NUMERICAL ASSESSMENT OF DEPOSIT SINTERING FOR COAL-BIOMASS CO-COMBUSTION

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Abstract
Biomass as a single fuel is still unable to satisfactorily replace coal as an energy resource in terms of thermal efficiency. Co-firing of biomass in existing coal-fired utility boilers is the immediate solution for reducing CO_2 emissions. However, ash deposition is a major problem to biomass-fired power generators. In this paper, a numerical slagging index based on the ash fusibility, viscosity and chemistry have been employed. The results of predictions correlate well with the reported experiment data for Russian coals-biomass blends, while the results of predictions using South African coal show significant inconsistencies with the experiment data on most of the tested biomass. The findings of this numerical assessment provide a generic numerical technique for assessing the slagging potential of coals/biomass blends in boilers.

Keywords: *Deposit; Sintering; Coal; Biomass; Slagging indices.*

Introduction

The strategy outline in the Kyotol Protocol is to obtain a target of 12.5% reduction of green house gasses by2012. Specifically, the UK has targeted the reduction of carbon dioxide by 20% by 2010, 60% by 2050 and as high as 80% by 2100 with the 1990 level taken as a basis (EC, 2011).The utilisation and development of biomass technologies is an important part of the program. This has led to growing interest in co-firing and many researchers have focused on improving the efficiency of coal and biomass combustion (Williams*et al.*, 2000).

However, the implementation of co-firing in existing coal-fired facilities is still under investigation. So far, the feasibility of different combustion systems has pointed out that the management of slagging and fouling problems are major issue that requires a much better understanding (Khodier, 2012, Niu *et al.* 2011, Ma *et al.* 2006, Gupta *et al.*, 1998). The different types of biomass sources intended for co-firing include wood residue, agricultural residues, energy crops and sewage sludge.
As yet, there are no available tools that can predict the slagging and fouling properties of a given fuel unequivocally. The ash fusion temperature, ash viscosity, and ash chemistry are the three basic tools for characterizing coal ash slagging and deposits during combustion (Degereji et al., 2011). Most of the ash deposits are derived from the inorganic components of coal, biomass and their blends (Degereji *et al.*, 2011, Garba *et al.*, 2012).

Numerical prediction of ash deposition is used to advance the understanding of the underlying processes that lead to deposit formation, and it is considered as a powerful tool for the design and optimization of the operating parameters. Several attempts have been made to accurately predict the slagging behaviour of solid fuels in boiler situations. The most commonly applied index is the basic-to-acid (B/A) ratio. Increasing the B/A of coal decreases its fusibility and hence increases the slagging potential. Coals having B/A $\geqslant$0.11 are considered as bad coals (Gupta *et al.*, 1998). There are many similar indices to describe ash behaviour of coal and biomass. However, it is difficult to extrapolate a specific value for coal blended with biomass because biomass significantly differed in chemical properties. At relatively low levels of co-firing biomass, alumino-silicate is predominant in the coal ash and the coal slagging index remains valid. However, at higher co-firing ratios, the fluxing agents in the biomass ash become very important and the coal slagging index cannot be applied to biomass with confidence.
The main objective of the present investigation is to employ a numerical slagging index to predict the slagging tendency of various coal/biomass blends in co-firing scenarios. In this paper, a numerical slagging index for coal/biomass blends, based on earlier development of a numerical slagging index which was found to successfully predict slagging potential of various coal/biomass blends (Garba *et al.*, 2012). The numerical slagging index for coal/biomass blends has been tested on two different sets of experimental data in order to understand the influence of the blending ratios on slagging potential.

Numerical Modelling

The coal numerical slagging index is generally expressed in terms of the incoming ash, γ, and the viscosity of the ash, μ, as follows :

$$S_x = \gamma / \log(\mu) \tag{1}$$

The incoming ash γ is defined as follows (Degereji *et al.*, 2010):

$$\gamma = \frac{ash\ content\ per\ kg}{CV\ (MJ/kg)} \tag{2}$$

For coal/biomass blends, we can predict the effects of the biomass addition on the deposit sintering by determining the viscosity of the blend ash from the ash content and the ash chemistry of the individual fuels (Wigley *et al.*, 2007, McLennen *et al.*, 2000, Backman *et al.*, 1997). Thus, the weight of the incoming ash has been defined in terms of the content of the ash and the heating value of the individual fuels as follows:

