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BIOMASS

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AGGLOMERATION DURING FLUIDIZED-BED COMBUSTION OF BIOMASS

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ABSTRACT

Wheat stalk is tested to investigate the formation of bed agglomeration. The results show that defluidization time decreases with the combustion temperature increasing. The minimum fluidization velocity of the bed material after the test increases. The K, Ca and Si elements play the most important role in bed defluidization.

INTRODUCTION

Fluidized beds are widely used for the combustion of biomass due to their advantages of burning a broad variety of fuels and significant economic importance. However, the bed agglomeration which can result in the unscheduled shutdown of fluidized bed reactors has become a serious problem. The typical biomass contains high alkali content, which is released from the fuel during combustion conversion. It may thereafter be transported to the surface of the bed particles forming a sticky layer, which favors agglomeration (Arvelakis *et al.* (1); Bartels *et al.* (2); Olanders and Steenari (3)).

In literature, the effects of running parameters (such as bed temperature, fluidization velocity, etc.) on the bed agglomeration have been reported. The temperature has a pronounced effect on the defluidization time, which can be significantly increased with increasing temperature (Lin *et al.* (4); Olofsson *et al.* (5); Scala and Chirone (6)). An SEM/EDX study of the agglomerates is conducted, focusing on the main fuel ash components and their interaction with the bed sand particles. The defluidization occurs with the increase in the experimental time (Brus *et al.* (7); Lin *et al.* (4); Llorente *et al.* (8); Ohman *et al.* (9) ;). Because the combustion operates at high temperature, some researchers have predicted and measured the minimum fluidization velocities (u_{mf}) influenced by the change in gas physical properties at high temperature. The results show that the minimum fluidization velocity decreases with the temperature increasing (Goo *et al.* (10); Guo *et al.* (11); Lin *et al.* (12); Subramani *et al.* (13)).

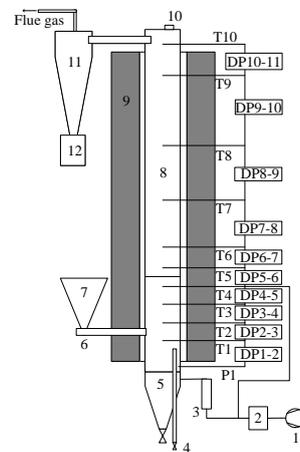
The fluidization character of bed material changes when the biomass combusts in the fluidized bed, which is the direct reason for the agglomeration, but the changed mechanism of the fluidization character has not been determined because there are not enough experimental evidences to verify these.

In the present study, wheat straw is used as the study object. The quartz sand is chosen as the bed material. The experiment is carried out in a lab-scale bubbling fluidized bed combustor. The effects of bed temperature on the defluidization time are studied. An SEM/EDX study of bed material samples has been carried out to investigate the effect of combustion on surface feature. The predicated minimum fluidization velocities, and the u_{mf} measured from the pressure drop in the bubbling bed at different temperatures, are investigated to study the fluidization characteristics of bed material effect at different combustion temperatures.

EXPERIMENTAL APPARATUS AND PROCEDURE

Apparatus

The experimental apparatus of 5 kW BFBC, schematically shown in Figure 1, consists of a bubbling fluidized bed combustor, a set of pressure transducers and thermocouples, a fuel feeding system, a data acquisition unit, a gas analysis system and an electric heat system. The combustor is made of high temperature resistant steel tube with an inner diameter of 100 mm and a height of 1750 mm. The combustor is electrically heated by three independently controlled heating elements. Compressed air from a gas compressor, controlled by precision mass flow controller and meter, is fed to the bottom of the combustor. Fuel is stored in a container and can be continuously fed to the combustor at 230 mm above the air distributor by a screw feeder. The data are logged to a computer by Agilent 34970A Data Acquisition Switch Unit. The fly ash in the flue gas is separated from the gas by a cyclone and collected into a container. The combustion and fluidization behaviors can be



1 air compressor; 2 air-drying machine; 3 mass flowmeter; 4 sampling tube; 5 air chamber; 6 screw feeder; 7 hopper; 8 combustor; 9 electric stove; 10 observation window; 11 cyclone; 12 ash hopper;

Figure 1 Diagram of the experiment system

visually observed through a window in the reactor top. Particles can be sampled from the sampling tube in the bottom during experiments.

