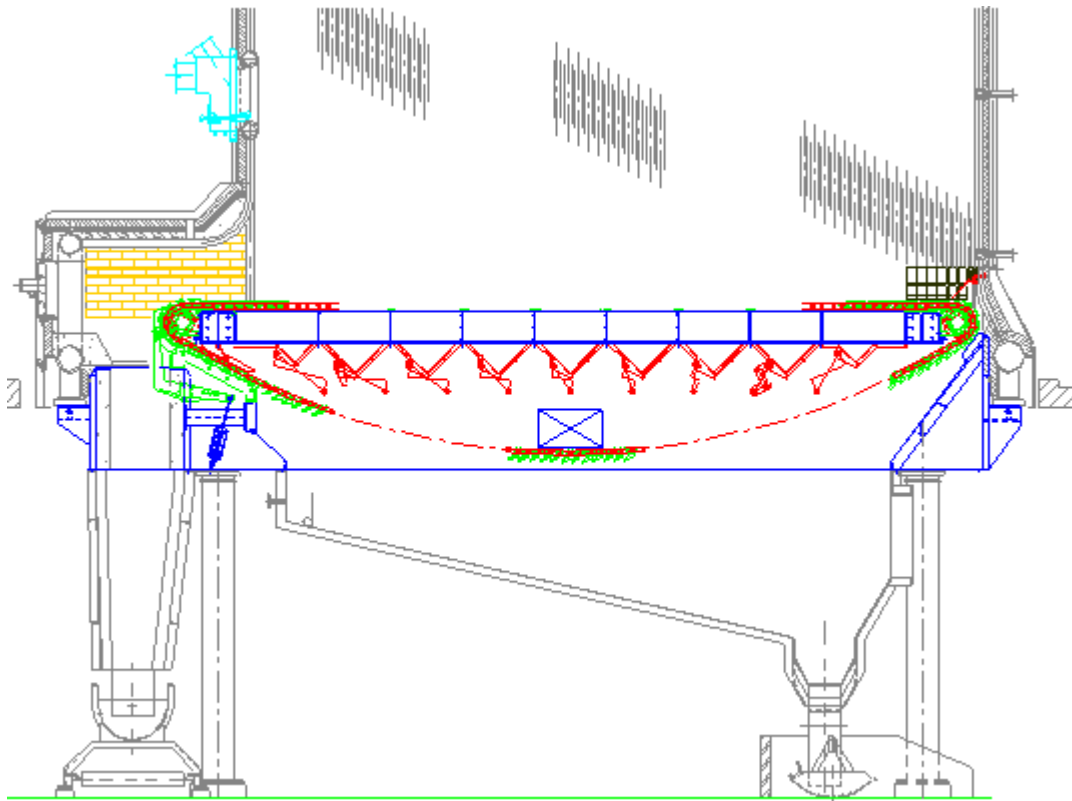
Fig. 1: Arrangement of TES Zoned CAD Stoker

These stokers were originally designed to burn high swelling index bituminous coal. They are, however, suitable for burning a wide range of coal qualities. They are also ideal for burning low ash biomass fuels although steam cleaned stationery grates are economically more attractive when these are burned on their own or in combination with oil or gas. The unit shown above is fully zoned. The advantages of zoning are discussed later.

The fuel data scheduled in Tables 1 and 2 (at end of paper) is needed in order to size a stoker, evaluate excess air requirements, predict unburned carbon losses and optimise stoker setting and furnace design. The same data is needed to evaluate the clinkering, slagging and fouling properties of coal and biomass fuels. The typical bagasse and coal analyses included in these Tables will be used in this paper to illustrate how these properties are used for this purpose.

Common analytical standards should be used to ensure that data is comparable. Low temperature analyses of the alkali metals in biomass fuel ash when compared with the results obtained from conventional high temperature techniques can help determine if fouling is likely to take place (Miles, 1995).

Biomass Characterisation

In common with fossil fuels, biomass fuels have four important properties :

> Heating value
> Chemical properties
> Physical properties
> Combustion properties.

However, unlike fossil fuels they have similar dry, ash free, ultimate analyses. For practical purposes, only their moistures, ash analyses and physical characteristics differentiate them.

The gross calorific value [GCV] of a biomass fuel, as determined in the laboratory with a "bomb" calorimeter, can be written in most cases in the form :

GCV = k (1 – m – a) kJ/kg

Where   m = the moisture fraction of the fuel, and
         a = the ash fraction of the fuel.

The constant k is usually between 17 500 and 21 000. Fuel moisture varies from 0.05 to 0.60 and the ash fraction from 0.01 to 0.13. The Sugar Milling Research Institute in South Africa (Don et al, 1977) has established that k for bagasse is 19 605. To correct for the fact that the calorific value of brix is less than that of fibre their form of the equation subtracts 3 115 x b from the result where b is the brix fraction of the fuel.

Heat liberation rate (GJ/h m^2 or kW/m^2) is used as a basis for spreader stoker sizing on a biomass fuel. The fuel moisture content, the primary air temperature and the fuel's fouling propensity are the significant factors which determine grate rating. In this paper the furnace plan area at the level at which the fuel is introduced into the furnace is used to calculate biomass grate heat release rate.

The work reported here introduces the concept of 'effective moisture content' because increasing the ash content of a given fuel effectively increases it's ratio of moisture to combustible material. To eliminate this detrimental effect from the calculations, all fuel analyses are reduced to an ash content of 2 %. In the cane sugar industry where 53 % moisture fuel having an ash content of 2 % can be burned relatively easily, one having the same moisture content but an ash content of 6 % may be difficult to burn as it has an 'effective' moisture of 55,26 %. The first fuel has a moisture to combustible ratio of 1.18:1 and the second a ratio of 1.29:1; i.e. almost 10 % more moisture per unit mass of combustible material whilst fuel moisture has only gone up by 2.26 % points.

Maximum grate heat release rates are obtained when burning a high proportion of the fuel in suspension. As fuel moisture increases, piles tend to form on the grate. These inhibit combustion. They can be prevented from forming by reducing grate loading or by drying them by passing hot primary air through them. They cannot be dried within a reasonable time scale by radiation from the furnace (Magasiner & de Kock, 1987).

