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Actuality Test - A Technique for Expeditious Agglomeration Detection in a Laboratory Scale - Fixed Bed Combustion of Biomass Fuels - Impact of KOH

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ABSTRACT: *This research has concentrated on the application of actuality/reality test for speedy confirmation of lumps/agglomerates formation thereby emphasizing the roles of alkali metals and silica in agglomeration during the combustion of some selected biomass fuels (miscanthus, white wood, and willow) in a laboratory-scale fixed bed. Biomass fuels are* CO_2 *neutral and very rich in alkali metals especially potassium, K and sodium. Potassium played predominant roles in the agglomeration formation of these selected biomass fuels. During the experiments, huge agglomerates were formed at a lower melting temperature of 350* ^0C *when potassium hydroxide, KOH and silica sand were heated together directly (reality test) in the combustion chamber (Gooch crucible). Harder and tougher agglomerates were produced at 502* ^0C*. This attested to the fact that, agglomerates are produced from the formation of a low melting temperature eutectic compound (alkali-silicate) in the form of K-silicate. The eutectic compound has a lower melting temperature than the melting temperature of the parent materials - the alkali metals or the silica from sand, which is the bed material. It therefore melts sharply in the bed and formed lumps in form of agglomerates. The results of this research have indicated that, potassium K and silica* SiO_2 *are very important in the formation of agglomerates during the combustion of biomass fuels. Gooch ceramic crucible is a very good combustion chamber for the combustion of biomass fuels experiments/tests in a laboratory – scale fixed bed. It accommodated more heat distribution into the combustion chamber than the conventional ceramic crucible.*

Keywords: *Lumps, alkali metals, Eutectic compounds, Gooch crucible, Laboratory-scale, bed.*

I. INTRODUCTION

Biomass has been adjudicated as CO_2 neutral because the amount of CO_2 intake by plants while growing is also released to the atmosphere during its combustion [1]. Biomass is a reliable and sustainable alternative energy source that does not contribute to the earth's surface heating but reduces greenhouse CO_2 emissions. Available fossil fuels (coal, crude oil, and natural gas) in the reserve are sprightly depleting therefore, cannot sustain the world's energy demand and supply. Moreover, the world's population growth that is growing at an alarming rate coupled with increase in the energy demand, have encouraged researchers to deduce ways to limit the consequences (perennial fuel scarcity, reduced quality assurance, and decrease in production competitiveness) of the sole dependency on these conventional energy resources. Researchers' interest is targeted at providing energy through a more dependable, reliable and renewable energy resources such as biomass, solar, wind power, geo-thermal, and hydropower. Energy derived from biomass fuels has been recognized as one of the earliest and ancient sources of energy which ranked fourth as energy resource, accounting for about 14% of the global energy in terms of domestic and industrial applications [2, 3]. Biomass fuels can be sourced from energy crops on short rotation, agricultural wastes / products, municipal wastes, sewage and industrial wastes. Biomass fuels for energy production are environmental friendly and offer other benefits as far as utilization of biomass fuels are concerned [1-3]. In spite of the fact that, thermal (proximate and ultimate), structural and the physical properties of biomass fuels differ greatly, other properties such as the sulphur content, the hydrogen content, and the ignition temperatures are very similar [3, 4]. However, because of the heterogeneous nature of biomass fuels, which accounted for the differences in their characteristics, different types of problems are usually experienced during the combustion of single biomass fuel or blends of biomass fuels. However, many complications that tends to truncate the whole combustion processes are encountered during the combustion of the selected problematic biomass fuels for this research (miscanthus, willow, and white wood). Some of such problems are agglomeration, erosion, fouling, and slagging [5]. The scope of this

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research has been limited to the reduction of agglomeration in laboratory-scale fixed bed combustion of biomass fuels using a Gooch crucible as the combustion chamber and silica sand as the bed materials while adding kaolin as additive.

II. BACKGROUND OF THE STUDY

Biomass possesses alkali metals, potassium K, sodium Na, and especially elements of group 1 in the periodic table in which, through reactions and interactions with silica sand (bed materials) during combustion, institutes some problems such as agglomeration, erosion, slagging, and fouling in the bed [5, 6]. Moreover, low melting points of the alkali metals present in biomass may have contributed largely to the low melting temperature possessed by biomass fuels. In addition, biomass fuels have low calorific value and high moisture content therefore, cannot burn easily on its own [6, 7]. In order to improve on the combustion characteristics of biomass fuels, it is usually co - fired with coal, which has higher calorific value.