$$\gamma = x(\gamma_c) + y(\gamma_b) \tag{3}$$

where x, y, γ_c and γ_b are the weight percent of the coal in the coal-biomass mixture, the weight percent of the biomass in the coal-biomass mixture, the weight of coal ash and the weight of biomass ash, respectively. The softening temperature (T_s) has been redefined to account for the softening temperatures of both the coal (T_c) and the biomass (T_b) as follows:

$$Log(\mu) = \frac{10^7 . m}{T_s} + c \tag{5}$$

Although the ash fusibility is not the only popular bases of characterizing ash deposition and slagging that must be taken into consideration when choosing the coal/biomass for a given application, it is the most important parameter used in assessing the strength of the fouling or slagging on the heat transfer surfaces of boilers. The sintering tendency depends on the ash fusion temperatures, such as the initial deformation temperature (IDT), softening temperature (ST), hemispherical temperature (HT) and flow temperature (FT) (Niu *et al.*, 2011). Numerous studies (Munir *et al.*, 2010, Abbas *et al.*, 1996, Jenkins *et al.*, 1998, Niu *et al.*, 2011) have expressed the fusibility of the ash as a function of the content of the acidic oxides (A) and basic oxides (B) commonly found in coal ash: A (SiO_2, Al_2O_3, TiO_2) and B (Fe_2O_3, CaO, MgO, Na_2O and K_2O). The ratio, B/A initially introduced for fossil fuels is the most commonly used parameter for correlating the ash fusibility with its composition. However, research has consistently shown that this approach can only yield good results if it is restricted to a small number of biomasses which have a very low phosphorus content (grasses, cereals and woods) but it is ineffective if it is applied to a large number of biomasses which have very high phosphorus content (processing by-products).

For a more accurate prediction of the ash fusibility, the effect of the phosphorus on the ash fusibility needs to be taken into account. A considerable fraction of pentoxide can facilitate the melting of the fly ash which can reduce the fusion temperature because of it low HT (569 °C) (Jenkins *et al.*, 1998).

In equation (5) the term T_s can be postulated as presented below using the softening temperature of the coal (T_c) and that of biomass (T_b), and their respective weight percent in the blend, as follows:

$$T_s = xTc^2 + (y/k)T_b^2 \tag{6}$$

where

$$T_c = a(SiO_2) + b(Al_2O_3) + c(Fe_2O_3) + d(CaO) + e(MgO) + f(\alpha) + g + 150^0 C \tag{7}$$

$$T_b = 1.81(CaO) + 4.20(Al_2O_3) - 2.41(K_2O) + 5.31(P_2O_5) + 1017^0 C \tag{8}$$

where the factor, *k* in equation (6), is introduced based on the basic-to-acidic oxides (B/A), or fluxing-to-sintering oxides (B+P_2O_5)/A and it is determined as follows:

$$k = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2} \tag{9}$$

or

$$k = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + P_2O_5}{SiO_2 + Al_2O_3 + TiO_2} \qquad (10)$$

Therefore, the empirical model proposed in equation (1) to (10) is expected to predict the degree of sintering of the coal and biomass blends, while using one of the sub-models for the overall softening temperature presented in equations (9) to (10).

Test Case

The work of Wigley *et al.*, 2007 was used as a test case for the numerical assessment of deposit sintering for coal-biomass co-combustion. After co-combustion of coal-biomass of EFR, deposits collected on the probes of the EFR were coated in an epoxy resin and cut to reveal a cross-section. Two cross-sections of the deposit were mounted in resin and polished for analysis in the scanning electron microscope (SEM). A more detailed description of the reactor can be found in (Hutchings *et al.*, 1996). The rate of the deposits sintering collected from the deposition of an entrained flow reactor during a co-firing test using the Russian and South African coals with five types of biomasses (miscanthus and short rotation coppice (SRC); olive residue and palm kernel expeller cake; and sawmill residue), with biomass addition of 0 wt %, 20 wt %, 40 wt % and 60wt % %, have been reported(Wigley *et al.*, 2007). The ash content and chemical composition for the coals and biomasses are presented in Table 1 (Wigley *et al.*, 2007).

Table 1.
Coal and biomass ash content (wt %) and chemical composition (wt %) (Wigley, Williamson, Malmgren and Riley, 2007; Phyllis, 2004).