A relationship between grate heat release rate, effective fuel moisture and primary air temperature has been established :
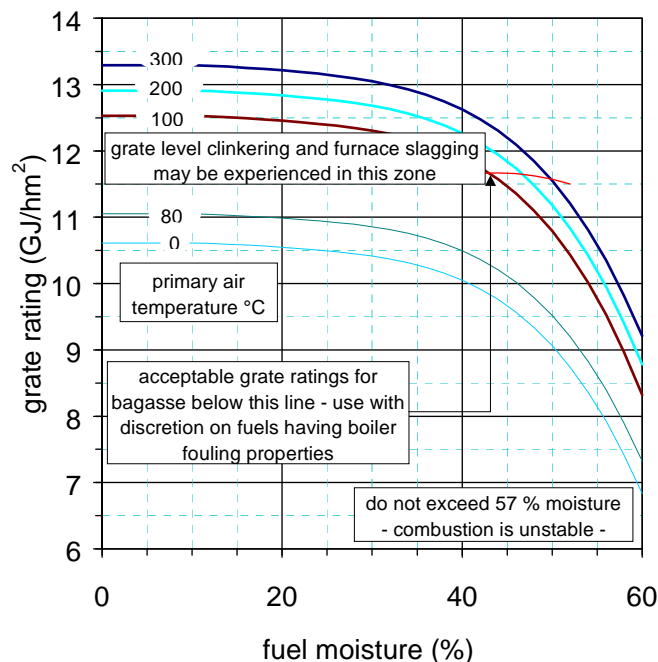

Fig. 2 : Biomass Fuel Stoker Rating

The grate heat release rate is a function of :

- Fuel moisture
- Primary air temperature
- Excess air required to complete combustion
- Furnace temperature
- Gas up-flow velocity
- Particle terminal velocity.

The excess air required to complete combustion as a function of effective fuel moisture is an empirical relationship. The one used in this analysis is a development of that published by Magasiner et al (1984). It is illustrated in Figure 3 :
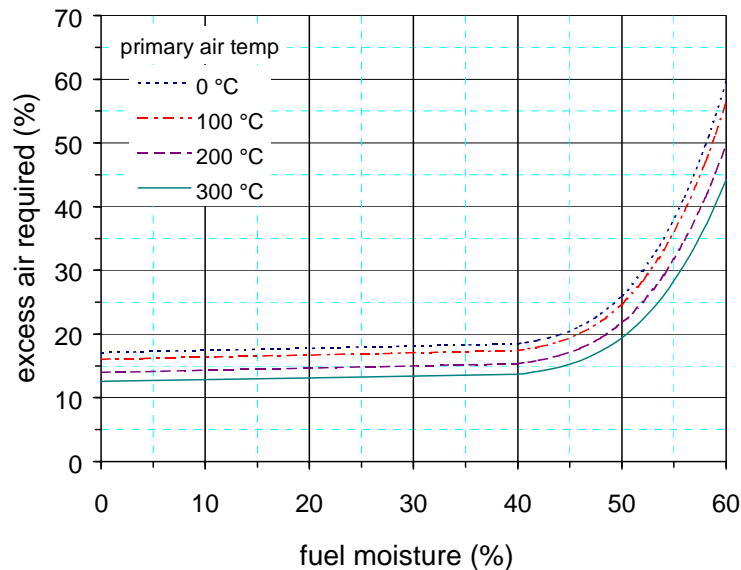

Fig. 3 : Biomass Fuel Excess Air Requirement

Interestingly, at fuel moistures above 50 %, the curve rises very steeply. This is largely because proportionately more primary air is needed to prevent piling. Combustion stability improves when excess air O_2 % [on a wet basis] can be contained within 2,0 and 3,5 % ($\pm$15 to 25 % excess air). As the amount of excess air required reduces as primary air temperature increases, it is best to use high primary air temperatures when burning high moisture fuels.

Furnace temperature and gas up-flow velocity are calculated from a knowledge of the furnace geometry and fuel chemistry. The particle terminal velocity is a function of gas viscosity, gas and particle densities and particle drag coefficient.

In correctly designed furnaces having proper overfire air systems, unburned carbon losses vary from 1 to 5 % depending on fuel moisture. Losses, as with excess air requirements, rise very steeply when fuel effective moisture goes over 52 %.

The effect which a biomass fuel's fouling propensity has on stoker and furnace rating was discussed by Magasiner and de Kock (1985) and again by Magasiner (1987), with special reference to the cane sugar industry. Later in this paper we discuss how ash chemistry can be used quantitatively to evaluate how prone a biomass fuel is to cause fouling and to form clinker and slag.

Coal

Northern Hemisphere coal can often be burned at significantly higher ratings on CAD stokers than most Southern Hemisphere and Indian (Gondwana Land) coal. For the same grate heat release rates, carbon losses from coals having similar proximate and ultimate analyses derived from Northern Hemisphere seams are usually lower than they are from Gondwana Land seams.

In the past, coal was characterised by defining its grading, proximate and ultimate analyses, GCV, ash fusion temperatures and swelling and Hardgrove indices. An understanding of why Gondwana Land coal is so much more difficult to burn and hence why lower stoker ratings are required, can be postulated by bringing its petrography into account.

In this paper, stoker effective area for coal firing is defined as the width of the stoker measured at the grate level times the distance from the center line of the rear wall tubes to the center line of the stoker front shaft.

There are two ways of defining stoker rating for coal burning : as the 'power released per unit of effective stoker area [as for biomass fuels] or as the 'mass of fuel burned per unit of time per unit of effective stoker area [kg/m^{2}h]. Where the ash content is relatively low, say less than 10 %, and where the coal is reactive, the first gives reasonably coherent results. For higher ash content, low reactivity coals, which need a longer time to burn out, the second gives better results. [The reason for this is straightforward. High ash content coals generate large quantities of ash. To get rid of this ash the stoker must be run at a higher speed. As it takes longer to burn out a high ash content coal, particularly if it is not very reactive, this is contrary to what is required to complete combustion. Rating the stoker on a mass per unit area basis automatically builds in a de-rating factor to accommodate this.]

