A study on initiation of ash agglomeration in fluidized bed gasification systems

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HIGHLIGHTS

- Gravity separated fractions analyses reveal local initiation of agglomeration.
- FactSage calculations help to predict slag formation in fluidized bed gasification.
- Slag formation occurs even at fluid bed temperatures in high rank coal gasification.
- Hematite increases alumino-silicate slag formation temperature, until it reduces.
- Integrated ash agglomeration model was developed to predict agglomeration kinetics.

ARTICLE INFO

ABSTRACT

Agglomeration in fluidized beds begins locally by the sticking of slag–liquid-covered particles. Analysis of the composite fuel is not adequate in predicting agglomeration problems. Separation of the high rank Pittsburgh seam coal into particle classes based on specific gravity (SG1: <1.3 g/cm³; SG2: 1.3–1.6 g/cm³; SG3: 1.6–2.6 g/cm³ and SG4: >2.6 g/cm³) and particle size (PS1 through PS7) helped to identify important particle-level slag–liquid formation tendencies. Slag–liquid formation tendencies under fluidized bed operating temperatures were determined both computationally and experimentally. Particles rich in certain iron and calcium phases melt at very low temperatures that are well within fluidized bed operating conditions. The iron rich particle classes (SG3 and SG4) showed the presence of several phases containing iron in different oxidation states. The presence of these iron phases was not detected in the composite bulk fuel. The possibilities of equilibrium liquid phase formation in the presence of different ratios of these iron and calcium oxides to alumino-silicates were determined. Presence of hematite was found to delay slag–liquid formation. Each of the particle classes showed distinct slag–liquid formation tendencies that indicate initiation of agglomeration around SG3 and SG4 particles. The study revealed the importance of particle class-level differences in mineral matter composition for the prediction of agglomeration during fluidized bed gasification.

A novel integrated ash agglomeration model that accounts for particle hydrodynamics as well as particle class level ash chemistry has been outlined to predict agglomeration kinetics.

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1. Introduction

Fluidized bed gasification is gaining importance due to the advantages of fuel-flexibility and low temperature sulfur capture [1]. Gasification of a wide-variety of fuels such as coals of different ranks and biomass is becoming an important, environmentally friendly means of generating power. Gasification in fluidized beds helps to avoid slag flow issues that can occur in entrained flow systems. However, problems of agglomeration of bed material can restrict the efficient utilization of this technology.

Agglomeration problems have been previously experienced in fluidized bed boilers. Similar problems have been witnessed even with fluidized bed gasification systems [2–4], such as the problems with the Pinon Pine gasifier [5]. Several studies have shown higher slag formation tendency in a reducing atmosphere [6–8], thereby

suggesting greater operational difficulties in the case of fluidized bed gasification. These issues call for more in-depth studies on mineral matter transformations under such operating conditions to understand their implications on plant operability.

There are several studies of ash slagging tendencies at high temperatures that are applicable to entrained flow gasifiers [6]. However, slag–liquid formation tendencies have not been extensively studied under the lower temperatures at which fluidized bed gasifiers operate. Small amounts of slag–liquid that form under fluidized bed conditions may be adequate to cause operational difficulties such as agglomeration. In order to estimate the rate of agglomeration for a given fuel, the slag–liquid formation tendencies of the ash particles under fluidized bed operating temperatures must be studied.

This study aims at understanding some of these slag–liquid formation tendencies at fluidized bed temperatures under a reducing atmosphere. Hitherto, techniques such as Initial Deformation Temperature (IDT) that involve visual detection of change in the shape of an ash cone to detect onset of slag formation and indices such as acid to base ratio have been used to predict the slag–liquid formation and agglomeration tendencies. However, several studies have shown that these methods, which depend entirely on the bulk fuel chemical composition, do not allow accurate predictions [9–11].

In order to understand the physics and chemistry at particle level, particle classes of the composite fuel, based on differences in density and size, were used in this study. This facilitates the understanding of slag–liquid formation tendencies at the particle level. The particle fractions were analyzed both computationally and experimentally. FactSage™ thermodynamic simulation software was used and the results were validated with high temperature X-ray diffraction and thermo-mechanical analyses.