Proximate analysis Wt % on dry basis			Ash composition		
Component	R. coal	S. coal	Component	R. coal	S. coal
Volatiles	30	36	SiO_2	60.1	54.1
Fixed carbon	76	73	Al_2O_3	24.0	33.5
Moisture	5.56	5.47	Fe_2O_3	6.0	3.1
Ash	12.6	12.1	CaO	4.1	4.1
CV(MJ/kg)	27	26.7	MgO	1.1	1.3
Ultimate analysis Wt % on dry basis			K_2O	3.0	0.7
C	76.5	68.67	Na_2O	0.4	0.1
H	4.5	4.66	TiO_2	1.2	1.7
O	4.9	26.54	MnO	0.1	0.0
N	1.9	1.78	P_2O_5	0.0	1.4
S	0.4	0.83			
Cl	0.25	0.00			

Results and Discussion

This section presents the predicted results using the numerical slagging index developed, and it compares the predicted results against the experiment data for two cases; Russian coal (R. coal) and South African coal (S. coal) with five types of biomasses. The two sub-models presented in equations (6) to (9) for the overall softening temperature of the coal/biomass blend are identify as the basic-to-acidic oxides (B/A), and fluxing-to-sintering oxides $(B+P_2O_5)/A$. A computer program was developed to calculate