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Authentication of Lumps Formation in a Laboratory Scale - Fixed bed Combustion of Biomass Fuels – Impact of Additive

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ABSTRACT: *This study has focused on the impact of additive / authentication of agglomeration behaviour in some selected biomass fuels - white wood, willow, and miscanthus during their combustion processes in a laboratory-scale fixed bed by which Gooch crucible was used as the combustion chamber. Biomass fuels contains huge quantity of alkali metals particularly potassium, K and sodium, Na with potassium playing the predominant roles in the agglomeration formation of these selected problematic biomass fuels. Agglomerates were formed in the combustion chamber at 750 ^{0}C and 802 ^{0}C under the atmospheric pressure. This was credited to the formation of eutectic compounds in the form of alkali-silicates (K-silicates or Na-silicates). The eutectic compound has a lower melting temperature than the melting temperature of either the alkali metals from the biomass fuels or the silica from the bed materials (sand). It therefore melts quickly in the bed and formed chunks in form of agglomerates. Scanning electron microscopy and energy dispersive x-ray spectroscopy (SEM and EDX) on the samples confirmed agglomerates formation during the combustion processes of these selected biomass fuels. EDX results indicated that, the interior of the agglomerates was overshadowed with Si from the sand while the exterior or the peripheries were dominated with alkali metals, K, and Na from the biomass fuels ash.*

Other trace elements present in the agglomerates are P, Al, Ca, Cl, Fe, and Mg. With the addition of 10%additive (kaolin) Al2 Si2 O5 (OH)4 to the bed materials and the combustion processes repeated under the same operating conditions, no agglomerate was formed at either 750 ^{0}C or 802 ^{0}C. The results have shown that, addition of 10% kaolin (additive) to the biomass particles grossly reduced formation of agglomerates in the bed. Gooch ceramic crucible is a very reliable tool for the agglomeration experiments in the laboratories during biomass fuel combustion for heat generation or combine heat and power generation (CHPG). This is also applicable to other combustion beds particularly fluidized bed combustion (FBC).

Keywords: *Alkali metals, Eutectic compound, Agglomeration, Kaolin, SEM, and EDX.*

I. INTRODUCTION

Apart from the fact that, fossil fuels are fast depleting from the reserve, the flue gases emanating from the combustion of these fuels are not environmental friendly and tend towards polluting the surroundings [1, 2]. These flue gases also constitutes substantially to greenhouse effects (CO2 and CH4) through surface heating [3,4]. Biomass on the other hand when compared with fossil fuels is renewable and environmental friendly [5, 6].

Relevance of biomass fuels to the development of global economy through reliable energy supply cannot be over emphasized. Biomass can significantly bring about 60% to 70% of the world energy if adequately harnessed [7,8,9]. The continuous world population increase also commensurate with high-energy demand for various applications such as heating homes in the extremely cold regions of the world, sustaining quality research at higher institutions of learning and research institutes, various hospital services, and industrial applications. Therefore, regular and uninterrupted supply of energy is required for the technological advancement and stability of global economy [10,11].

The world over dependence on the supply of energy through the conventional means (The fossil fuels; the coal, crude oil and natural gas) is posing economic-instability especially in the developing countries of the world [12,13]. Many commercial activities in these countries had been crippled because of the shortage in the supply of the fossil fuels. The continuous dependent on these fuels poses varieties of danger to the society such as air pollution and increased greenhouse effect. These fuels are reducing at a faster rate from the reserve therefore more dependable, highly economical and environmentally friendly energy resources should be harnessed to salvage the energy sector from total dependent on fossil fuels that are no longer reliable. Moreover, biomass fuels possess some qualities that make it stand out and this include less ash content, reduced carbon monoxide CO, and less unburnt carbon [2, 11, 14].

Respiration in biomass (plants) requires that, carbon dioxide $CO2$ is taking in while oxygen $O2$ is released to the atmosphere. During photosynthesis, the absorbed $CO2$ in conjunction with water is used to manufacture biomass food in the presence of sunlight and chlorophyll while $O2$ is released to the atmosphere for the respiration in man [15, 16].