In modern boilers the furnace plan area is closely related to the effective stoker area. Higher stoker ratings, therefore, result in higher furnace gas up-flow velocities. These in turn result in larger particles being carried over into the cooler passes of the boiler where the temperature is too low for combustion to be completed. Small, highly reactive particles, on the other hand, are much easier to burn out in the furnace enclosure. As larger particles are more difficult to burn because their exposed surface area is relatively small, those, which are carried over, have even less chance of burning out than the smaller ones.

This leads to two conclusions for low reactivity coals. Firstly, to provide sufficient time for the coal to be burned out lower gas upflow velocities are needed and hence the stoker rating must be lower than for highly reactive coals. Secondly, to maximise the time that coal is retained in the furnace, as much of it as is possible must be burned on the grate rather than in suspension. The grading of low reactivity coals must, therefore, be coarser than highly reactive coals. A corollary to this last conclusion is that the grading of coarse, low reactivity coals must be more uniform than highly reactive coals in order to ensure that an optimum number of particles land on the grate. Figure 4 (over the page) plots practical gradings for high and low reactivity coals:
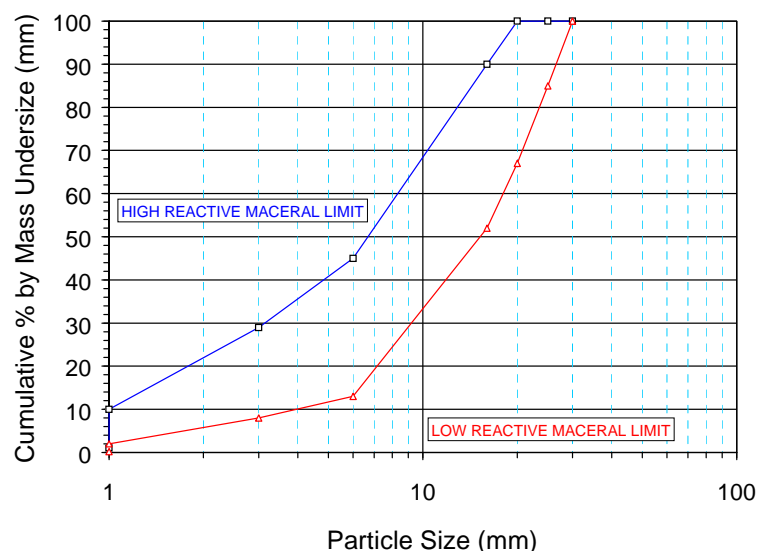
Fig. 4 : Preferred Coal Grading

The Impact of Petrographic Composition on Stoker Rating

Thermo Gravimetric Analysis (TGA) is an experimental tool to establish coal reactivity. TGA reactivity is determined by measuring the rate at which the mass of a burning coal sample reduces with time. Only a few specialist laboratories are equipped to do this type of work. The technique is time consuming and it is rarely possible to use it during the quick turnaround investigative phase of a project. Over the last few years we have attempted to find a more user-friendly method of establishing coal reactivity. Our investigations have led us to the conclusion that relatively inexpensive petrographic analyses are able to provide a practical answer to the problem. TGA is still needed for an in depth study if no process experience with a coal is available.

Coal petrography can be described broadly as the microscopic determination of the organic and inorganic constituents of coal and the degree of metamorphosis, or rank, which the coal has obtained. Petrographic constituents can be directly correlated to important properties affecting the combustion behavior of coal. Differences in coal qualities from differing regions and even within single seams can be readily identified.

The term 'maceral' is used to represent the different plant tissue from which the coal was originally formed. Vitrinite, liptinite (previously called exinite) and inertinite are the main maceral categories. Vitrinite, for instance, is derived from cell walls, cell contents of precipitated gels preserved under water and is relatively oxygen rich. Algae, spores and waxy leaves for example formed liptinite, the hydrogen-rich maceral type. Inertinite originated from plant tissue that had oxidised, altered, degraded or burnt in the peat stage of coal formation, and is carbon rich.

The term microlithotype describes the association of the macerals and mineral matter. The degree of "mixing" of the macerals and the nature of the minerals bound within the coal will influence its mechanical and technological properties. A coal with a higher inertinite content will burn with a longer flame at higher temperatures whilst a vitrinite rich coal will burn more quickly and produce a shorter flame. This often results in boilers designed to burn Northern Hemisphere coal suffering from high steam temperature when burning Gondwana Land coal.

Sanyal (1983) observed that steam temperature was influenced by maceral constituents in a pulverised fuel fired boiler burning Polish and South African coals. He attributed this to the longer time needed to burn out the latter coal compared to the former. Earlier, Yakorskii et al (1968) reported that combustibles in ash were largely the result of incompletely burnt inertinite particles.

Volatile content is often taken as an indication of coal rank. However, two coals with the same volatile content may perform differently. For instance, one may be an anthracite [high rank, low volatile] as is typically found in South Africa's KwaZulu-Natal coal fields, whereas the second may be a heat affected bituminous coal [low rank, low volatile] associated with some coal seams in the Witbank and Highveld coalfields.   Using vitrinite reflectance petrographic techniques [rank analysis], these differences can be readily detected and quantified.

Northern Hemisphere coals usually have a high vitrinite content [> 70 %], with the non-vitrinite fraction being predominantly liptinite.   The inertinite content is usually < 20 %. Gondwana Land coals, on the other hand, have a low vitrinite content [< 60 %], low liptinite contents and high inertinite content [> 40 %]. Vitrinite and liptinite are both reactive. They enhance the rate of combustion. Inertinite has a low reactivity, which retards combustion. Gondwana Land coals are thus inherently less reactive than Northern Hemisphere coals and can therefore only be burned at efficiencies approaching Northern Hemisphere coals at lower stoker ratings.   They also frequently have higher ash contents, which aggravates the problem.

Figure 5 postulates a possible relationship between 'effective reactive macerals' and grate rating for various volatile calorific values.   Effective Re-active Macerals [ERM] for this purpose is arbitrarily defined as :

vitrinite + liptinite + [reactive inertinite + reactive inertodetrinite] / 2.