Fuel and bed material

The fuel used is Chinese wheat straw. The straw was pelletized to a size range 5-15 mm. The proximate and ultimate analyses of the straw pellets are shown in Table 1. The chemical analysis of fuel pellets by inductively coupled plasma-optical emission spectroscopy (ICP-OES) (IRIS Intrepid II XPS, Thermo Fisher Scientific Inc.) is shown in Table 2. It is indicated that the fuel typically has high potassium content. Quartz sand (the Composition shown in table 3) with various size ranges is used as bed material in the experiments.

Table 1 Composition of fuel (wt.%)

	M_{ad}	A_{ad}	V_{ad}	FC_{ad}	C_{ad}	H_{ad}	N_{ad}	O_{ad}	S_{ad}
wheat straw	1.8	6.84	71.98	19.38	44.29	5.50	0.56	40.81	0.20

Table 2 Inorganic elements of fuel (ug/g)

	Al	Ca	Fe	K	Mg	P	Si	Na
wheat straw	324.9	3375	732.9	17962	1773	487.6	237.4	1016

Table 3 Composition of bed materials (wt.%)

	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	K_2O	SO_3
quartz sand	97.55	0.58	0.42	0.75	0.28	0.14	0.09

Experimental procedure

In all experiments the same amount of sand particles was used with a bed height of approximate 300 mm in the stationary state in the combustor. The BFB combustor was heated up to 600°C by electrical heater, and biomass stored in a hopper was then fed gradually into the combustor. The average temperature 380 mm above the distributor was used as bed temperature. The tests started when the bed temperatures reached the defined values. Bed temperature was roughly fixed at 750°C, 800°C, 850°C, 900°C and 950 °C. The BFB combustor was operated according to the parameters in Table 4. All the experiments were carried out continuously and separately. The defluidization was marked by a sharp decrease in the pressure drop over the bed. If no defluidization occurred, the experiments lasted 15h. The time from the test starting to defluidization occurring is defined as the defluidization time. After the experiment, the particles sampled during combustion were analyzed by SEM/EDX and XRF.

Table 4 Operating parameters

Parameter	Range
Biomass pellets feeding rate (kg/h)	0.5

Fluidization velocity (m/s)	0.26-0.36
Excess air ratio	1.1-1.3
Average temperature along the furnace (°C)	27-800

RESULTS AND DISCUSSION

The influence of bed temperature

The defluidization time as a function of bed temperature is plotted in Figure 2. The results present that the influence of temperature on the defluidization time is significant. The defluidization time is 13.83 h when the bed temperature is 750°C, and when the temperature is 950°C, it is only 0.17 h. As the temperature increases, the defluidization time decreases. When the defluidization occurs, the pressure drop of the bed is over 10 kPa/min. At the same time, the bed temperature increases at the rate of 40 °C/min. The agglomerate is sticky when the defluidization occurs, but it is to be broken when the temperature decreases to the room temperature.

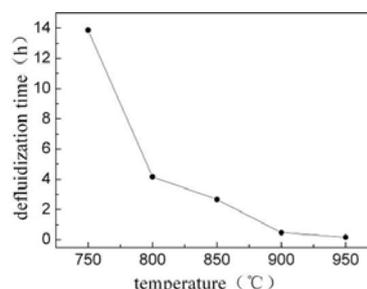


Figure 2 Influence of temperature on the defluidization time

The influence of gas velocity

As bed temperature is 900°C, the influence of gas velocity is examined by changing the gas flow rate. The combustion stoichiometry is kept the same by taking the second air from 580 mm above the distributor. The experimental results are listed in Figure 3. The defluidization time will be extended as the gas velocity increases. The high gas velocity in the bed will lead to a better mixing of the particles and increase the force acting on agglomerates, and the fuel ash in the gas will increase. These two factors will both decelerate the defluidization. The defluidization occurs in all experiments, therefore, the increase in gas velocity could extend the defluidization time, but can't avoid defluidization.