However, different types of problems such as fouling, agglomeration, erosion, and slagging have been discovered to associate with the process of generation of alternative energy from biomass (combustion), hence this research. The scope of this research encompasses authentication/control of agglomeration in a laboratory - scale fixed bed combustion of biomass fuels while applying kaolin as the additive and using a Gooch crucible as the combustion chamber. 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 [17,18]. Biomass fuels can be sourced from energy crops (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 [19]. Many complications that tend 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 [20]. Biomass contains alkali metals, potassium K, sodium Na, and mostly elements of group 1 in the periodic table, which through reactions and interactions with silica sand (bed materials) during combustion, cause some problems such as agglomeration, erosion, slagging, and fouling in the bed [20, 21]. 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 [21, 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. Eutectic temperatures are largely dependent on the melting points of alkali metals. The oxides of these alkali metals particularly Potassium ($K2O$) react with sand particles ($SiO2$) to form sticky substances called agglomerates [19, 20].

Moreover, there are other deposits formed during the combustion of biomass fuels and these includes; NaCl, KCl, $K2SO4$, and CaO. Alkali getter (additive) mostly kaolin when added to biomass has been identified to form a eutectic compound which has a higher melting point than either the silica from sand particles or the alkali metals particularly Potassium, K from biomass [20,7,22]. Biomass possesses high potentials to contribute to the energy requirement of the world. It is a renewable energy source mostly from organic matters and agricultural crops otherwise known as energy crops. The highest volume of this is obtainable from wood and wood wastes [17,23,24]. Moreover, domestic solid wastes in terms of percentage total, Table 1.1 are available on a large scale and can easily be accessed for heat and power generation. The moderate sulphur S content possessed by biomass has led to the generation of low sulphur dioxide $SO2$ emissions. Biomass also possesses the characteristics to replace the fossil fuel energy that is fast depleting from the reserves, because it is renewable and has the potentials for ash management and utilization. Biomass energy utilization is about 27% out of 6 EJ/yr in the European Union countries [25,26]. When biomass dies, decay or burnt, the overall $CO2$ it had stored in its entire lifetime is released to the atmosphere thereby, making the whole combustion process of biomass fuels, CO_2 neutral.

The leaves that drop off from the biomass tree is also a very rich source of manure and nutrients to the soil for un - interrupted growth of micro - organisms [27,28].

Different categories of conversion technologies include the fixed bed and the fluidized beds. Fixed bed was the traditional method of biomass / coal conversion in the past [29]. Fluidized bed on the other hand may be atmospheric (circulating or bubbling), or pressurized type. Conversion of organic wastes to useful fuels (synthetic) can be achieved through pyrolysis, gasification, bioconversion, and hydrogenation processes.

II. MATERIALS/EXPERIMENTAL SET UP

Platinum thermocouple was inserted into the combustion chamber through a 7.5 mm diameter hole on the Gooch crucible lid. Equipment engaged in this experiment includes 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 smoke tunnel, Figure 2.1. Materials used for the experiment are biomass fuels (willow chips, miscanthus pellets, and white wood pellets), silica sand (bed materials), coal (Cerrejon coal), and kaolin (additive).The thermocouple was connected to a temperature data lodger (Pico instrument) linked to a computer system to capture the temperature within the combustion chamber as phase transformation progresses.