[inertinite is also known as semifusinite; inertodetrinite is (part of inertinite]
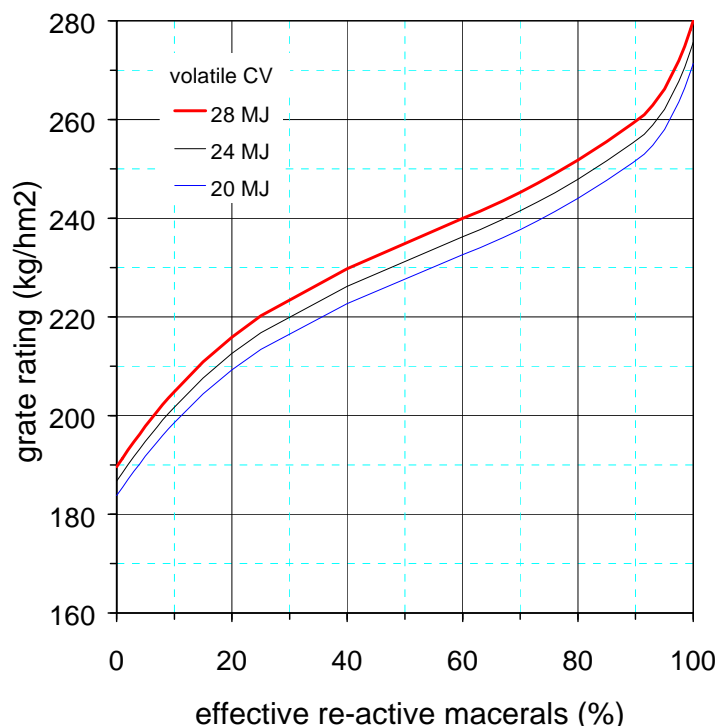
Fig. 5 : Stoker Rating

The curve is distilled from site observations over a period of many years and our in-house records of tests carried out on stoker fired boilers installed in the USA, Colombia and South Africa.   Although the shape of the curve at the higher maceral end is anomalous the maximum rating reflected appears to be substantially correct. In any event, we believe that Fig 5 presents a good basis from which to move forward. Because installation and operating characteristics varied from place to place, the results must be viewed with some degree of caution. The model will be refined as new data becomes available.

The curve has been tempered by a concept, which we term 'ignitability'. This concept, which was developed by John de KOCK, accommodates the fact that portions of the volatile constituents of some coals are inert and therefore instead of promoting ignition, retard it. The ignitability of the volatiles, or volatile energy level, is expressed as it's specific heating value. We have found that if the figure is > 28 MJ/kg the coal will ignite easily. If it is less, ignition difficulties may be experienced. If it is < 18 MJ/kg full-scale tests may be needed to establish a suitable stoker rating.

The amount of excess air required to complete combustion is also a function of the effective reactive maceral content of the coal. Figure 6 postulates a relationship between them. It takes into account ash content and fuel moisture. This curve is also distilled from site observations and our in-house records :
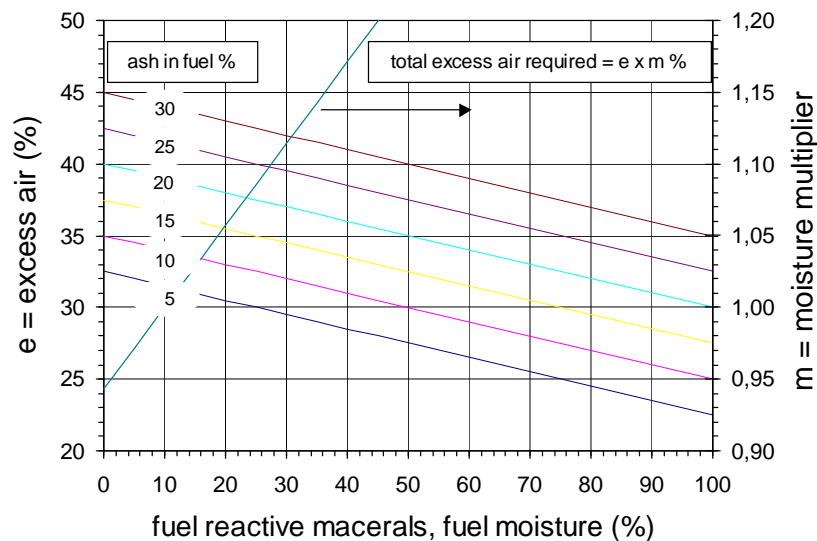
Fig. 6 : Coal Excess Air Requirement

The curves shown in Fig 5 yield reasonable unburned carbon losses. These are a function of :

- Ash % coal
- Grate rating
- Coal grading [maximum size, % minus 1 mm and uniformity coefficient]
- % excess air required to complete combustion
- Furnace geometry and overfire air design
- Furnace upflow velocity
- Gas temperature leaving furnace
- Total effective reactive macerals
- Ash chemistry
- Ash sintering and fusion temperature [reducing atmosphere]
- Undergrate air temperature
- Exfoliation property of coal.

As the total carbon loss is a function of the amount of coal burned, i.e. the amount of ash produced, the calculation is clearly iterative. We have developed algorithms to facilitate these calculations and a computer program to help with their iterative nature.

Typical results for South African and Colombian coals are tabled below:

	South African Coal		Colombian Coal	
	Predicted %	Measured %	Predicted %	Measured %
Coarse ash	1.80	1.72	1.23	2.04
Grit carried over	2.63	2.58	1.68	1.62

Table 3: Predicted vs. Measured Unburned Carbon Losses

We believe that the higher than expected Colombian coarse ash loss is due to the fact that in this instance the stoker runs from the front of the furnace to the rear rather than the conventional rear to front. With the arrangement as installed, it is possible to throw coal into the ash pit without giving it a chance to burn.

Dual Fuel Operation

Grate rating and excess air are the two main parameters which affect unburned carbon loss and carbon monoxide production. The amount of excess air required is affected by the way in which the primary air is introduced into the furnace. To achieve best results, particularly on dual fired installations, it is important to be able to control how this air is introduced along the length of the stoker; i.e. from front to back. To achieve this objective, the stoker must be zoned as is shown in Fig 1.

Fig 7 shows the auto-controlled zoning dampers installed on a 100 t/h bagasse/coal fired boiler. Zoning is also advantageous on single fuel units where high efficiencies are required or where stringent emission limits have to be achieved :

Fig. 7 : View of TES Auto-controlled Zoning Damper Operating Gear

Clinker and Slag Formation, Boiler Fouling

Minerals in fuels transform on heating to form ash. The propensity of a fuel to establish problematic formations depends on its elemental volatility and the viscosity of resultant ash. Volatility of the fuel is dependent on the proportion of organically bonded elements and temperature. The viscosity depends on the chemistry of the ash, localised conditions (oxidising/reducing) and temperature.