the slagging index based on the given sub-models.For the South African coal, the ranking from the microstructures of the deposits from experiment was: Sawmill<SRC<Miscanthus<Olive<Palm. Comparing the result of predictionin Figure 1 and 2 with the experiment shows that the model predicted the experimental trend up to 20wt %biomass addition (Sawmill<SRC<Miscanthus<Olive<Palm) but fail to delivers accurate prediction at 40wt %(Sawmill<Miscanthus<SRC<Olive<Palm)and 60wt %biomass additions (Sawmill<Miscanthus<SRC<Olive<Palm). The deviation of the model prediction is higher at 60wt % than at 40wt %biomass addition. Miscanthus, which has a high K_2O content, shows higher degree of sintering of deposits for the South African coal because this coal has a much lower K_2O content than the Russian coal.
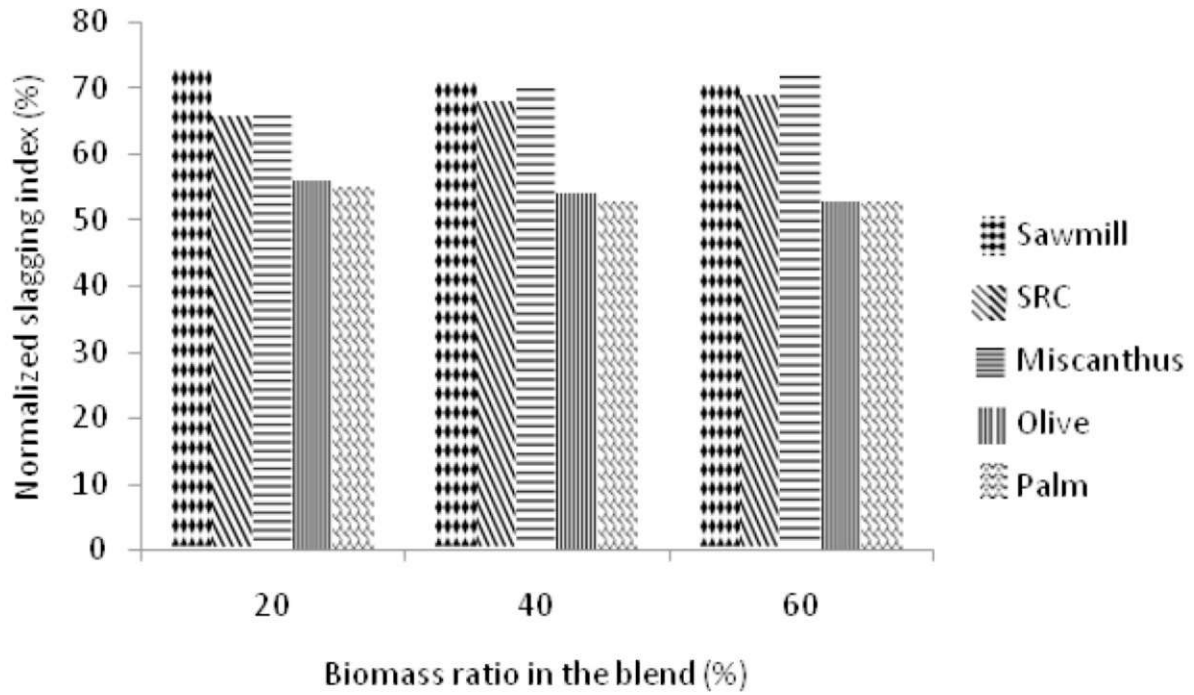
Figure1: The degree of sintering for a mixture of South Africa coal with biomass based on B/A sub-model 1.
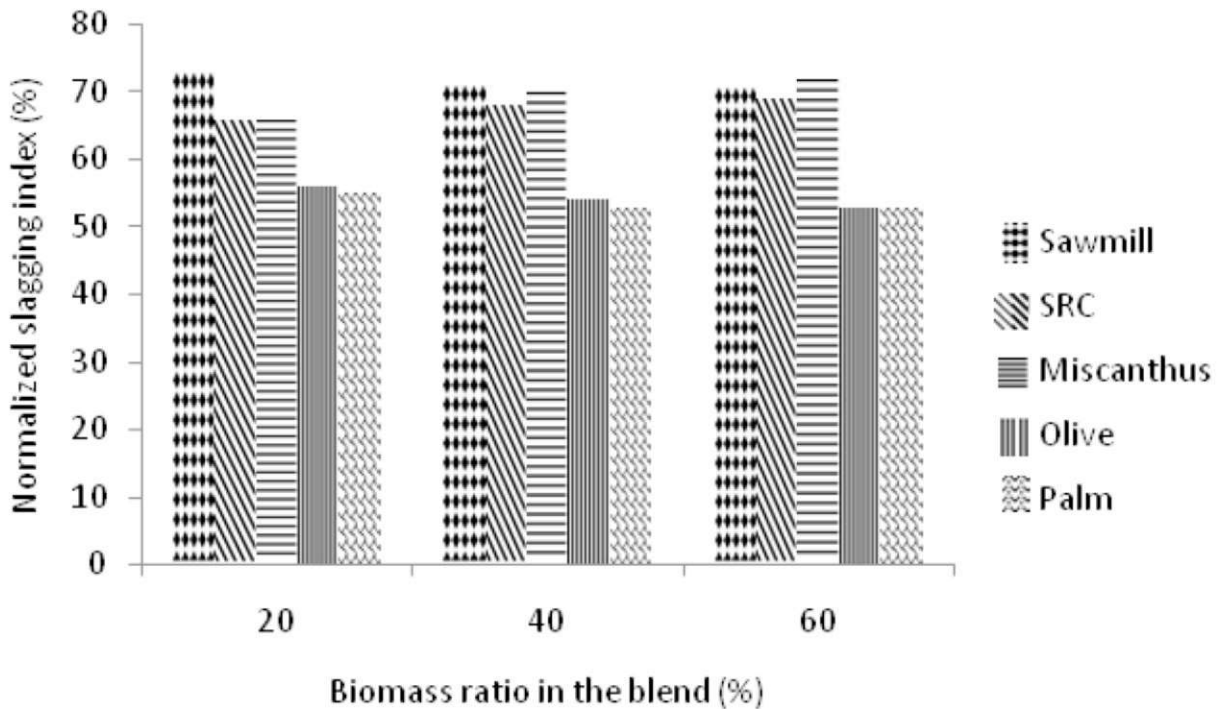