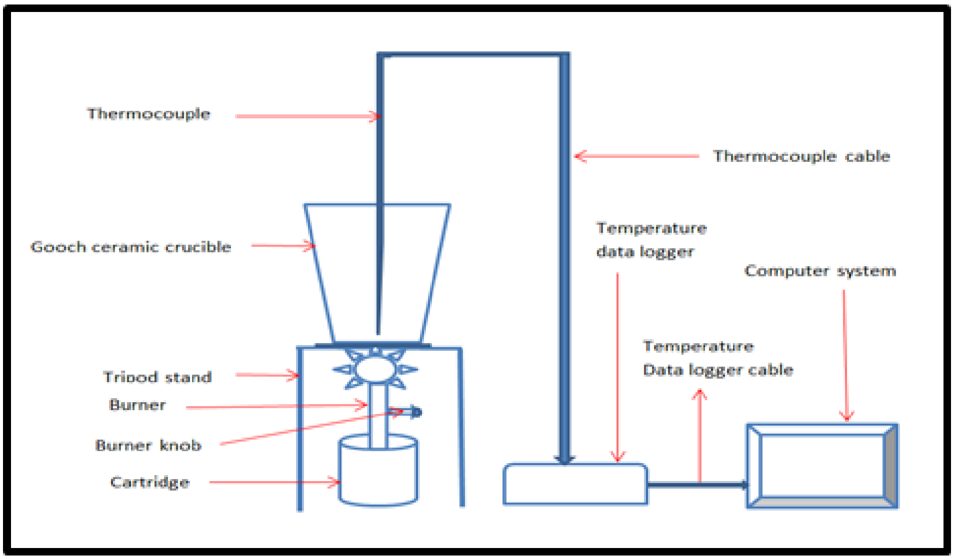

Figure 2 1 Rig set-up

Temperature of the surrounding fluids depicted that, the chamber has the highest temperature when compared with the temperature of the surrounding. This may have been attributed to the fact that, the combustion chamber was fully lagged with thermal insulation sheets to conserve more heat [27, 28]. Heat is transferred into the combustion chamber through the perforated area (grate like) located at the bottom of the chamber (Gooch alumina crucible). The Gooch crucible can be used to filter substances (filtrates and substrates) into another container but in this case, for the first time, it has been used as combustion chamber. This is similar to a distributor plate made of metal sheets used in Fluidized bed combustor.

III. RESULT

Results obtained from series of the combustion experiments conducted on the<1mm diameter miscanthus, wood, and willow Particles(single and blends the biomass fuels) with the intention to authenticate agglomeration behaviour in them are discussed. The experimental strategy was in the order of burning of individual single biomass fuels and blends of these biomass fuels (miscanthus, willow, white wood, and silica sand) with and without the addition of kaolin. Upon close examination on the samples collected after the combustion process, at 700 0C, no agglomerate was spotted in the samples but at 750 0C, traces of flake-like lumps were observed in the samples. These signs mark the beginning of agglomeration in the combustion chamber. Meanwhile, at 802 0C, the samples were observed to have increased in size, formed different shapes, and fused together into huge lumps of agglomerates. This was also experienced in other selected biomass fuels. The combustion experiment was repeated for three times and the average data compiled. Huge lumps of particles found in the samples confirm that, agglomeration has occurred in the combustion bed while burning the selected problematic biomass fuels- miscanthus, willow and wood, Figure 3.1.

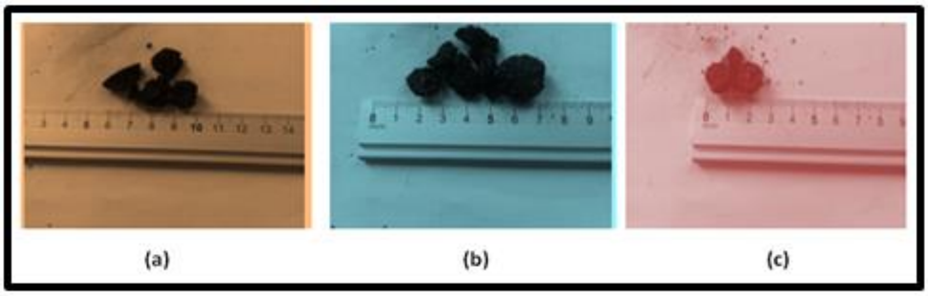

Figure 3.1: (a) Agglomerates from <1mm white wood particles at 802 ^{0}C. (b) Agglomerates from <1mm miscanthus particles at 802 ^{0}C, (c) Agglomerates from <1mm willow particles at 802 ^{0}C

Initial size of the samples was <1mm diameter before the combustion process. After the combustion of the particles, the size of agglomerates formed in white wood and miscanthus particles increased to an average of 10mm diameter while the size of the agglomerates produced in willow is about 7mm diameter, Figures 3.1a, 3.1b, and 3.1c respectively. This is a clear indication that, agglomeration had occurred in the bed. If not controlled, it can truncate the whole combustion process. Temperature distribution in the combustion chamber at 802 ^{0}C is depicted in Figures 3.2. The experience was the same in other selected biomass samples.