Clinker and Slag Formation

Low viscosity ash is molten and will readily coalesce to form a large molten mass or cause the agglomeration of bed particles on the stoker grate. This is called clinker. Unlike pulverised fuel fired boilers, stoker fired boilers have a longer residence time, which favours the formation of clinker. As the molten mass is cooling, mineral phases can crystallise out of the melt, which is the catalyst for the formation of hard clinkers. In contrast, a high viscosity, 'dry' ash does not coalesce readily, thus restricting the formation of clinkers.

A slag deposit is formed when a molten ash particle, transported by updrafts, collides into the furnace wall. Alternatively, if the heat transfer surface is covered with a molten, sticky slag layer then it is highly probable that 'dry' ash particle will also adhere to the surface.

A sintered deposit can also form when particles at high temperature impact on heat transfer surfaces. Sintering is a complicated process, encompassing a variety of phenomena that take place when a powder is transformed into a compact material (Nowok, 1996). Contrary to the objective of the ceramics and glass industries, which is to enhance the strength of materials through sintering, boiler designers try to prevent high strength deposits growing on heat transfer surfaces.

Different approaches can be used to predict the clinkering/slagging propensity of a fuel. The common approach is to measure ash deformation temperatures under reducing and oxidising conditions or to use the numerous slagging indices which are available and are based on the acid [SiO_2, Al_2O_3] to base [CaO, MgO, K_2O, Fe_2O_3 and Na_2O] composition of the ash. The table below schedules values for two of these indices when it is unlikely that clinker/slagging problems may occur, when they may occur and when it is almost certain that they will occur :

	slagging unlikely	slagging possible	slagging probable
Slagging Index A	< 0.6	0.6 to 2.6	> 2.6
Slagging Index B	> 1340	1340 to 1150	< 1150

Table 4: Typical Slagging Indices

Index A is the product of the base/acid ratio and the total sulphur content while Index B is the [maximum hemisphere temperature plus four times the minimum initial deformation temperature[/ 5. These indices should be used as a general guideline as it is common knowledge that indices based on Northern Hemisphere coals are not necessarily applicable to Southern Hemisphere coals. These observed differences could be attributed to differences in coal formation environments and the nature of the mineralogy. For instance, if the major Fe-bearing mineral is siderite ($FeCO_3$) and not pyrite (FeS_2) then slagging index A is not necessarily applicable.

In comparison to coal, biomass is likely to have a higher proportion of alkali-earth elements [K, Ca, Mg and Na] which are organically bound [attached to carbon structures] rather than associated with minerals. On combusting biomass, these elements are volatile and create a fume, which can initiate slag formation. Thus applying a slagging index designed for coal is not necessarily applicable to biomass.

An alternative approach to slagging indices is to use phase diagrams. If applied correctly, phase diagrams can also be used to predict the melting temperatures of the ash much more quickly than laboratory techniques. The compilation of phase diagrams dates back more than 100 years. F.P. Hall and H. Insley published 178 diagrams in the October 1933 issue of the American Ceramic Society Journal These are still used today.

The two critical temperatures derived from a phase diagram are the solidus and liquidus temperatures. During the heating of a solid, the solidus (S_h) is the temperature at which the solid will start melting and the liquidus (L_h) is the temperature at which melting is complete. During cooling, the liquidus (L_c) is the temperature at which the first phase will crystallise from the molten melt and the solidus (S_c) is the temperature when crystallisation is complete.

Thus, phase diagrams can be used to predict the temperature at which phases will melt during heating (solidus S_h)) or the temperature (liquidus L_c) at which phases will start crystallising from a molten mass during cooling. In terms of predicting slagging propensity of a coal/biomass mixture the solidus (S_h) will be an indication of the temperatures at which 'sticky' fly ash particles are likely to be formed. In terms of forming solid clinkers, the liquidus (L_c) temperature is an indication of when the crystals will start crystallising from the melt and will be the initiation (like a catalyst) of clinker formation. Alternatively, the solidus (S_h) is an indication of the final sintering temperature.

In addition to predicting melting and clinker formation and sintering temperatures, phase diagrams can be used to predict the composition of the clinkers and possibly obtain an idea of the temperature history to which the clinker was exposed.

Depending on the number of elemental components, a binary, ternary or quaternary phase diagram is used. Based on the distribution of the components in the ash analysis, a phase diagram is selected and the ash elemental analysis is normalised and plotted.

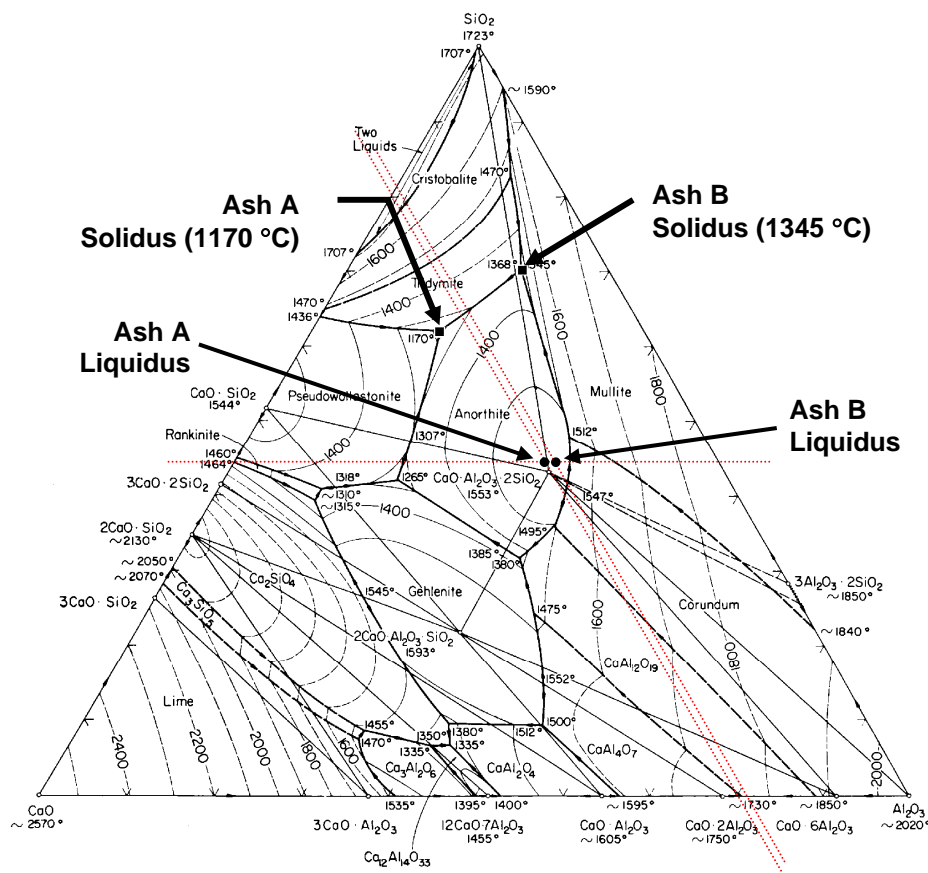In a ternary phase diagram, each point of the triangle represents 100% of that component :