Agglomeration is the formation of sticky coagulates in combustion beds during the combustion of biomass or biomass blend with coal. This occurs because of the reactions between the alkali metals (mostly K and Na) present in biomass and silica in the sand particles (bed materials) leading to the formation of eutectic compound which has a melting point lower than the melting point of either the alkali or the silica from sand particles [8, 9].

Absolute dependence on the conventional energy supply (fossil fuels) should be discouraged completely across the globe. Apart from the fact that, the resources are fast depleting from the reserve, the flue gases emanating from the combustion of these fuels are not environmentally friendly but tends toward polluting the surroundings [10, 11]. These flue gases also constitutes greatly to greenhouse effects (CO_2 and CH_4) through surface heating [12, 13]. Biomass on the other hand, when compared with fossil fuels, is renewable [14, 15].

In a global context, a renewable and environmentally friendly energy source that will contribute immensely to the economic growth of the society is required hence, adoption of biomass as alternative energy source to substitute the almost exhausted fossil fuels. Various problems (erosion, agglomeration, slagging, and fouling) have been identified to associate with the process of generation of alternative energy from biomass, hence this research. The scope of this research encapsulates application of a reality tests to ascertain agglomeration in a laboratory - scale fixed bed combustion of biomass fuels using a Gooch crucible as the combustion chamber and kaolin as the additive.

III. MATERIALS AND METHODS

The materials/equipment used are high alumina Gooch crucible, Roxio Burner, butane/propane mix cartridges, wire gauze, platinum thermocouple, stainless steel tripod stand, temperature data acquisition or data lodger (Pico instrument) and a smoke tunnel. Materials used for the experiment are biomass fuels (willow chips, miscanthus pellets, and white wood pellets), silica sand (bed materials), KOH, and kaolin (additive). The experiment was carried out at the combustion laboratory of the Mechanical Engineering department, University of Sheffield, United Kingdom.

During the conduct of the experiment, heat is transferred into the combustion chamber through the perforated area located at the rear of the chamber by both convection and conduction. This is similar to a distributor plate made of metal sheets used in Fluidized bed combustor. The reality/actuality tests were carried out by heating a mixture of 60g of potassium hydroxide, KOH and 180g of silica sand in the chamber. Most potassium compounds possessed high melting point temperatures; potassium sulphites K_2SO_2 , 1069 ^{0}C, potassium chloride KCl, 770 ^{0}C, potassium oxide K_2O, 740 ^{0}C, potassium carbonate K_2CO_3, 891 ^{0}C. However, potassium hydroxide, KOH possessed relatively low melting point, 360 ^{0}C therefore, it was selected for the reality/actuality tests. The melting point of silica, SiO_2 is 1700 ^{0}C. The experiments were conducted under the same operating conditions and control as the previous combustion of biomass fuels experiments.

IV. RESULTS ANALYSES

At 350 ^{0}C, some samples were collected from the combustion chamber and examined. Huge forms of agglomerates were formed at a very low temperature of 350 ^{0}C, Figure 4.1A. This temperature is lower than the melting point of any of the parent materials (silica and potassium hydroxide). Further heating of the mixtures to a higher temperature of 502 ^{0}C produced stronger, tougher, and harder lumps, Figure 4.1B

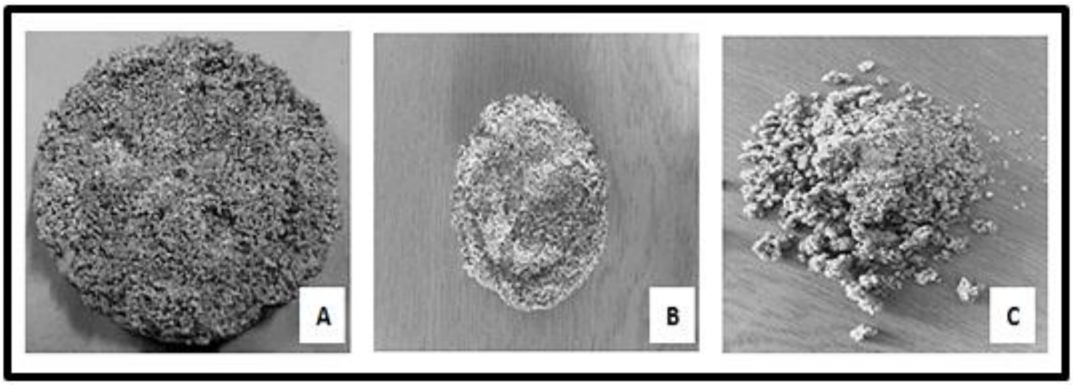

Figure 4-1: (A) Agglomerates at 350 ^{0}C, (B) Harder agglomerates at 502 ^{0}C
(C) Brittle agglomerates produced at 502 ^{0}C with kaolin addition.