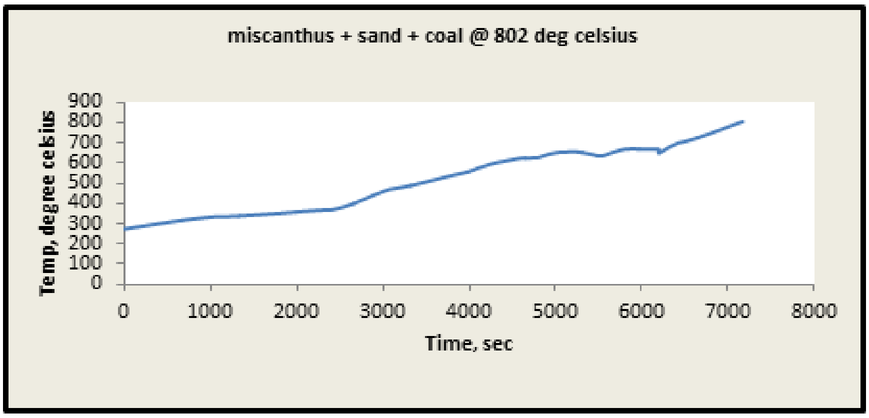

Figure 3 2: Miscanthus + Sand + Coal at 802 0C

IV. DISCUSSION

4.1 Influence of Additive and Pressure on Agglomeration Tendencies

Impact of additive and pressure on the agglomeration behaviour of the selected biomass fuels is discussed. Simulation results obtained from the application Fact sage software indicated that, with the addition of additive (kaolin) to the bed contents, pressure has tremendous influence on the formation of agglomerates in the combustion beds.

The higher the pressure in the bed, the higher the temperature and the longer the time at which agglomeration will occur in the bed. Considering the binary phase diagrams emanated from the application of Factsage software on the combustion of these selected biomass fuels (willow, miscanthus, and white wood), only two components were compared simultaneously (kaolin and alkali compounds) while in the ternary phase diagrams, three components were compared together simultaneously (alkali compounds, kaolin, and silica). Moreover, at a pressure of 1 bar, simulation results gathered from the series of binary phase diagrams predicted the occurrence of agglomeration at elevated temperatures of 1200 ^{0}C and 1708 ^{0}C in the combustion if the dominant alkali metals are potassium, K and sodium, Na respectively Figures 4.1 and 4.2 respectively.

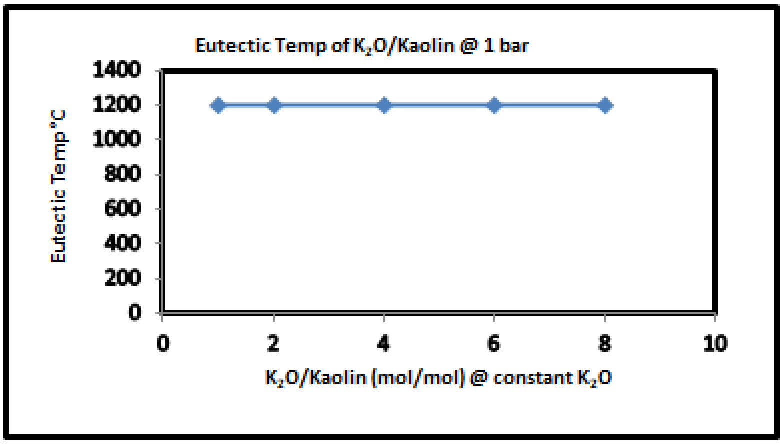

Figure4 1: Eutectic Temperature with Factsage software application at 1200 ^{0}C

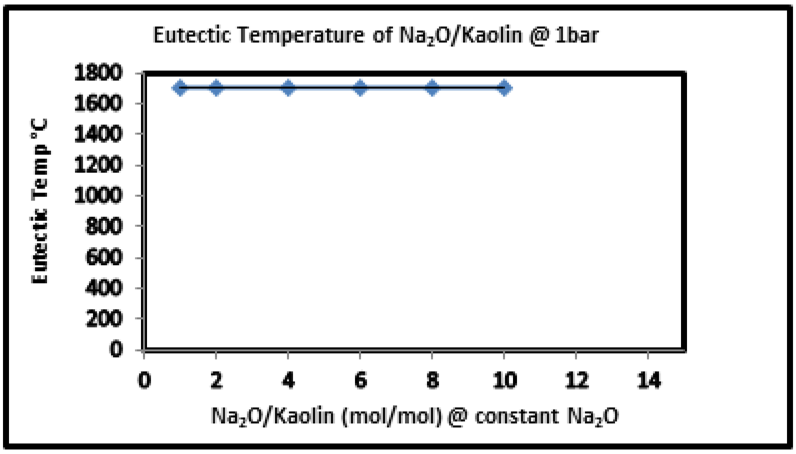

Figure 4 2: Eutectic Temperature with Factsage software application at 1700 ^{0}C

However, temperature at which agglomeration occurs in the bed increases as the pressure increases. At a pressure of 5 bar, and if the dominant alkali metal is potassium K, eutectic temperature was predicted to be 1566 ^{0}C, Figure 4.3

