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Analysis of bed agglomeration during gasification of wheat straw in a bubbling fluidised bed gasifier using mullite as bed material

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ABSTRACT

The quantity and composition of the ash content of straw poses technical challenges to its thermal conversion and have been widely reported to cause severe ash sintering and bed agglomeration during fluidised bed gasification. Literature indicates that a combination of reactor design and bed material measures is required to avoid defluidisation at temperatures above 800 °C. Using scanning electron microscopy and energy dispersive X-ray spectroscopy this study investigated the initial agglomeration of a mullite bed during the gasification of wheat straw in a small scale, air blown bubbling fluidised bed. The results show that the temperatures along the height of the bed converge prior to any marked drop in pressure or heating of the lower freeboard. This convergence was seen to occur at temperatures close to 750 °C in repeated gasification experiments. Energy dispersive X-ray spectroscopy indicates coating-induced agglomeration caused by the reaction of alkali metals with silica. Scanning electron microscopy under high magnification revealed a layered structure to the agglomerates, where ash particles are subsumed into a fused material. This suggests the formation of agglomerates by the three step agglomeration process postulated by other authors. Analysis of indices used to predict agglomeration on the basis of a fuel's ash content and composition indicates that the Alkali Index is the most accurate, successfully predicting agglomeration for 7 of the 9 fuels where agglomeration was observed.

1. Introduction

The gasification of wood has been successfully demonstrated in numerous conversion plants throughout Europe. In comparison, the experience with other biomass fuels is limited as the performance of a gasifier is affected by biomass type [1]. Straw is a prime example where a lack of engineering expertise relating to its gasification characteristics has been identified [1]. The technical reliability of straw gasification systems has been classified as low, outranked marginally by sludge and significantly by woody biomass which has the highest reliability. These reliability issues are associated with severe problems of ash sintering and bed agglomeration [2] which are influenced by the composition of the fuel. Ash-related problems have been identified as the main obstacle to the realisation of viable and economic applications of biomass gasification [3]. Bed agglomeration is often a precursor to the unscheduled shut-down of fluidised bed gasifiers [4] and is the foremost ash-related problem affecting the performance of fluidised beds. The alkali content of the biomass is seen as the main contributor [5].

The two major pathways to agglomeration are melt-induced and coating-induced agglomeration [6]. The less common melt-induced process relates to particles adhering together by a molten phase whose chemical structure is similar to that of the fuel ash [7]. This mechanism is associated predominantly with fuels with elevated alkali, sulphur, and chlorine contents which form low melting point eutectics [6]. The more typical coating-induced mechanism involves a sticky layer forming on the surface of particles and fusing individual particles together [6]. The sintering of these coatings initiates agglomeration and where ash melting does not occur, full agglomeration proceeds [7,8]. This process is associated with the reaction of alkalis with silica or sulphur. Reactions between alkali and alkali metals (mainly potassium) and the bed material of silica sand have been reported as initiating this coating process [8] but there have been conflicting views [6].

A fuel's tendency to cause agglomeration is mainly dependent on temperature and the ash composition and content of the fuel. Temperature is known to have a significant impact on the agglomeration process and has been highlighted as the most important parameter in fluidised bed gasifiers, with higher temperatures increasing agglomeration tendencies [3]. Temperature uniformity is important in combating agglomeration. Fluidised bed reactors, with their relatively low operating temperatures and isothermal operating conditions [9], are therefore attractive for use with fuels which pose ash-related problems. Slagging

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Table 1
Operating conditions adopted in the three gasification tests studying agglomeration in the small scale bubbling fluidised bed gasifier.

Run	Fuel	Average equivalence ratio	Average bed temperature (°C)[a]
1	Wheat straw	0.27	770
2	Wheat straw	0.23	728
3	Wheat straw	0.17	654

[a] The bed temperature is taken as the average of the readings from thermocouples T2, T3, and T4.

is generally associated with fuels with ash contents which exceed 5–6% and severe slagging may prevail when ash contents are greater than 12%.