Fig. 8 : CaO-Al$_2$O$_3$-SiO$_2$ phase diagram.

The diagram is taken from Osborn and A.Muan. A circle indicates liquidus temperature [Lh totally molten] and a square indicates the solidus temperature [Sh start melting] for idealised compositions A and B.

The liquidus point can be easily defined by the composition of the three ash components selected. The solidus point depends on which of the many compounds present will melt first. The diagram shows that an ash with 45% SiO_2, 20% CaO and 35% Al_2O_3 [composition A] will start melting at 1 170 °C, whereas an ash with 45% SiO_2, 19% CaO and 36% Al_2O_3 [composition B] will start melting at 1 345 °C. Thus a 1% difference in the Al_2O_3 and CaO content results in 175 °C variation in predicted melting points. Interpreting a complex phase diagram such as the SiO_2-Al_2O_3-CaO diagram requires a good understanding of the principals of phase diagrams and what they represent and hence how to move from composition A or B to the respective solidus temperatures.

Phase diagram selection is dependent on the dominant elemental components of the ash. Ideally, the components should account for more than 90% of the total elemental composition. For example, Table 5 shows typical ash analyses for a coal, straw and bagasse. If coal and bagasse were to be combined in variable proportions, then the CaO-Al_2O_3-SiO_2 phase diagram would not be suitable because the Fe_2O_3 and K_2O contents of the ash are too high. A quaternary diagram for CaO-Al_2O_3-Fe_2O_3-SiO_2 or K_2O-Al_2O_3-Fe_2O_3-SiO_2 might be better. Complex software is available for predicting liquidus and solidus temperatures for these complex quaternary phase diagrams.

	Straw	Bagasse	Coal
Al_2O_3	3.63	7.70	29.10
CaO	12.48	2.04	5.05
Fe_2O_3	2.09	11.60	3.39
K_2O	16.43	3.58	0.40
MgO	2.49	1.50	2.10
Na_2O	1.23	0.50	0.50
SiO_2	55.66	68.30	52.90
SO_3	3.97	1.27	3.40
TiO_2	0.22	0.95	1.48
P_2O_5	2.72	0.83	1.49

Table 5 : Analysis of Fuels

Based on the analyses of Table 5 and the hypothetical example quoted above, mixing bagasse [similar to A] with coal would be less likely to cause slagging than mixing straw [similar to B] with coal. This is attributed to the comparatively high proportion of K_2O, SO_3, CaO and P_2O_5 and predicted lower solidus temperature [S_h start melting] for the straw.

Boiler Fouling

The condensation, adherence and later sintering of volatile ash components on to convection heating surfaces causes fouling. The volatile components are usually the alkali metal oxides [K_2O and Na_2O]

There are a number of indices, which point to fouling with biomass fuels. The ratio of the alkali metal oxides to silica [$(K_2O+Na_2O)/SiO_2$] (Magasiner & De Kock, 1987) and to the gross calorific value [(K_2O+Na_2O) x % ash/GCV)] (Miles et al, 1995) have been found to be reliable indicators. These two indices supplement each other. Because the latter measures the absolute amount of alkali metal oxides per unit of heat input it may not indicate a potential fouling problem when the total ash content of the fuel is small and the alkali metal oxide to silica ratio is very high.

On the other hand the first may overstate the potential problem when this ratio is moderate or perhaps high even though the total amount of the offending materials is too small to affect the commercial operation of the plant. Table 6 below schedules values for these indices when it is unlikely that fouling problems may occur, when they may occur and when it is almost certain that they will occur :

	fouling unlikely	fouling possible	fouling probable
TES Index	< 0,17	0,17 to 0,34	> 0,34
DOE Index	< 0,10	0,10 to 1,00	> 1,00

Table 6: Fouling Indices

Fouling when burning coal is more complex due to the presence of sulphur, which allows calcium oxides to volatilise. However, coal is assumed to be a fouling fuel and hence coal fired boilers are invariably fitted with sootblowers. This means that the more important parameter in fouling from coal is the mechanical strength of the ash deposit.

Recent work undertaken in Europe (Heinzel et al, 2000; Platbrood & Van der Elst, 2000) and published last year in the USA presents a correlation between the elemental signature of the ash and its sintered strength. The relationship is complex. In general it indicates that the alkali metal oxides and calcium oxide increase the compressive strength and that aluminium and iron oxides reduce it.

The biggest challenge is to predict when clinkering, slagging and fouling will occur when mixed firing. The only solution is to predict the likely ash chemistry from the expected proportion of each fuel being burnt. The same techniques as have been discussed for the individual fuels can then be applied, a decision being required as to which is most relevant. We are not aware of any solid scientific basis for predicting results confidently at this stage. Previous experience with the fuels is an invaluable aid in minimising risk.

Conclusions

Biomass fuels, and bagasse in particular, can be readily characterised with respect to their combustion performance. Grate rating, the amount of excess air required to complete combustion and combustion efficiency are all a function, interalia, of fuel moisture. Because it is the ratio of moisture to combustible material that determines how well a fuel will burn it is important to determine the "effective" moisture of a fuel by factoring ash content into the equation. Increasing the ash content effectively increases this ratio. Well proven methods such as the SMRI formula can be used to define bagasse calorific value. Similar formulae, without brix corrections, can be used for other fuels.

