Applied Thermal Engineering 70 (2014) 737–747

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

# The characteristics of bed agglomeration/defluidization in fluidized bed firing palm fruit bunch and rice straw

Pawin Chaivatamaset [a,*], Panchan Sricharoon [a], Suvit Tia [a], Bernd Bilitewski [b]

[a] Combustion Research Laboratory, Department of Chemical Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand
[b] Institute of Waste Management and Contaminated Sites Treatment, Technische Universität Dresden, Pirna 01796, Germany

## HIGHLIGHTS

- The bed agglomeration was investigated during the FBC of palm bunch and rice straw.
- Bed temperature, sand size, air velocity and static bed height affected the bed agglomeration tendency.
- The combustion of bunch showed higher in the bed agglomeration tendency than that of straw.
- The formation of the ash derived K-silicate melts was responsible for the agglomeration.
- The collision between the burning fuel particles and the bed particles dominated the ash migration.

## ARTICLE INFO

*Article history:*
Received 7 October 2013
Accepted 7 May 2014
Available online 6 June 2014

*Keywords:*
Fluidized bed combustion
Bed agglomeration
Palm fruit bunch
Rice straw

## ABSTRACT

The behaviors of bed particle agglomeration and defluidization were investigated during the combustion of oil palm bunch and rice straw in a laboratory scale bubbling fluidized bed reactor. The study focused on (1) the effects of fuel inorganic properties and operating variables on the bed agglomeration tendency and (2) the elucidation in the behaviors of fuel inorganic elements and the governing mode of the agglomeration. It was experimentally found that the defluidization caused by the bed agglomeration was clearly detectable from the decrease of measured bed pressure. The accumulation and growth of the agglomerates provided the partial to complete defluidization. The fuel inorganic composition was the significant influence on the bed agglomeration. The combustion of palm bunch showed higher in the bed agglomeration tendency than the straw combustion in every experimental condition. The defluidization was accelerated in response to the increase in bed temperature and bed particle size, and the decrease of air velocity and static bed height. In the SEM/EDS analysis, the agglomeration was attributed to the formation of the molten substance rich in silicon and fuel derived potassium, likely the potassium silicate compounds, which presented as the adhesive coating and bonding layer. The filling of irregularity on the bed particle surface by the liquid material to form the adhesive layer was dominated by the collision with burning fuel particles. The propagation/reaction inward the bed particles by some reactive constituents was found. The thermodynamic analysis on the ternary phase diagram corroborated that the formation of the liquid material derived from the fuel inorganic elements controlled the agglomeration; the large melt fraction in the adhesive materials at the observed bed temperature range (62–99%) was estimated.


## 1. Introduction

Fluidized bed is the particulate technique employs beds of refractory particles suspended and circulated by upward flowing air/gas. This feature provided well-recognized advantages [1,2], such as high heat transfer, large contact surface area, good gas–solid mixing, which have been exploited in the combustion of solid fuels, especially agricultural residues. However, biomass fuel from agricultural residues generally contains inorganic constituents that form liquid substances during combustion [3,4]. These substances cause bed particle agglomeration which affects the operation of fluidized bed. It gradually restricts particle circulation, decreases combustion efficiency and can even shut down fluidized bed (defluidization) [5]. Therefore, bed agglomeration is the greatest concern in fluidized bed combustion (FBC).

* Corresponding author. Tel.: +662 470 7538; fax: +662 470 7539.
*E-mail addresses:* pawin.cha@kmutt.ac.th, ipawsath@yahoo.com (P. Chaivatamaset).

http://dx.doi.org/10.1016/j.applthermaleng.2014.05.061
1359-4311/

According to previous intensive studies, bed agglomeration/defluidization was a consequence of complex interactions between fuel inorganic elements and bed particle, and was associated with the physical and chemical properties of fuel and bed particle, the characteristics of fluidized bed and reaction mechanisms [6–12]. In a view point of bed agglomeration, alkali potassium, refractory silicon, alkali earth calcium and non-metallic chlorine, sulfur and phosphorus were the important elements for biomass FBC, since they formed the low melting point compounds which their liquid phase depositing on the bed particle surface was generated by melting and chemical reaction [13] during combustion. The presence of molten coating on bed particles was early demonstrated [8–12]. When bed particles that molten phase presented on their surface touched adjacent particles, material at the point of contact migrated forming necks between bed grains. If the bonding force of the necks overcame breaking force, resulting from the collision and attrition of particles in bed, agglomerates were formed and defluidization began. Potassium was the key contributor to ash related problems including bed agglomeration, and its pathways during combustion were proposed in specific studies [14,15]. Three mechanisms responsible for agglomeration in FBC were described [16]. First was due to the presence of non-viscous liquid phase consisting of molten salts. The amount of liquid controlled the bridge formation. Cooling below the solidus temperature (*temperature which a substance is completely solid*) gave the crystallization of bonding agent and the densification of agglomerates. Second was due to viscous flow, which occurred in a silicate ash. The silicate ash deposit formed a highly viscous liquid layer on the surface of particles, when its temperature was above the solidus temperature. Flowing of this layer formed a neck between adjacent particles. On cooling, the neck and coating froze to a glassy substance. Third was due to chemical reaction to form a third compound binding bed particles. It was responsible for fuel ashes rich in calcium. Sulfation and carbonation of calcium ash species were typical [17,18].

