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Predicting the slagging potential of co-fired coal with sewage sludge and wood biomass

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HIGHLIGHTS

- ▶ A numerical coal slagging index has been modified to predict co-firing.
- ▶ The modified slagging index (MSI) has been tested on coal with 20% biomass.
- ▶ MSI predictions are consistent with experimental data on co-firing.
- ▶ K, Ti and Fe play a major role in predicting the overall ash slagging behaviour.

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ABSTRACT

Operational issues, such as slagging, fouling and corrosion of boilers during co-firing are yet to be fully understood. A numerical slagging index (NSI) to predict the slagging potential of coals and coal blends has been developed by some of the present authors, and this has been successfully validated with some Australian bituminous coals. In this paper, the NSI has been modified in order to predict the slagging potential of coal and biomass blends. The modified slagging index (MSI) considers the effects of the ash properties, the ash content and the heating values of the individual fuels in predicting the slagging potential of each blend. The results of the MSI predictions on coal/sewage sludge and coal/saw-dust blends produce a very good correlation with the reported experimental data. It has been observed that the ash content and the composition of the ash in the blends can be used to predict the behaviour of the ash mixture according to the proportional weights of the individual fuels.

1. Introduction

The co-firing of biomass with pulverized coal is widely used in order to reduce CO_2 emissions. It has been estimated that a reduction of about 300 Mt of CO_2 emissions can be achieved if only 5% of the total world energy generated using coal is substituted with biomass (IEA, 2009) [1]. Biomass, from a sustainable cultivation can be considered as almost CO_2 neutral and environmentally friendly, but it greatly differs from coal due to its origin and chemical composition [2]. However, the complex chemical nature of the inorganic component of the biomass may result in an increased slagging tendency [3]. Also, biomass has a higher volatile matter and oxygen content and a lower density, ash content and heating value than coal. Therefore, an in-depth understanding of the characteristics of the blended fuels including their deposition tendency is necessary in order to achieve high co-firing efficiency and low maintenance costs [4].

Although considerable research activities are ongoing in order to understand the deposition mechanism in co-firing [5–7], there are no available tools that predict the slagging and fouling of ash from biomass and biomass-coal blends. Therefore, coal specific ash fusibility correlations are used in practice [8–11]. For blends with less than 20% biomass, the ash mixture remains predominantly an alumino-silicate, and the pure coal slagging index can be used with caution to predict the slagging potential of such blends [12,13]. A number of empirical indices which can explain the fouling and slagging behaviour of coals, to some extent, can be found in the literature [10]. However, it has been shown, for example by Baxter et al. [10] and Degereji et al. [14] that so far, there is no single slagging index that is suitable to predict the slagging tendencies for a variety of coals and biomass blends.

Moreover, using pure coal slagging indices to assess co-firing may not guarantee accurate predictions, since the ash behaviour during co-firing is not yet fully understood [15]. The composition

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of biomass differs from that of coal, for example, the inorganic matter in coal is largely in the form of minerals, while a substantial part of the alkali metals in biomass are present as salts [16]. According to Heinzel et al. [17], whether co-fired deposits show the behaviour of two single ashes or a mixture of ash under boiler conditions needs to be understood. Also, knowledge of the nature of the potassium release during biomass combustion is still inadequate. Although the potassium species found in fly ash during co-firing are believed to be mainly in the form KCl, K_2SO_4, K-silicate and K–aluminium-silicates [16], other species, such as $CaSO_4$, which may possess lower mobility than K_2SO_4, can also deposit on the heat transfer surfaces [15].

One of the main objectives of the present investigation is to develop a numerical slagging index which can predict the slagging tendency of various coal/biomass blends in co-firing. In this paper, we have proposed a 'modified slagging index' (MSI) for coal/biomass blends and this is based on our earlier development of a 'numerical slagging index' (NSI) which was found to successfully predict the slagging potential of various coals [14] and coal blends [18]. The proposed MSI for coal/biomass blends has been tested on three different sets of experimental data in order to understand the influence of blending ratios on the slagging potential.

2. Influence of the fuel properties on slagging

A number of empirical relationships based on the chemical composition of the coal are reported to have successfully predicted the slagging and fouling behaviour of coal blends [14]. However, they were shown to have severe limitations when predicting the slagging tendency of the biomass/coal co-firing. Although the ash loading from the biomass may be low compared to that of coal, the composition of the mineral matter within the biomass ash is as broad as that of coal ash and thus creates complex slagging and fouling behaviour. Moreover, it is believed that the lack of knowledge of the co-firing combustion conditions, as well as the fuel and ash compositions of the biomass fuels, entail poor slagging predictions. Hence, it is a prerequisite to understand the fuel properties and ash behaviour of the coal, biomass and their blends, together with the combustion conditions and potential chemical interactions, before the development of a reliable co-firing slagging tool [12].