The amount of excess air needed to complete combustion rises rapidly as effective fuel moistures increase above about 50 %.

Grate rating can be defined as a function of effective fuel moisture and primary air temperature. This relationship is also dependent on excess air required to complete combustion, furnace temperature, gas up-flow velocity and particle terminal velocity.

Biomass fuels, having ash contents of less than 8 %, can generally be burned on stationary grates. If they have higher ash contents it may be better to burn them on CAD stokers.

Coal is often used as an auxiliary fuel in biomass fired co-generation power stations. Because of the need to get rid of the large quantities of ash generated by this fuel, CAD stokers are used on this type of installation

Thermo Gravimetric Analysis can be used in the laboratory to determine the relative performance of a particular coal. In practice, the method has its limitations because specialised equipment must be used to carry out the tests. We believe that maceral analysis can be used instead. In this paper we have postulated a relationship between what we define as the 'effective re-active maceral' content of a coal and the amount that can be burned at reasonable efficiency per unit area of grate. We have also defined a relationship between this parameter and the amount of excess air needed to complete combustion.

These relationships were developed from data collected from a number of geographical areas. Because installation characteristics varied from place to place, the results must be viewed with some degree of caution. They have, however, so far proved reasonably reliable. The analysis will be fine-tuned as more data is collected in the future.

The use of phase diagrams to determine the effect which ash chemistry has on the potential of a fuel to form clinker on the grate and slag on the furnace walls is dealt with. This type of analysis is shown to be of particular importance in determining how the ashes of coal and biomass fuels can react detrimentally to enhance the formation of clinker and slag.

The use of ash chemistry to determine whether a biomass fuel has the potential to cause boiler fouling is discussed. Two fouling indices are identified for this purpose. These indices have proved reasonably reliable practical indicators.

When a boiler is fired with such disparate fuels as biomass and coal the boiler designer needs a thorough understanding of the fuel characteristics. It is not only necessary to be able to size the equipment but to be able to predict unburned carbon loss, the amount of excess air required to achieve this loss and the potential for boiler fouling and clinker and slag formation. Zoning the stoker (Page et al, 2000) along its length provides a useful tool to help optimise combustion and minimise emissions.

TABLE 1
FUEL AND SITE DATA

SITE	Illovo Sugar Ltd - UBOMBO MILL
site altitude (masl)	118
ambient air temperature (°C)	29
FUEL	Bagasse
SOURCE OF SAMPLE (Colliery if applicable)	Ubombo Mill

FUEL ANALYSES				ASH ANALYSES				
PROXIMATE ANALYSES (as received)				Silica	SiO_2	%		68.30
Fixed carbon	%	6.40		Alumina	Al_2O_3	%		7.70
Volatiles	%	40.87		Titania	TiO_2	%		0.95
Moisture (inherent)	%	5.40		**total acid**		%		76.95
Moisture (free)	%	45.78		Ferric oxide	Fe_2O_3	%		11.60
Ash	%	1.55		Lime	CaO	%		2.04
TOTAL	%	100.00		Magnesia	MgO	%		1.50
Brix (for bagasse)	%	2.46		Potassium oxide	K_2O	%		3.58
ULTIMATE ANALYSES (as received)				Sodium oxide	Na_2O	%		0.50
Carbon	%	22.12		**total base**		%		19.22
Hydrogen	%	2.81		Sulphur trioxide	SO_3	%		1.27
Sulphur	%	0.06		Phosphorous pentoxide	P_2O_5	%		0.83
Nitrogen	%	0.18		Loss on ignition		%		0.85
Oxygen BY DIFFERENCE	%	22.10		**total other**		%		2.95
Moisture	%	51.18		**TOTAL**		%		99.12
Ash	%	1.55						
TOTAL	%	100.00		**TRACE ELEMENTS**				
				Cadmium	Cd	ppm		N/A
GCV (smri)	kJ/kg	9 191		Mercury	Hg	ppm		N/A
NCV (smri)	kJ/kg	7 304		Antinomy	Sb	ppm		N/A
				Arsenic	As	ppm		N/A
BULK DENSITY (as received)	kg/m3	79		Lead	Pb	ppm		<70
				Selenium	Se	ppm		N/A
FREE SWELLING INDEX (for coal)		N/A		Zinc	Zn	ppm		4.7
HARDGROVE INDEX (for coal)		N/A						
				Chrome	Cr	ppm		36.4
CONSTITUENTS IN FUEL (air dried)				Copper	Cu	ppm		40.7
Phosphorous	%	N/A		Manganese	Mn	ppm		58.9
Chlorine	%	N/A		Nickel	Ni	ppm		N/A
Flourine	%	N/A		Vanadium	V	ppm		0.6
				Tin	Sn	ppm		N/A
MACERAL ANALYSIS (for coal)								
Vitrinite	%	N/A		**ASH FUSION TEMPERATURES - reducing atmosphere**				
Liptinite (Previously Exinite)	%	N/A		Initial Deformation Temperature		°C		1 310
Inertinite - reactive semi-fusinite	%	N/A		Sintering Temperature		°C		1 400
Inertinite - reactive inertodetrinite	%	N/A		Hemispherical Temperature		°C		+1 400
Inertinite - balance	%	N/A		Flow Temperature		°C		+1 400
Total reactive macerals	%	N/A						
Total effective reactive macerals (TES definition)	%	N/A		**ASH FUSION TEMPERATURES - oxidising atmosphere**				
Vitrinite reflectance	%	N/A		Initial Deformation Temperature		°C		1 380
Rank category		N/A		Sintering Temperature		°C		+1 400
				Hemispherical Temperature		°C		+1 400
FUEL GRADING				Flow Temperature		°C		+1 400
Particle Size								
30 mm minus		N/A						

Analysed by: C&N Coal Consultancy

Johannesburg

Signature: Nikki WAGNER

Date: 8th Nov 1999   **ref No.**   99164

Particle Size		
30 mm minus		N/A
25 mm minus		N/A
20 mm minus		N/A
16 mm minus		N/A
6 mm minus		31.2
3 mm minus		N/A
1 mm minus		N/A
0,1 mm minus		N/A

