Advanced Powder Technology 27 (2016) 215–222

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Numerical and experimental study of tensile stresses of biomass combustion ash with temperature variation

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ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form 8 December 2015
Accepted 14 December 2015
Available online 28 December 2015

Keywords:
Biomass ash
Particle cohesive force
Tensile strength
Discrete element method
Bonded Particle Model

ABSTRACT

The consequent lack of basic understanding of the cohesiveness of ash particles at high temperature is a major hindrance to advancing biomass combustion technology. This paper presents an investigation of the effect of temperature on tensile strength by a combined experimental and numerical method. Experimentally, tensile strength and fracture distance of palm residues combusted at 820 °C were measured as a function of temperature (25–800 °C). The results showed that the tensile strength is strongly dependent on temperature and the liquid bridge between particles may transform into partially solid bonds with increasing temperature. In numerical simulation by means of discrete element method (DEM), the cohesive force between particles was modelled using the so called Bonded Particle Model (BPM) and Capillary Force Model (CFM). The parameters of BMP and CFM models at different temperatures were determined by an empirical equation. Comparison with the existing test results showed that the model can reasonably describe the behaviour of biomass combustion ash under various temperatures. It was therefore confirmed that the proposed cohesive force model can be used in the DEM-based simulation of biomass ash deposition in the combustion devices, leading to better understand the phenomena of shedding and erosion in the future.

1. Introduction

Recent years have witnessed a rapid growth of the use of biomass as a fuel in combustion devices, especially in small-medium size power and/or heat plants [1]. Thus, extensive investigations have been carried out worldwide recently to enhance biomass combustion efficiency. Biomass fuel is often a waste material produced by industrial processes, or forest and agricultural residues, and the peculiar characteristics of such a fuel may cause problems to the burner [2]. One of these is related to deposit formation, as biomass combustion produces ash which may have a low softening/melting temperature due to its relatively high alkali content [3]. Accordingly, the ash particles entrained in the gas flow may be sticky even at relatively low temperatures, with an ensuing high chance of formation of deposits over the furnace walls and heat exchange tube [4,5], which reduces the furnace efficiency and requires frequent stops for overhauling [6,7]. The consequent lack of basic understanding of the cohesiveness of ash particles is a major hindrance to advance of biomass combustion technology.

In our previous works, tensile strength and thermal and thermomechanical properties of biomass ash particles were measured and the behaviour at high temperature conditions has been discussed based on the microscopic observation by a computer-controlled FE-SEM with a temperature-control chamber [8–11]. In order to reduce the ash deposition, the adhesion behaviour of ash particles with coarse particles having different chemical compositions was characterized by a high temperature type of a powder bed tensile strength tester [12]. To fundamentally understand the cohesiveness of ash particle, however, the detailed knowledge of the interparticle force over the process is required. Such information, however, is difficult to obtain from experiments directly. While some studies have used discrete element method (DEM) to investigate the behaviours of cohesive granule material [13–19], there is no DEM study on investigating the cohesiveness of biomass combustion ash due to the lack of cohesive force model considering the effect of temperature variation. The relationship between the interparticle interactions and the bulk solid properties

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http://dx.doi.org/10.1016/j.apt.2015.12.007
0921-8831/

might make it possible to characterize particle cohesiveness by means of tensile strength [20–23].

This work includes two parts: the experimental study and DEM simulations. In experimental part, tensile strength was measured as a function of temperature (25–800 °C) for ash deposit of palm residues combusted at 820 °C. Thermal properties and FE-SEM [8] observation of phase transition were also reported. In DEM simulations part, a combined Bonded Particle Model (BPM) and Capillary Force Model (CFM) was proposed to model the cohesiveness between particles at various temperatures. Two empirical equations were proposed to link the parameters of BMP and CFM model with temperatures. Microscopic information from DEM simulations was used to investigate the phase transition of biomass ash with increasing temperature.

2. Experiments

2.1. Materials

The sample used in this work is the fly ash from boiler test facility which combusted the palm residues at the furnace temperature 820 °C. The chemical components of the sample were determined by XRF. The size distribution was measured by laser diffraction and scattering method. Some of these properties are shown in Table 1.

2.2. Thermal properties

Thermal gravimetric and thermomechanical analysis were performed by TG-DTA and TMA system. All data were collected at 10 K/min heating rate up to 1000 °C in atmospheric air. TMA data were taken under a static load of 98 mN. The results of TG-DTA and TMA are shown in Fig. 1. The sample weight slightly decreased when the temperature increasing from 400 to 500 °C, and then sharply decreased from 600 °C to 1000 °C. The sample shrinkage occurred above 650 °C while the volatilization was observed with TG.