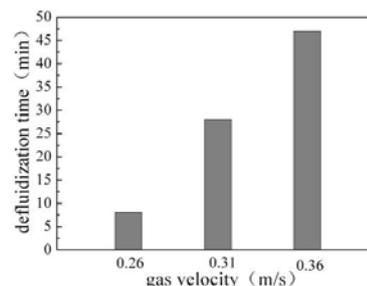


Figure 3 Influence of gas velocity on the defluidization time

The influence of the particle size

The effect of the sand particle size on the defluidization time is given in Figure 4. At the same ratio of u/u_{mf} and combustion temperature, it appears that sand particle has

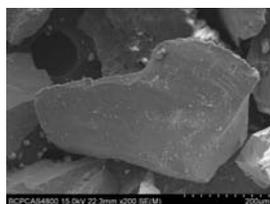
no effect on the defluidization time. Large particles have a low specific outer space area, resulting in a thicker ash coating layer, which accelerates the defluidization. However, the minimum fluidization velocity is high for large particles. The increase in the high gas velocity will decelerate the defluidization. The influence

of gas velocity and particle size of bed material is in agreement with that reported by Bartels *et al.*(2), Scala and Chirone(6) and Lin *et al.*(4) in experimental studies.

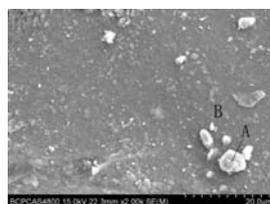
SEM/EDX analysis

At the end of each combustion test, some of the bed materials were examined by SEM/EDX analyses. An example of sands before test can clearly be viewed in Figure 5. In particular, Figure 5b clearly shows the surface of the sands, which looks smooth and clean. The examples of sands after test are viewed in Figures 6 and 7, and Figure 6b shows the SEM micrographs of typical sands from the bed after defluidization at 750°C. The surface appears to be composed of small particles attached to the sands. The Figure 7b shows the SEM micrographs of typical sands from the bed after defluidization at 800°C, and the sand particles appear to be completely embedded in a fused layer of material.

Compared with Figure 6b, the degree of the sand particles sticking and melting on the surface is greater. Results of EDX spot analyses of selected zones of the sands (points A-B in Figure 6b, points C-D in Figure 7b) are reported in Table 5. An enrichment of potassium can be clearly observed in the fused layer.

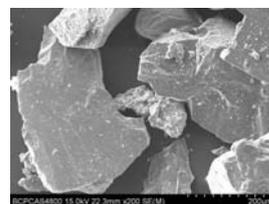


a

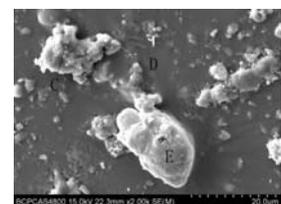


b

Figure 6 SEM image of particles and EDX analyses on the surface (sampled after defluidization, $T=750^{\circ}\text{C}$)



a



b

Figure 7 SEM image of particles and EDX analyses on the surface (sampled after defluidization, $T=800^{\circ}\text{C}$)

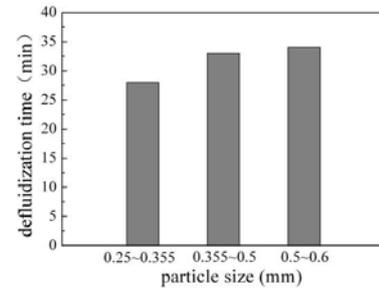


Figure 4 Influence of sand particle on the defluidization time

In the combustion experiment, the onset of bed agglomeration is attributed to the

presence of alkali species in the ash of biomass fuels, which interact with silica sand under high temperature conditions leading to the formation of low-melting point eutectics. The particles stick together with the melt, which induces agglomeration. The molten ash particles are considered to act as neck to bond the bed particles in the agglomerate formation process (Lin *et al.* (4)). The melting of coating layers of bed particles is considered to be responsible for the bed agglomeration (Nijenhuis *et al.* (14); Ohman *et al.* (15)). The stickiness of small fuel ash particles displayed Figures 6 and 7 are the direct reason for agglomeration.