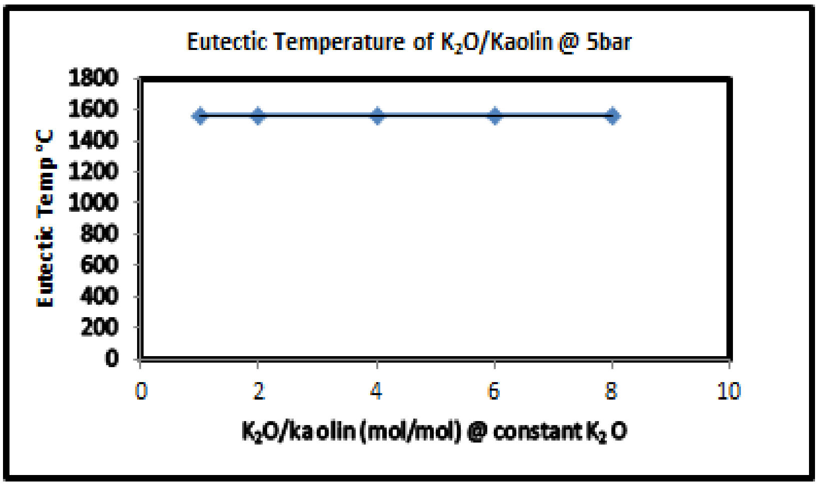

Figure 4.3: Eutectic Temperature with Factsage software application at 1600 ^{0}C

4.2 Scanning Electron Microscopy (SEM) Analyses of the Samples (Willow, Miscanthus, and White Wood) After Combustion

Post combustion analyses carried out on the bed samples with specific interest on the SEM confirmed agglomerates formation in the bed, Figures 4.3 to 4.7. Letters on the figures represents nomenclature for easy identification and discussions of the images. There are two noticeable sections on image C based on its brightness. The overall dark area in Figures 4.3C and 4.3D is made up of the mixture of coal and resin used for the preparation of the specimen for SEM analyses while the brighter sections contained the molten < 1mm willow and miscanthus particles respectively at 750 0C and 8020C. SEM images of the three samples are shown in Figures 4.3 to 4.6.

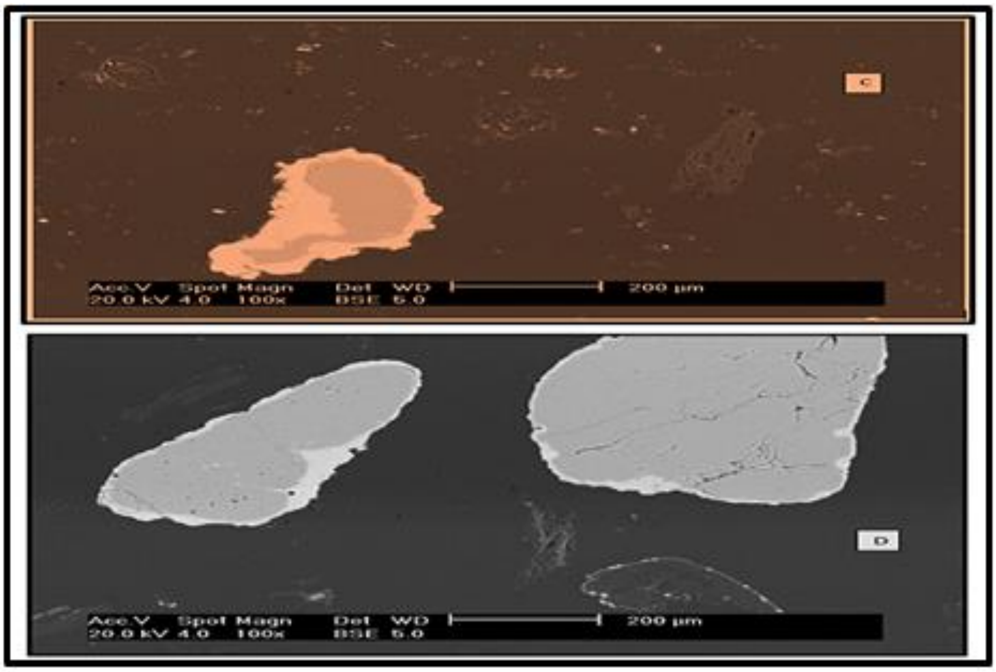

Figure 4.3(C) SEM image of agglomerates from the combustion of <1mm willow particles at 750 ^0C
(D) SEM image of agglomerates from the combustion of <1mm miscanthus particles at 802 ^0C