The nature of the agglomerates produced has been attributed to the alterations in the chemistry and agglomeration mechanisms, which was facilitated by the addition of kaolin to the mixture. The potassium hydroxide melts sharply and the resulting moist particles reacted with silica from the bed materials (sand). A eutectic mixture was formed in the form of alkali silicate, K_2SiO_3 (potassium silicate). Potassium silicate has a lower melting point of 976 ^{0}C lower than that of silica 1700 ^{0}C therefore, it melts quickly on the surface of the bed materials and formed massive lumps. With this discovery, it clearly connotes that, potassium K plays leading and prominent roles in the formation of agglomerates in the bed during the combustion of biomass fuels. Additive, kaolin was added to the mixture and the experiment was repeated under the same operating conditions. Weaker and brittle agglomerate was produced, Figure 4.1C. This is a confirmation that, addition of kaolin to the bed contents before combustion will grossly reduce the occurrence of agglomeration during the combustion process of the selected biomass fuels (willow, miscanthus, and white wood). It is also a clarification that, addition of kaolin to the mixture will contribute significantly to reduce agglomeration in the beds.

V. DISCUSSIONS

5.1 Influence of kaolin on the Reality Tests.

Additive (10 % kaolin) was pre-mixed with the mixture of KOH and silica sand. Throughout the combustion of the mixture, no agglomeration was observed in the bed at 350 ^{0}C and 502 ^{0}C compared to when the mixture was combusted without the addition of kaolin. Kaolin, $Al_2Si_2O_5(OH)_4$ has great affinity to form eutectic mixtures with the alkali present in the biomass fuels in the form of Alkali-Alumina-Silicate at higher temperatures. This mixture has a higher melting point than the parent materials (alkali, sand, and kaolin). Therefore, kaolin was adopted as the preferred additive for this research. Addition of kaolin hindered sintering of the mixtures and subsequent melting or fusion that may have followed. Samples retrieved from the mixtures KOH, silica sand, and kaolin at 305 ^{0}C and 502 ^{0}C did not show any trace of bonded particles. With this, it is advisable to always add kaolin to blends of biomass fuels or single biomass fuel as a suitable additive while conducting combustion experiments on them or when they are being processed for industrial heat and power generation. SEM images of the samples revealed the morphological structure and shapes of the lumps produced at 350 ^{0}C and 502 ^{0}C, Figure 5.1