Figure 2: The degree of sintering for a mixture of South Africa coal with biomass based on B/A sub-model 2.

Since the models based on melting behaviour of the ash, the relative rankings of all the biomasses were the same for both sub-models.A careful observation of the sub-models (equations 8 and 9), reveals that the overall softening temperature is formulated based on the contributions of the basic to acidic oxides ratio

B/A, an increase in the B/A value of the blend will lower its melting point (Jungt *et al.*, 1991, Backman *et al.*, 1997, Mueller *et al.*, 2005). Lower melting temperature of the basic components can lead to substantial amount of liquid formation which then binds the un-melted and precipitated solids together, and thus increase the deposit sintering.
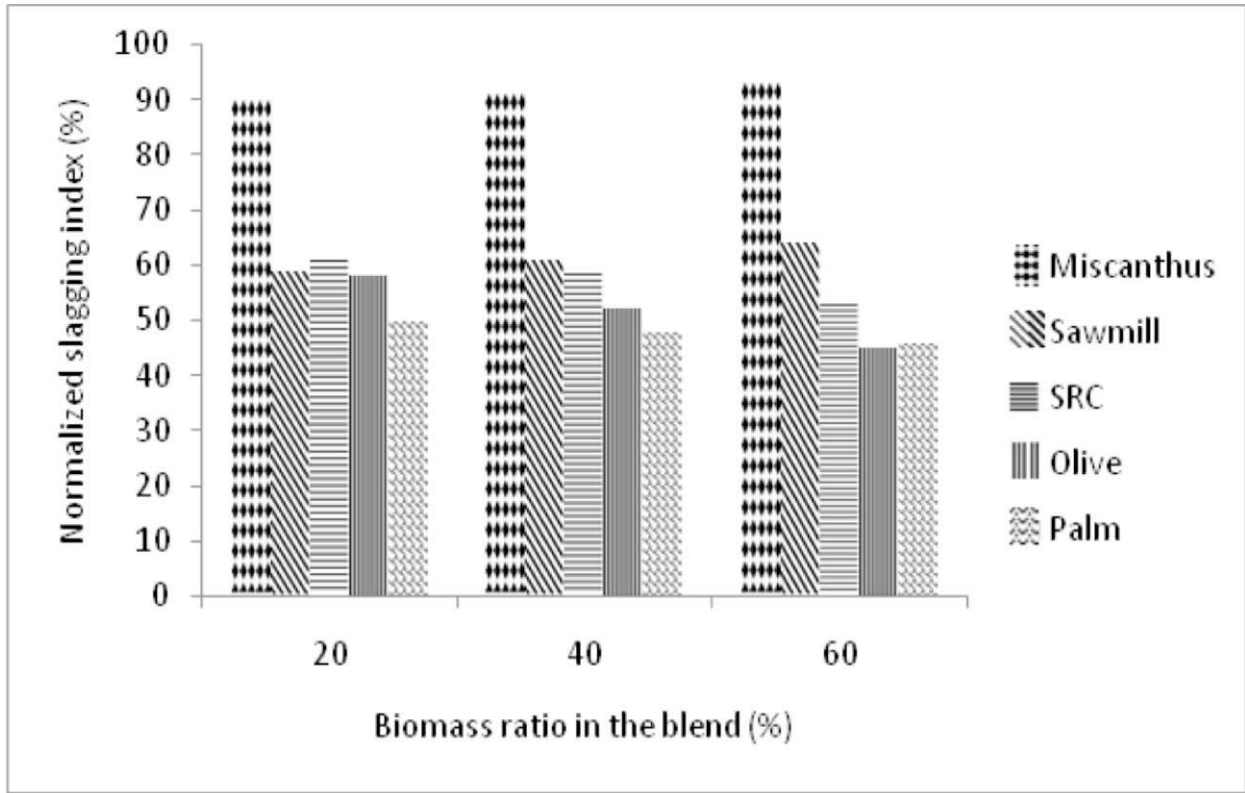

Figure 3: The degree of sintering for a mixture of Russian coal with biomass based on B/A sub-model.
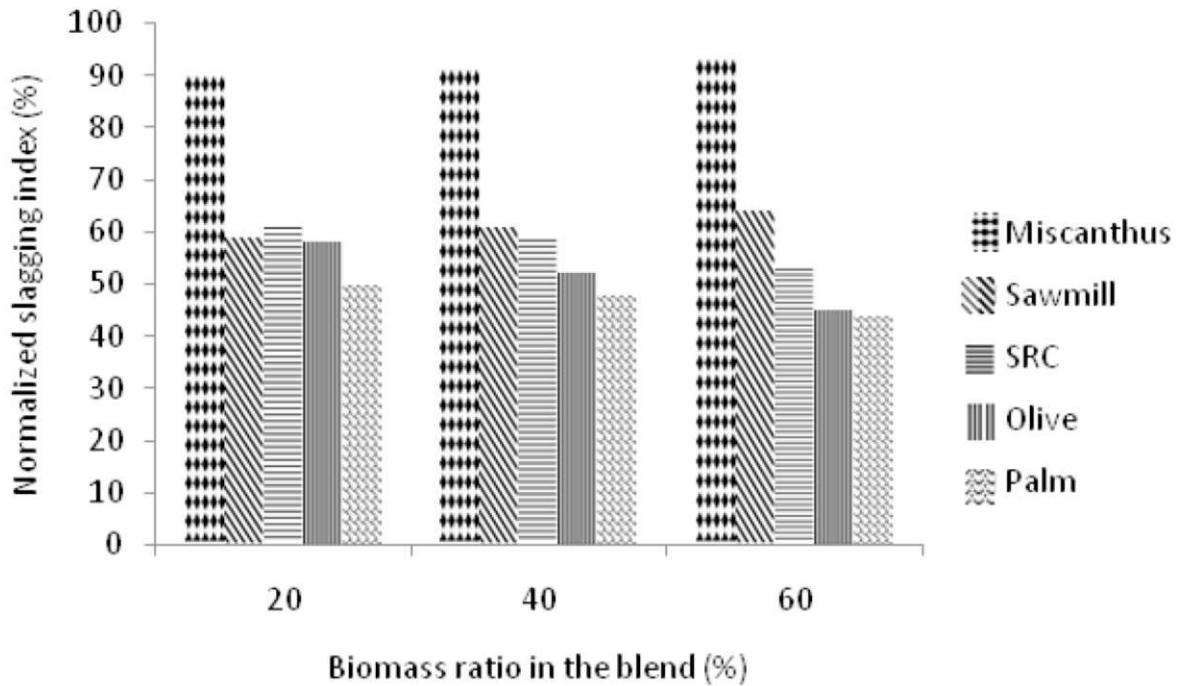