2.3. Tensile strength

The tensile strength of ash particle bed from 25 to 800 °C was determined using split-type powder bed tensile strength tester [9] for high-temperature measurement as shown in Fig. 2. A sample in cylindrical 50ϕ mm × 10 mm quartz glass cell was preliminarily pressed at 2.66 kPa for 10 min at room temperature, and then heated at 10 K/min up to a specified temperature. The relationship between the tensile load and displacement of the movable half of bed was measured, and tensile strength of the powder bed was determined from maximum tensile stress load and the cross section of the powder bed. The measurement was repeated three times to obtain the mean value.

Fig. 3a shows the tensile stress load vs. displacement curve from room temperature to 800 °C. As shown in Fig. 3b, the values of tensile strength and displacement at different temperatures were determined by the maximum load observed on the curves in Fig. 3a. Tensile strength first increased when temperature increasing from room temperature to 500 °C and then decreased as the temperature increased further. Fracture displacement had a similar

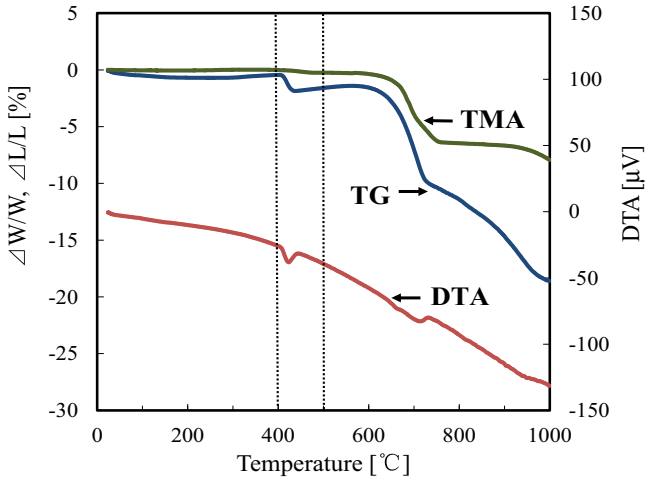

Fig. 1. Data of TG-DTA and TMA.

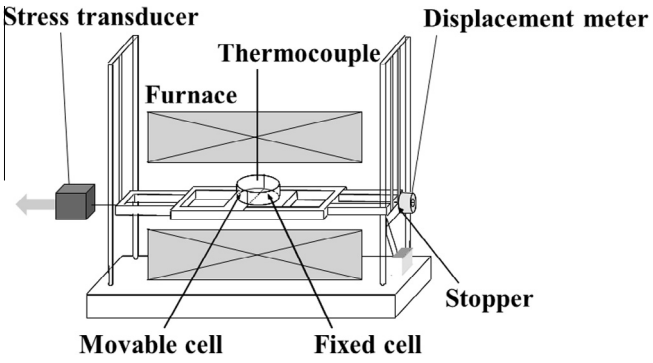

Fig. 2. Split-type powder bed tensile strength tester for high-temperature measurement [9].

changing trend with the tensile strength, but no corresponding relation between them can be observed. The main reason is due to the phase transition with increasing temperature. Fig. 4 shows the SEM images of the palm residues at different temperatures. Computer-controlled FE-SEM composed of a chamber unit for the heat treatment was used in this study [11]. It is observed that phase transition took place with an increasing temperature. This mechanism will be discussed in detail in the next section.

3. Dem simulation

3.1. DEM model and simulation conditions

3.1.1. DEM model

The DEM model adopted in this work has been validated in our previous work [20,24]. This model treats granular materials as an assembly of discrete particles whose trajectories and rotation can be described by Newton's law of motion given by

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_j \left(\mathbf{F}_{ij}^n + \mathbf{F}_{ij}^s + \mathbf{F}_{ij}^v + \mathbf{F}_{ij}^{\mathrm{cap}} + \mathbf{F}_{ij}^{b,n} + \mathbf{F}_{ij}^{b,s} \right) + \boldsymbol{m}_i g \qquad (1)$$

Table 1
Particle diameter and chemical components.

Furnace temp.	Median size (d50)	Chemical component (wt.%)							
		MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	Fe_2O_3
820 °C	8.91 μm	11.02	3.61	10.31	2.60	3.67	13.51	56.51	1.59