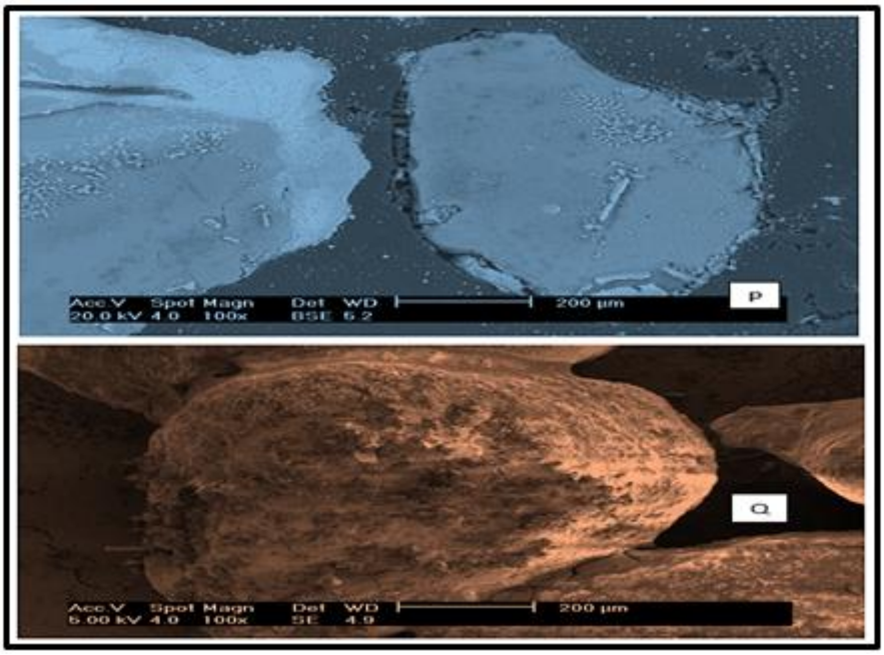

Figure 5-1: (P) SEM image of agglomerates from the combustion of Sand particles + KOH at 350 ^{0}C, (Q) SEM image of agglomerates from the combustion of Sand particles + KOH at 502 ^{0}C

The two brighter features, Figure 5.1 P are the lumps formed in the bed during the combustion of the mixture of potassium hydroxide, KOH and silica sand at 350^{0}C while the darker areas surrounding the lumps is mostly comprised of carbon and oxygen from resin. The massive block- like structure in figure 5.1 Q is the hard, tough, and strong agglomerates formed in the bed during the combustion of potassium hydroxide, KOH and silica sand at 502 ^{0}C. Formation of this structure was because of the reaction between the potassium K and the silica from sand (bed materials). The reaction produced a low melting temperature eutectic mixture in the form of alkali-silicate (potassium silicate) that melts speedily at a low temperature of 502 ^{0}C lower than the melting point of silica.

Generally, the results showed that, agglomerates were formed because of a great adhesion between the molten fuel particles in form of alkali – silicate (potassium-silicate or sodium silicate) and the bed particles. The alkali – silicate (potassium silicate or sodium silicate) has a lower melting point than the parent materials (alkali and silica) therefore, melts considerably and quickly on the surface of the bed materials with the inner core comprise of mostly the bed materials while the outer layer possesses characteristics related to fuel ash.

5.2 Energy Dispersive X-Ray Spectroscopy (EDX)

Technique adopted for these analyses is the EDX Spot analysis of the selected areas on the electron images. The machine focused on different spots called the spectra, each spectrum was analyzed and the elemental composition at that spot established. Carbon, C and oxygen, O was mostly present in all the images plotted. These elements were believed to have emanated from the adhesive (resin) applied to bind the samples together firmly. SEM and SEM-EDX images of the mixture of KOH with silica sand melted at 350 ^{0}C are shown in Figure 5.2 while the summary of the elemental compositions of each spectrum are contained in Table 5.1.

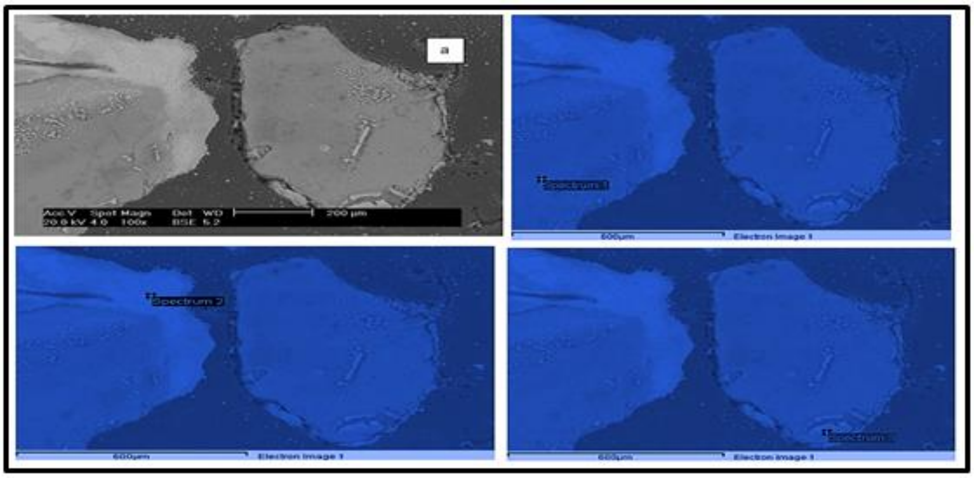

Figure 5-2: SEM images of the mixture of KOH with silica sand melted at 350 ^{0}C and SEM-EDX images of the selected areas (spectra 1, 2, 3) in panel a.