TABLE 2

FUEL AND SITE DATA

SITE	Illovo Sugar Ltd - UBOMBO MILL
site altitude (masl)	118
ambient air temperature (°C)	29
FUEL	Coal
SOURCE OF SAMPLE (Colliery if applicable)	Strathrae Colliery

FUEL ANALYSES

PROXIMATE ANALYSES (as received)

Fixed carbon	%	57.40
Volatiles	%	24.20
Moisture (inherent)	%	1.68
Moisture (free)	%	2.12
Ash	%	14.60
TOTAL	%	100.00
Brix (for bagasse)	%	N/A

ULTIMATE ANALYSES (as received)

Carbon	%	67.90
Hydrogen	%	3.50
Sulphur	%	0.30
Nitrogen	%	1.82
Oxygen BY DIFFERENCE	%	8.08
Moisture	%	3.80
Ash	%	14.60
TOTAL	%	100.00

GCV	kJ/kg		26 620
NCV	kJ/kg		25 821
BULK DENSITY (as received)	kg/m3		817
FREE SWELLING INDEX (for coal)			0.0
HARDGROVE INDEX (for coal)			49

CONSTITUENTS IN FUEL (air dried)

Phosphorous	%	0.098
Chlorine	%	0.006
Fluorine	%	0.002

MACERAL ANALYSIS (for coal)

Vitrinite	%	20.6
Liptinite (Previously Exinite)	%	4.4
Inertinite - reactive semi-fusinite	%	23.2
Inertinite - reactive inertodetrinite	%	22.2
Inertinite - balance	%	20.6
Total reactive macerals	%	72.2
Total effective reactive macerals (TES definition)	%	52.2
Vitrinite reflectance	%	0.6
Rank category		Medium C

FUEL GRADING

Particle Size

30 mm minus		0.0
25 mm minus		100.0
20 mm minus		92.2
16 mm minus		81.6
6 mm minus		14.6
3 mm minus		7.9
1 mm minus		3.3
0,1 mm minus		0.5

ASH ANALYSES

Silica	SiO_2	%	52.90
Alumina	Al_2O_3	%	29.10
Titania	TiO_2	%	1.48
total acid		%	83.48
Ferric oxide	Fe_2O_3	%	3.39
Lime	CaO	%	5.05
Magnesia	MgO	%	2.10
Potassium oxide	K_2O	%	0.40
Sodium oxide	Na_2O	%	0,50
total base		%	11.44
Sulphur trioxide	SO_3	%	3.40
Phosphorous pentoxide	P_2O_5	%	1.49
Loss on ignition		%	0.65
total other		%	5.54
TOTAL		%	100.46

TRACE ELEMENTS

Cadmium	Cd	ppm	N/A
Mercury	Hg	ppm	N/A
Antimony	Sb	ppm	N/A
Arsenic	As	ppm	N/A
Lead	Pb	ppm	<70
Selenium	Se	ppm	N/A
Zinc	Zn	ppm	12.1
Chrome	Cr	ppm	95.1
Copper	Cu	ppm	4.6
Manganese	Mn	ppm	99.9
Nickel	Ni	ppm	N/A
Vanadium	V	ppm	3.9
Tin	Sn	ppm	N/A

ASH FUSION TEMPERATURES - reducing atmosphere

Initial Deformation Temperature	°C	+1 400
Sintering Temperature	°C	+1 400
Hemispherical Temperature	°C	+1 400
Flow Temperature	°C	+1 400

ASH FUSION TEMPERATURES - oxidising atmosphere

Initial Deformation Temperature	°C	+1 400
Sintering Temperature	°C	+1 400
Hemispherical Temperature	°C	+1 400
Flow Temperature	°C	+1 400

Analysed by: C&N Coal Consultancy

Johannesburg

Signature: Nikki WAGNER

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References

Don C E, Mellet P, Ravno B D, and Bodger R (1977) Calorific Values of South African Bagasse. *Proceedings of The South African Sugar Technologists' Association,* pp 169 -173

Magasiner N and De Kock J, (1987). Design Criteria for Fibrous Fuel Fired Boilers. *Institute of Energy, London in Energy World*

Magasiner N, Naude D P and McIntyre P J (1977) Operating Experience on Single and Three Pass Boilers in the Cane Sugar Industry with Particular Reference to Erosion and Drum Water Level Stability*. Proceedings of The South African Sugar Technologists' Association,* pp 123 - 129

Magasiner N (1987) The Effect of Fuel Moisture Content on the Performance of a Typical Bagasse Fired Watertube Boiler *Proceedings of The South African Sugar Technologists' Association, pp 86 - 89.*

Sanyal A (1983) The role of coal macerals in combustion. *Journal of the Institute of Energy, p 9.*

Yarkorskii et al (1968) Influence of the petrographic composition of coal on the efficiency of pf fired furnaces *Teploenergetika*.

Miles P.E T R, Miles Jn T R, Baxter L L, Bryers R W, Jenkins B M, Oden L L (1995) Alkali Deposits Found in Biomass Power Plants – A preliminary Investigation of Their Extent and Nature *Summary Report for National Renewable Energy Laboratory.*

Nowok J W (1996) Densification, Shrinkage and Strength Development in Selected Coal Ashes. *Journal of the Institute of Energy,* pp 9 -11.

Heinzel ., Lopez Ch, Maier J, Spliethoff H, Hein K R G (2000) Ash, deposit and corrosion characteristics of coal-biomass blends in a O.JMW pulverized fuel test facility. *Effects of coal quality on power plant management. Park City Marriott Hotel, May 8-11, 2000, Park City, Utah.*

Platbrood G, Van der Elst W (2000) Correlation of fouling and slagging characteristics with origin and quantitative mineral ash constitution of coals obtained after low temperature ashing and X-ray diffraction analysis by the Rietveld method. *Effects of coal quality on power plant management Park City Marriott hotel, May 8-11, 2000, Park City, Utah.*

Page B, McIntyre P and Verbanck H (2000) Operating Experience with High Combustion Efficiency Continuous Ash Discharge Stokers. *Proceedings of The South African Sugar Technologists' Association, pp 290 - 294.*