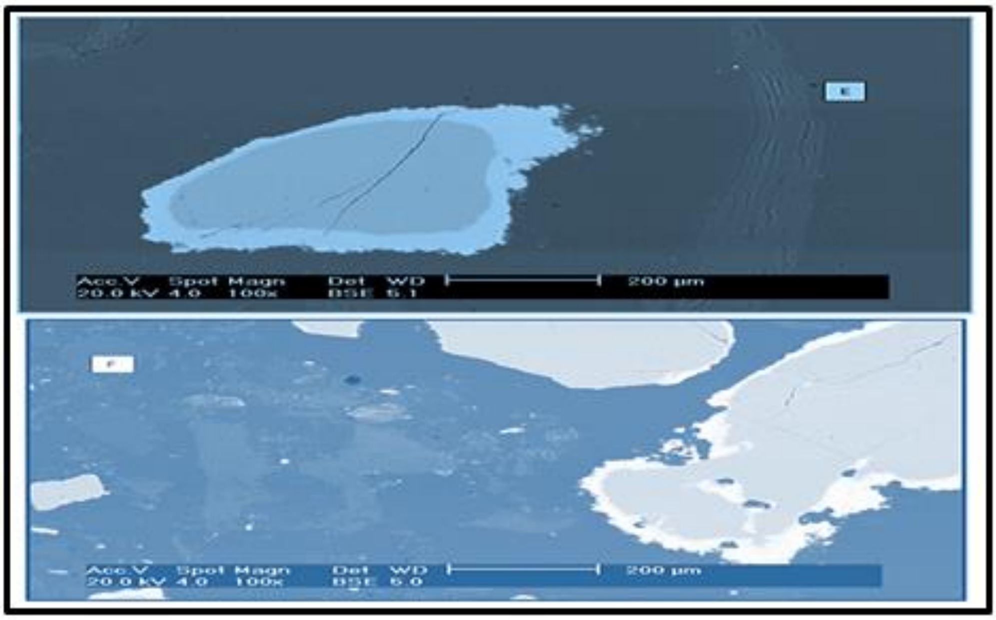

Figure 4 4 (E) SEM image of agglomerates from the combustion of <1mm white wood particles at 802 ^0C (F) SEM image of agglomerates from the combustion of <1mm willow particles at 802 ^0C

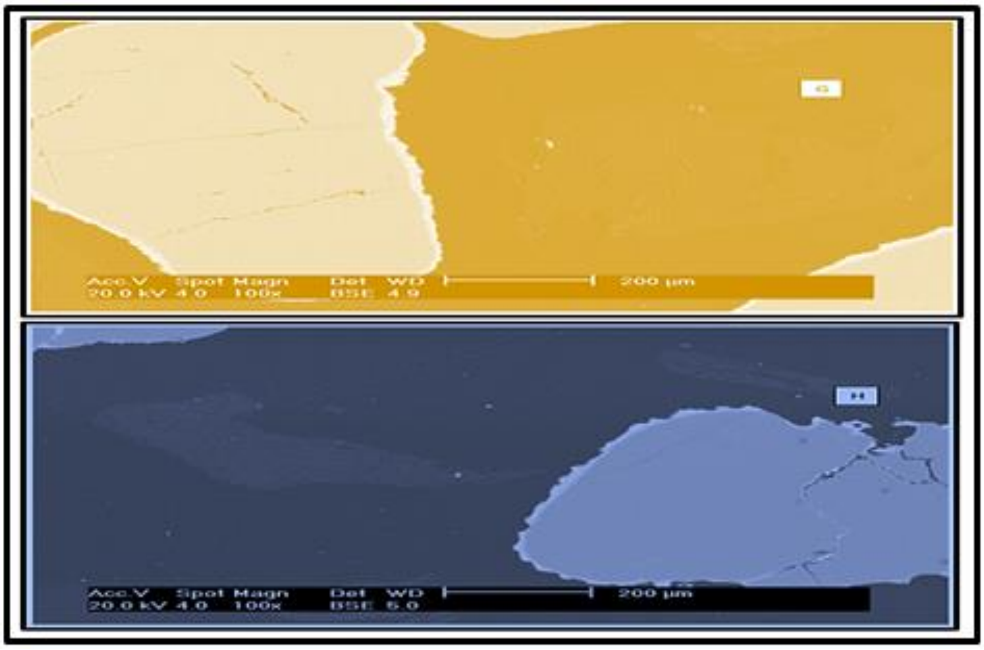

Figure 4.5(G) SEM image of agglomerates from the combustion of <1mm mixture of wood + miscanthus particles at 802 0C, (H) SEM image of agglomerates from the combustion of the mixture of willow + wood particles at 802 ^{0}C