More intimate understanding to the fate of inorganic elements in fuel during combustion and their resultant effects on bed agglomeration is required for the success of applying FBC to produce energy from specific biomass. Therefore, the present study was carried out in order to provide further insight to the complex behaviors of bed agglomeration during the combustion of palm fruit bunch and rice straw. The objectives were to investigate experimentally the effects of fuel characteristics and operating variables on the bed agglomeration tendency and to further elucidate the behaviors of fuel inorganic elements and the governing mechanisms of agglomeration.

## 2. Experimental

### 2.1. Biomass and bed material

Two biomass fuels selected for the bed agglomeration experiment were palm empty fruit bunch and rice straw. Empty fruit bunch (EFB), empty husks left over after oil extraction from palm fruit, is generated as a residue from palm oil mill. In Thailand [19], part of EFB is utilized as solid fuel to produce steam and electricity in palm oil mills and used as fertilizer and culture media. However, large quantities still have no specific use. Rice straw is the dry stalk of rice, after the grains have been harvested on fields. The small amount of straw produced in Thailand [19] has agricultural uses, such as mulch, media and roughage, while the large is left over.

The proximate, ultimate and ash analyses of the fuels were given in Table 1. The fuels contained the high volatile substance and low fixed carbon. They also had the high oxygen content, and low chlorine and sulfur contents. Silicon was rich in the biomass ashes, expressed as oxide form. The potassium content in both fuels was relatively high. The potassium and chlorine contents in the bunch were significantly greater than those of straw, while the difference of the alkali earth contents was slightly. Therefore, the fluidization during the combustion of these fuels was expected to be problematic to some extent from their potassium and chlorine contents.

**Table 1**
Characteristics of the biomass fuels.

| Density ($kg/m^3$) | Palm empty brunch | Rice straw |
|---|---|---|
| Bulk[a] [ASTM E873-82(98)] | 28.69 | 42.56 |
| Proximate analysis[a] (%wt) [ASTM E870-82(2006)] | | |
| Moisture | (63.44[b]) 9.23 | 10.09 |
| Volatile | 74.48 | 69.49 |
| Fixed carbon | 19.29 | 16.38 |
| Ash | 6.22 | 14.13 |
| HHV[c] (kJ/kg) | 17,530 | 15,215 |
| Ultimate analysis[c] (%wt) | | |
| Carbon | 34.71 | 28.62 |
| Hydrogen | 4.47 | 3.76 |
| Oxygen [diff] | 53.79 | 52.49 |
| Nitrogen | 0.64 | 0.89 |
| Sulphur | 0.05 | 0.09 |
| Chlorine [ASTM E776-87(2004)] | 0.15 | 0.02 |
| Inorganic elements (%wt) | | |
| $SiO_2$ | 51.80 | 60.10 |
| $Al_2O_3$ | 0.47 | 0.00 |
| CaO | 0.95 | 0.80 |
| MgO | 18.06 | 21.97 |
| $Na_2O$ | 0.33 | 0.80 |
| $K_2O$ | 21.39 | 10.57 |
| $P_2O_5$ | 4.06 | 2.45 |
| $Fe_2O_3$ | 0.72 | 0.20 |
| Other | 2.22 | 3.11 |

[a] as fired basis.
[b] as received basis.
[c] as dry basis, [diff]: determined by difference.

The bed particle used for the experiment was silica sand. Its chemical properties analyzed by X-ray fluorescent (XRF) and X-ray diffraction (XRD) were given in Table 2 (expressed as oxide form) and Fig. 1, respectively. The bed material was assertive $SiO_2$ compound (Melting point: 1600 °C) in the hexagonal crystalline structure. Since it was to be a controlled condition in the experiment, the adopted size ranges of the sand were intentionally fixed in the narrow distribution, as shown in Fig. 2. The size ranges of 300–355 μm (average size: 323 μm) and 425–500 μm (459 μm) were employed. However, the diminutive fractions of smaller size ranges were still found, due to ordinarily imperfect sifting and cracking.

### 2.2. Apparatus

The agglomeration experiment was completed in the laboratory scale bubbling fluidized bed unit schematically illustrated in Fig. 3. The reactor was a stainless steel cylindrical tube of 9 cm. ID and 1.8 m height, placed in an electrical tube furnace applied to preheat

**Table 2**
Compositions of silica sand.

| Physical properties | |
|---|---|
| Material density ($kg/m^3$) | 2510 |
| Elemental compositions (wt%) | |
| $SiO_2$ | 99.55 |
| MgO | 0.008 |
| CaO | 0.02 |
| $Al_2O_3$ | 0.16 |
| $Fe_2O_3$ | 0.05 |