Table 5 EDX analyses of particles on the surface (wt. %)

spot	O	Si	K	Ca	Cl	Mg	P
A	52.23	17.20	10.96	8.54	4.52	2.52	4.04
B	53.52	46.48	nd	nd	nd	nd	nd
C	49.88	27.09	15.41	7.62	nd	nd	nd
D	47.83	43.54	8.63	nd	nd	nd	nd
E	48.80	35.99	15.21	nd	nd	nd	nd

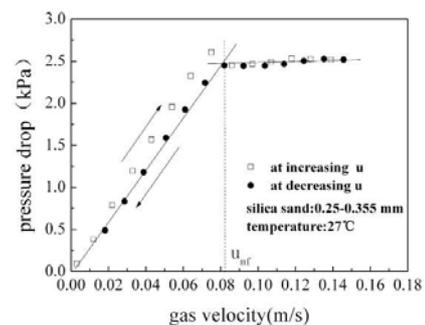
Particle size analysis

The Mastersizer 2000 particle size analyzer (Malvern Instruments Ltd) was used to analyze the sands sampled before and after experiment separately. The results are shown in Table 6. After the test, the average particle size is increased. The particle size of sands sampled from the bed material after defluidization at 800°C is greater than that after defluidization at 750°C. As the bed temperature increases, the melt layer coating on the sands will increase.

Table 6 The particle size analysis of sands

Name	Sampled before test	Sampled after test	
		750°C	800°C
Average particle size (um)	308.015	321.779	330.475

Effect of temperature on minimum fluidization velocity



Using the 5 kW BFB, the measured minimum fluidization velocities from the pressure drop in the bubbling bed with variation of gas velocity are shown in Figure 8. The experiments cover the temperature range of 27-800°C. The electrical furnace and a PID controller, driven by a thermocouple immersed in the bed, were used to keep temperature at the value required in each experiment. The effect of temperature on u_{mf} , determined in this study, is shown in Figure 9.

Figure 8 Typical diagram of the pressure drop at varying fluidization velocity

At the minimum fluidization conditions, Wen & Yu used a modified Ergun equation to predict u_{mf} . The comparison of calculated and experimental data is shown in Figure 9. The u_{mf} of sand particles before the test increases with the increase in temperature. The calculated results agree well with the experimental data, and the maximum of relative error approximates 27 %. However, for the sand particles after the combustion experiment, in the range of 400-750°C, u_{mf} increases with the increase in temperature. In the combustion condition, the sand particles react with fuel ash, leading to the change in the fluidization characteristics of sand particles at high temperature.

During biomass fuels combustion in a fluidized bed, potassium in the biomass fuels interacts with silica sand under high temperature conditions, leading to the formation of eutectics, which attach on the surface of sand, thus, the average particle size increases. Melt and coating layer induces defluidization. After the combustion experiment, the melt and coating layer is melted again when the temperature increases.

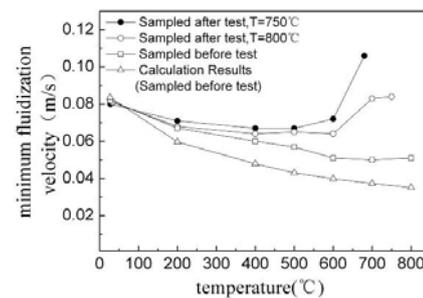


Figure 9 Influence of temperature on the minimum fluidization velocity

CONCLUSIONS

During biomass combustion in a fluidized bed, the eutectics are formed mainly by the reaction between the alkali species in wheat straw ash and the silica in bed particles. The melt layer on the surface of sands particle mainly contains potassium, some calcium and magnesium, and also a few phosphorus and chlorine are found in the melt layer. The defluidization time decreases with the combustion temperature increasing. When the gas velocity increases, the defluidization time extends obviously. And the size of the sand particles does not affect the defluidization time. The u_{mf} of sands decreases with temperature increasing. However, the u_{mf} of sand particle after combustion experiment increases with temperature increasing.

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