Compared to the influence of temperature, the effects of ash composition are less well understood. Generalised estimates have been established and utilised to develop indices to predict agglomeration tendencies on the basis of a fuel's ash composition and content. The reliability of such indices has, however, been questioned [7] as they do not take account of the influence of the bed material on the process. For example, the ash fusion temperature is seen as not predicting agglomeration in all cases and although it is widely employed, the standard American Society for Testing and Materials (ASTM) ash fusion test [10] is inadequate for predicting ash-related problems for biomass and energy crops [11]. With this in mind such indices should be used only as a general guide to ash behaviour.

Widely-adopted predictive indices include the Alkali Index, the Bed Agglomeration Index, and the Base to Acid Ratio. The Alkali Index is based on the ratio of K_2O and Na_2O to the higher heating value (HHV) and is calculated as follows:

$$\text{Alkali Index}\left(\text{kg}\ \ \text{GJ}^{-1}\right) = \left(1 * 10^{6}/\text{HHV}_{\text{dry basis}}\right) * \text{wt.\%}(K_2O + Na_2O)$$

where

HHV	the higher heating value of the fuel (kJ kg^{-1}); and
wt.%	the weight percentage of the ash components in the fuel.

Fuels with Alkali Index values which exceed 0.17 kg GJ^{-1} are deemed to be problematic, while fouling and slagging will most likely occur with ratios in excess of 0.34 kg GJ^{-1}. Where the HHV of the fuel is unavailable for the calculation of the Alkali Index, the following correlation derived by Parikh et al. [12] can be utilised:

$$\text{HHV}\left(\text{MJ}\ \ \text{kg}^{-1}\right) = -3.0368 + (0.2218 * \text{VM}) + (0.2601 * \text{FC})$$

where

VM = volatile matter content; and
FC = fixed carbon content, each reported on a dry basis.

Agglomeration is also associated with Bed Agglomeration Index (BAI) values of lower than 0.15 [13]. The BAI is calculated as:

$$\text{BAI} = \%(FE_2O_3)/\%(K_2O + Na_2O).$$

Another index widely used to predict the ash behaviour of a fuel is the Base to Acid Ratio ($R_{b/a}$). It was developed for fossil fuels with low phosphorous quantities and in its original form does not take account of the increased fouling tendencies associated with phosphorous in the form of P_2O_5. As the P_2O_5 content of biomass fuels is relatively high the calculation has been modified as follows to take P_2O_5 into account Kupka et al. [14]:

$$R_{b/a} = \%(Fe_2O_3 + CaO + MgO + K_2O + Na_2O + P_2O_5)/\%(SiO_2 + TiO_2 + Al_2O_3).$$

Table 2
Particle size distribution of mullite used as bed material (after C–E Minerals [20]).

USS sieve	8	12	14	20	30 600 μm	40	50	70	100	140	200	270	325	PAN*
grade	2.36 mm	1.70 mm	1.40 mm	850 μm		425 μm	300 μm	212 μm	150 μm	106 μm	75 μm	53 μm	45 μm	
10 × 18$^{(1)}$	0–3	10–25		60–82	0–15									0–5
10 × 28$^{(1)}$	0	15–25	45–65	6–16	5–15	0–6								0–2
14 × 28$^{(1)}$		0	1 max	30–55	35–45	10–25	5 max							1.5 max
16 × 30$^{(1,2)}$			0–3	65–75		4 max								1 max
22S$^{(1,2)}$			TR	15–25	32–47	27–37	4–10						3 max	TR
35S$^{(1,2)}$			TR	1–5	21–38	40–54		9–19		2–8				3 max
50S$^{(1,2)}$				0	1–9	22–37	26–40	12–22	6–16	1–6				3 max
60S$^{(1,2)}$					0	0–5	30–48	30–44	9–22	2–7				3 max
20 × 50$^{(1,2)}$			TR	0–8	20–50		50–72						2 max	TR
25 × 80$^{(1,2)}$				0–5	20 min 30 avg	80–93	7–12						3 max	
50 × 100$^{(1)}$						TR	5–20		70–86	0–15	3 max		1 max	TR
60 × 200$^{(1)}$							0	0–11		65–90	5–20	0–6		3 max
200 IC-C $^{(1,2,3)}$									TR		15–25			75–85
325 IC-C $^{(1,2,3)}$									TR				5–15	85–95

Grade available in AL_2O_3 content (1) 47% (2) 60% (3) 70%.
* PAN designates the percentage of material passing the last reported screen for each size.