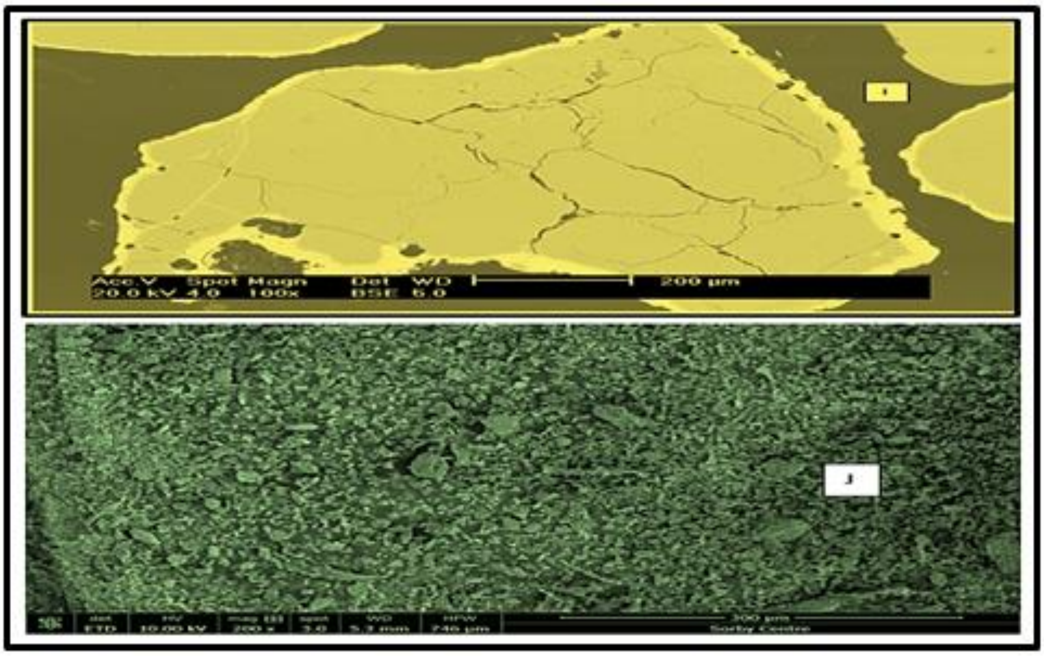

Figure 4.6(I) SEM image of agglomerates from the combustion of the mixture of miscanthus + Willow particles at 802 ^{0}C, (J) Powder image of the mixture of Kaolin + wood particles at 802 ^{0}C.

4.3 Energy Dispersive X-Ray Spectroscopy (EDX) Analyses of the Samples (willow, miscanthus, and white wood) after combustion.

EDX Spot analysis of the selected areas on the electron images was adopted as the main technique for these analyses. The machine focused on different spots called the spectra. Elemental composition at each spot established, Table 4.1.

Table 4-1: EDX Spot analysis of blends of willow, white wood, and miscanthus at 802 ⁰C

Wt %	Wood + Willow					Miscanthus + Wood					Willow + Miscanthus				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Si	74	40	46	0	0	39	20	0	0	0	67	61	0	0	0
K	0	23	21	0	0	0	12	0	0	0	10	0	0	0	0
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mg	0	4	2	0	0	0	2	0	0	0	1	0	0	0	0
Al	0	4	4	0	0	0	2	0	0	0	0	0	0	0	0
Ca	0	3	3	0	0	0	3	0	0	0	2	0	0	0	0
S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	1	2	0	0	0	2	0	0	0	0	0	0	0	0
Fe	0	0	3	0	0	0	1	0	0	0	1	0	0	0	0

Numbers 1,2,3,4 and 5 represents the spectra. The elements present in each spectrum are as shown in Table 4.1. Figure 4.7 comprised of SEM-EDX images of the mixture of 50% wood and 50% miscanthus particles melted at 802 0C. Spectrum 1 of panel a consisted of mostly Si (38.52 wt %). The light grey region indicated the melted alkali-silicate mixture. Spectrum 2 comprised of mostly Si (19.54 wt %) and other elements like; K-Feldspar (11.45 wt %), Mg (2.23 wt %), Al (2.15 wt %), P (1.74 wt %), Fe (1.28 wt %). Ca (3.16 wt %).Spectrum 3 of the electron image comprised mostly of, carbon C (74.53 wt %) and oxygen O (20.00 wt %) that emanated from the adhesive while Ca (3.16 wt %)