Although a coal and biomass may exhibit certain gross similarities in their properties, they have substantial specific variations in the ash elements, see Table 1. For example, in Case 3 of Table 1, the content of Al_2O_3 in ash for pure coal is 15.33 wt% , while for pure biomass is 4.33 wt%. Also, CaO and TiO_2 contents in pure coal ash are 7.51 and 9.25 wt%, respectively, while in pure biomass ash the value for CaO and TiO_2 are 25.44 and 18.47 wt%, respectively. Moreover, in the case of coal/biomass blends, even though the blends are made in the form of the percentage of the fuels, in terms of either weight or energy, certain properties of the blends, such as reactivity, may not be additive [12].

In an attempt to answer the question 'whether the ash from the blends behaves as two individual ashes or as an ash mixture', in this investigation, the ash of the blends is considered with dual characteristics. In the initial stage, the coal ash and the biomass ash are assumed to stand alone. However, at high levels of reactivity, the components of the individual ashes may interact and result in additional species. The coal numerical slagging index presented in our earlier investigations [14,18] considered the viscosity, fusibility and the weight of the ash in the coal to assess the slagging potential of the coal. In order to develop the co-firing slagging index, we have employed the working principles of the coal NSI, where the ash viscosity, the ash fusibility and the weight of the ash in both the coal and biomass are considered. However, we observed that the content of some of the important species in the ash, such as Fe_2O_3, K_2O and TiO_2, continue to change with increasing biomass ratio (BR) (see Fig. 1), and therefore, we postulate that there is a need to account for the effect of these changes in the MSI in order to obtain a better prediction.

In addition, the volatile release of some elements, such as potassium, chlorine, and sodium, both during and after devolatilization, coupled with the furnace thermodynamics, may strongly influence the slagging potential of the blends. Therefore, there is a need to establish the rates at which some of the alkali metals react with silicates, iron oxide and calcium oxide that are released from the coal ash. Also, the effects of mineral transformations and mineral associations are important.

3. Numerical modelling

The numerical modelling presented in this section is based on the assumption that the individual properties of the fuels, ashes and the interactions between them at high temperatures are responsible for the ash slagging. Ash particles that transverse the boundary layer and hit the boiler walls may stick, and thus may cause slagging. The stickiness of a silica rich particle can be determined from its viscosity [14], while for a particle rich in salt, its stickiness can be determined from its softening temperature and/or melt fraction [19]. Also, it was found that the alkali metal content (K, Na and Ca), as well as Al_2O_3 and P_2O_5, were enriched in the deposited ash under co-firing conditions [15]. Fig. 1 presents the experimental mineral concentrations and their trends within the fly ash from various biomass ratios [4]. It is interesting to note that the decrease in Fe_2O_3, and increase in TiO_2 content in the fly ash with the higher contribution of the biomass in the blend is significant. In this investigation, the coal numerical slagging index we developed earlier [14,18] has been modified in order to account for the effect of biomass in the blends.

The coal numerical slagging index (S_x) is generally expressed in terms of the incoming ash, γ, and ash viscosity, μ, as follows [18]:

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

The weight of the incoming ash has been defined in terms of the ash content and the heating value of the individual fuels as follows:

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

For coal/biomass blends, we can predict the effects of biomass additions on deposit sintering by determining the viscosity (μ) of the ash blend from the ash content and ash chemistry of the individual fuels as follows [3]:

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

where x, y, γ_c and γ_b are the ratio of the coal in the blend, the ratio of the biomass in the blend, the weight of the coal ash and the weight of the biomass ash, respectively. Also, the modified Watt–Fereday ash viscosity model used in our previous calculations [18] has been redefined, as in Eq. (4), in order to account for the softening temperatures of both the coal (T_c) and the biomass (T_b), as defined in equations (5) and (6), respectively, as follows:

$$\mathrm{Log}(\mu) = \frac{m.10^7}{T_s^2} + c \tag{4}$$

$$T_c = a(SiO_2) + b(Al_2O_3) + c(Fe_2O_3) + d(CaO) + e(MgO) + f(\alpha) + g + 150\ ^\circ C \tag{5}$$

$$T_b = 1.81CaO + 4.2Al_2O_3 - 2.4K_2O + 5.3P_2O_5 + 1017\ ^\circ C \tag{6}$$

and the constants a–g are parameters based on the SiO_2, Al_2O_3 and Fe_2O_3 contents in the ash [18]. In Eq. (4), the term T_s can be