Figure 4: The degree of sintering for a mixture of Russian coal with biomass based on $(B+P_2O_5)/A$ sub-model.

For the Russian coal, the degree of sintering increased in the order:Miscanthus<Sawmill<SRC<Olive<Palm.Sub-model 1 using Russian coal (Figure 3) was able to predict the experimental trend of the degree of sintering up to BR $\leqslant$ 40 wt % (Miscanthus<Sawmill<SRC<Olive<Palm) but it fails to accurately predict experimental trend when biomass additionwas wt 60wt% (Miscanthus<Sawmill<SRC<Palm<Olive). The reason for this failure was because the ratio B/A ratio have been initially introduced for coals with very low phosphorus content, which therefore was not included in equation (9). However, for a more accurate prediction of the ash fusibility, the effect of the phosphorus on ash fusibility has been accounted for in equation (10).

The ranking of sintered deposits based on the sub-model 2 match the experiment trend: Miscanthus<Sawmill<SRC<Palm<Olive as shown in Figure 4. Sub-model 2 was considered more realistic for all levels of biomass addition because of the low HT of P_2O_5 significantly increased the melting phase. At low hemispherical temperatures where the ash stickiness is dependent on the viscosity, the deposition formation and deposit sintering are more efficient at low viscosities. P is present in oxidized form (V) as various phosphates in the biomass. Upon the combustion breakdown of the biomass, it is initially probably released as P_2O_5 that is relatively volatile ($P_2O_5(g)$) at the combustion temperatures. According to Korbee *et al.* (2003) P_2O_5 may under certain conditions be reduced by the CaO in the fuel to formed $Ca_3(PO4)_2$. Under such circumstances the volatility of elemental phosphorus may be high. This schematic description was primarily valid for palm kernel cake where the phosphorus content is higher than the silicon content as shown in Table 1, a condition that has a major impact on the ash transformation reactions.

From Figure 4, Sub-model 2 has a higher basic component than sub-model 1.The higher basic component in sub-model 2 might enhances the fluxing of the quartz by the alkalis more efficiently than does the sub-model 1. This fact is clearly seen in where the palm bar moves from the second highest sintering tendency in Figure 3 to the first position in Figure 4. This is a consequence of its significantly higher P_2O_5 content (42.7 wt %), which causes a significant deposit sintering and fusion. The order of the sintering tendency predicted by sub-model 2 for the coal/blend was, from highest to lowest, palm kernel, olive, SRC, sawmill and miscanthus, i.e. the tests suggest that palm kernel ashes are more prone to form a deposit than those from olive residue.

The prediction using viscosity calculation reported in Wigley *et al.* (2007) shows that for 20wt %biomass replacement was Miscanthus<Sawmill<SRC<Palm<Olive, which is different from the ranking observed for Russian coal. For intermediate levels of replacement of Russian coal by biomass, the degree of deposit sintering was predicted to increased in the following order: Miscanthus<Sawmill<SRC<Palm=Olive(Wigley *et al.*, 2007) (Figure 4), which was very close to the ranking observed for this coal. For more than 60 wt % biomass replacement,deviation from the ranking observed in this coal increases.While the viscosity calculation reported in Wigley *et al.* (2007) was only able to predict the experimental trend at the intermediate levels of replacement of Russian coal by biomass, the model developed in this work delivers an accurate experimental trend for all levels of biomass addition.

Conclusion
A numerical slagging index model which predicts the slagging tendencies of the various biomass/coal blends in co-firing scenarios has been employed in this paper. The working principle of the numerical slagging index is based on the weight of ash, heating value of the individual fuels, individual softening temperatures and ash chemistry.The results of prediction correlate well with the reported experimental data of the Russian coals-biomass blends, while the results of predictions using South African coal show significant inconsistencies with the experimental data on most of the tested biomass.

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