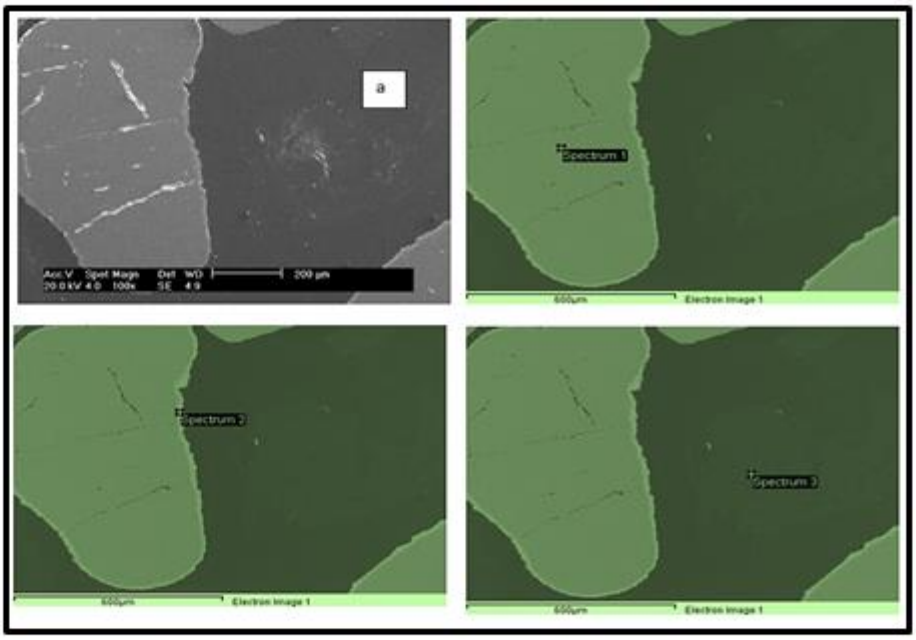

Figure 4.7: SEM image of the mixture of wood with miscanthus melted at 802 ^0C and SEM-EDX images of the selected areas in panel a.

V. CONCLUSION

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 (alkali and silica) therefore, melts quickly in the bed during combustion.

All the combustion experiments conducted on the selected biomass fuels (white wood, miscanthus, and willow) produced agglomerates except when additive (kaolin) was added to the mixture and no agglomerate was formed. Moreover, there was elongation in the size of the biomass particles from <1mm to 10mm diameter during the combustion involving wood and miscanthus while combustion involving willow particles produced elongated particles from <1mm to about 6mm diameter. Comparing the samples before and after combustion, there was a huge increase in the size and shapes of the samples after combustion in the bed. This served as confirmation that, agglomeration had occurred in the bed.

Post combustion analyses, scanning electron microscopy (SEM) analyses conducted explicitly revealed the morphological structures of all the samples considered. The SEM revealed the structures, shape, and sizes of the agglomerates produced during the combustion processes.(EDX) Energy Dispersive X-Ray Spectroscopy affirmed the elemental compositions making up the samples. Spot analyses, element mapping, and spectra analyses showed that, the samples were massively dominated by the alkali - potassium, K, sodium, Na, and the alkali earth metals, magnesium, Mg, calcium, Ca. In addition, silicon, Si was present in large quantity in all the samples. Some trace elements - phosphorous P, iron Fe, Silicon S, and Chlorine Cl. Concentration of each element varies per spot depending on the spotted area. Impact of additive (kaolin) on the control of agglomeration during the combustion of the selected biomass fuels was fully established. No agglomerate was produced when Kaolin was pre-mixed with the bed contents to examine the agglomeration tendencies and behaviour of the biomass fuels in the experiments conducted. Steady combustion of biomass fuels to generate heat, power, or combine heat and power is greatly guaranteed for national industrial growth with the addition of kaolin to the mixtures. Outcome of this research had shown that, introduction of a Gooch ceramic crucible as the combustion chamber enhanced high temperature distribution within the chamber. This is a major contribution to knowledge in this research work. Temperature of 802 0C was able to melt the biomass fuels particles during the combustion processes.

VI. ACKNOWLEDGEMENT

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