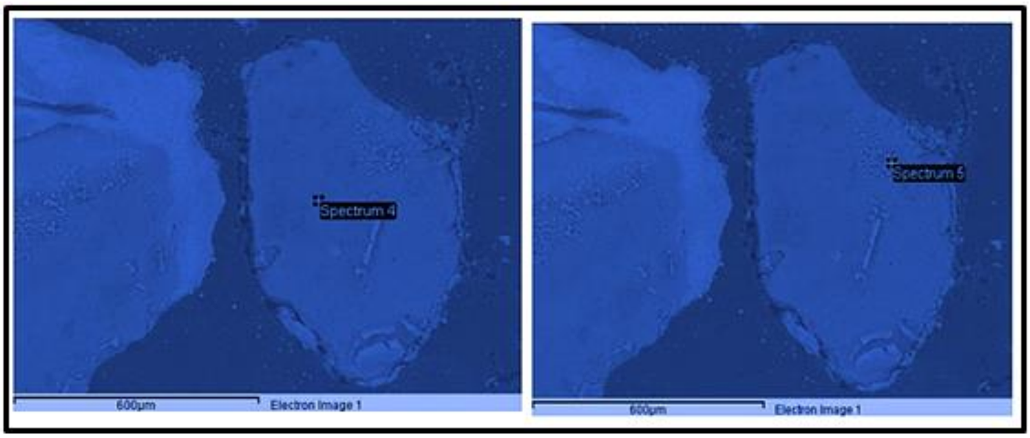

Figure 5-3: (a) SEM image of the mixture of KOH with silica sand melted at 350 ^{0}C and SEM-EDX images of the selected areas (spectra 4 and 5) in panel a.

The two light grey portions in Figure 5.2 panel a, comprised of the molten fraction of the KOH and silica sand in the reality tests conducted at 350 ^{0} C. Spectrum 1 of figure 5.2 is mostly dominated by silicon Si (78.26 wt %) and potassium K-Feldspar (1.80 wt %). Spectrum 2 contained mostly potassium K-Feldspar (41.07 wt %), Si (12.40 wt %), and Fe (0.61 wt %) as a trace element. Concentration of K in this region is higher than that in spectrum 1. In addition to Si, K, and Fe in spectrum 2, spectrum 3 contained Calcium, Ca (0.88 wt %) although in a negligible amount. Spectra 4, and 5, Figure 5.3 were mostly dominated by silicon Si (50.90 wt %), (72.87 wt %), and (52.41 wt %) respectively. Concisely, Si and K generally dominated the sample. Si and K completely dominated agglomerates emanated from the reality tests while Ca and Fe were trace elements in the mixture, Table 5.1.

Table 5-1: EDX spot analysis results of KOH + Sand at 350 ^{0}C

Wt %	Spectrum				
	1	2	3	4	5
Si	78	12	51	73	52
K	2	41	14	4	20
Ca	0	0	1	0	0
Fe	0	1	1	0	0

VI. CONCLUSIONS

The reality/actuality tests conducted by heating KOH + silica sand formed the main technique and approach in this research. It was established that, formation of a low melting temperature alkali-silicate in the form of potassium, K –silicates or sodium, Na – silicates were the bed rock upon which agglomeration in the combustion beds depended. The low melting temperature alkali-silicate (eutectic compound) has a lower melting temperature than the parent materials therefore, melts quickly in the bed during combustion. The reality experiments conducted specifically buttressed quick formation of agglomerates via alkali-silicates formation in the bed when the mixture of Potassium hydroxide KOH and silica sand was heated together directly. At 350 ^{0}C, lumps of particles in form of agglomerates were produced. At 502 ^{0}C, stronger and harder agglomerates were produced. This also confirmed alkali-silicate existence in agglomeration chemistry. Brittle and weak lumps were produced when 10% kaolin was added to the mixture of KOH and silica sand. Outcome of this research are also applicable to other combustion beds especially the fluidized beds. Gooch ceramic crucible as the combustion chamber was to ensure that, higher temperature distribution is sustained within the chamber. EDX confirmed the elemental compositions of the agglomerates. The inner core contained silicon, Si while the outer layer contained mostly potassium, K. SEM showcased the structure and shapes of the agglomerates formed. Addition of additive, kaolin facilitated chemical reaction in the bed and produced a higher melting temperature (eutectic compound) in the form of alkali-alumina-silicates which would only melt at elevated temperatures. Therefore, kaolin is a reliable additive to control or reduce agglomeration during the combustion of biomass fuels in combustion beds (fixed and fluidized beds).

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