2. Materials and methods

2.1. Division of composite coal into fractions based on size and density

Pittsburgh no. 8 coal was separated into fractions using different specific gravity liquids and float–sink gravity separation techniques utilized in an earlier study [12]. Coal was mixed with organic liquids having the specific gravities of 1.3, 1.6 and 2.6. The fraction heavier than the liquid was allowed to sink and thus separated from the lower specific gravity particles that remained afloat. The specific gravities of the organic liquids were chosen based on the desired mineral rich fractions being generated. For example, the need for the separation of a distinct particle class dominated by the heavier iron rich particles led to the choice of 2.6 as the highest specific gravity. At the same time, the attempt was made to keep reasonable ash yields for each of the fractions generated. The whole coal is termed as SG0. The four fractions generated were denoted as SG1, SG2, SG3 and SG4 in the order of increasing specific gravity. The chemical composition of ash from each of these fractions was obtained using XRF (Table 1). Each gravity-separated fraction was then separated into seven size classes using sieves of different mesh sizes. Experimental results in this paper are reported from the finer size class only (75–106 μm – PS6).

2.2. Generation of ash for experimental analyses

The coal fractions were heated in a proximate analyzer up to 650 °C. A moisture removal step was done at 110 °C for an hour, which was followed by ashing. The ashing was done at 650 °C until a constant mass of the residue was achieved. In this way, ash, which had not been subjected to relatively high temperatures, was generated from the coal fractions.

Table 1
XRF ash analyses of particle classes (75–106 μm) of Pittsburgh seam coal [2].

Species	Wt. percent in fuel ash (%)				
PS6	SG0	SG1 [1.3 float]	SG2 [1.3 sink, 1.6 float]	SG3 [1.6 sink, 2.6 float]	SG4 [2.6 sink]
SiO_2	46.4	49.9	55.3	51.8	12.5
Al_2O_3	22.0	28.7	25.2	20.8	4.67
Fe_2O_3	24.5	9.41	11.3	18.9	76.0
CaO	3.41	5.05	2.78	4.87	5.79
TiO_2	1.05	2.47	1.22	0.74	0.21
K_2O	1.56	1.85	1.98	1.48	0.24
MgO	0.73	1.32	1.08	0.76	0.29
Na_2O	0.42	0.76	0.91	0.52	0.13
SrO	0.11	0.34	0.10	0.04	0.29
BaO	0.08	0.17	0.07	0.03	0.03
MnO	0.03	0.02	0.03	0.02	0.07

2.3. Thermodynamic equilibrium phase calculations using FactSage™ [13]

Simulations were run using FactSage™ version 5.2 for each of the four gravity-separated fractions (75–106 μm). Ash from each gravity fraction was allowed to equilibrate individually with a reducing gasification medium. The reducing gasification medium consisted of 32.6% carbon monoxide, 27.6% hydrogen, 14.3% carbon dioxide and balance water vapor at atmospheric pressure. The mass ratio of the total amount of reducing gas to the carbon content of the fraction was taken as 0.2 based on an average value reported in literature from commercial gasifiers [14–16]. Since these gasifiers use mainly lignite, sub-bituminous coals and a few bituminous coals, the carbon content was considered as 55 wt.% for calculation of the ratio.

FactSage™ computes the Gibbs free energy for various possible compounds at a given temperature and pressure using thermodynamic properties from FACT databases while maintaining the elemental balances. The FACT Slag A database was used for the slag phase thermodynamic properties. All the phases available in this Slag A database as well as phases available in the FACT database for pure solids, liquids and gases were used unless the number of phases exceeded the maximum allowed in a single calculation. If the number of possible phases exceeded this limitation, the hydrocarbon phases and the phases containing water of hydration from the solid and liquid phase were not included in the calculation, since they would not exist at the high temperatures studied. The ash compositional analysis as oxides was used as input. Shannon et al. shows that the results are not significantly affected by the forms of sulfur [12]. Therefore only sulfur, in its elemental form, was used as input in this study. The FactSage™ calculations were used to obtain the stable solid, liquid, gaseous and slag–liquid phases at equilibrium. The temperature at which slag–liquid formation was initiated was also estimated. In order to obtain the initial slag formation temperature, the FactSage™ calculations were first performed at 900 °C and then performed by gradually increasing the temperature in increments of 10 °C until slag–liquid presence was seen. Similarly, if slag–liquid was present at 900 °C, the temperature was lowered in increments of 10 °C until no more slag–liquid was seen. Once the initial slag–liquid formation temperature had been determined, the FactSage calculations were done using step intervals of 50 °C.

The weight percentage of slag for each of the gravity separated fractions was calculated using the equilibrium amounts of solid and liquid phases. The percentage of slag in the bed depends on the slag formation tendency of each gravity fraction and also the ash content of that fraction and the contribution of that fraction to the whole coal. The weight percent of total slag in the bed is