Fuel 128 (2014) 14–20

Contents lists available at ScienceDirect

Fuel

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

Experimental determination of agglomeration tendency in fluidized bed combustion of biomass by measuring slip resistance

Chunjiang Yu *, Zifeng Tang, Leiyun Zeng, Chen Chen, Bin Gong

State Key Laboratory of Clean Energy Utilization, Zhejiang University, Zheda Road 38#, Hangzhou 310027, China

HIGHLIGHTS

- A device is designed for testing the mechanical properties of bed material.
- The force between particles in fluidized bed is restored to a particular degree.
- The formation of agglomerates has a significant effect on the slip resistance.
- A high temperature and a long combustion time result in a high slip resistance.

ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form 1 March 2014
Accepted 3 March 2014
Available online 15 March 2014

Keywords:
Slip resistance
Fluidized bed
Biomass combustion
Agglomeration
Torque measurement

ABSTRACT

A method by measuring the slip resistance between particles was used to determine the agglomeration tendency in fluidized bed combustion of biomass. Solid particles were taken from different stages of biomass combustion in a fluidized bed and loaded into a bench-scale test apparatus with two concentric cylinders. A precision variable frequency motor and a torque sensor were employed to measure the torque driven by the inner cylinder at a constant speed, which is directly related to the slip resistance of the solid particles. The measurement results showed significant difference in the slip resistance of the bed solids taken from different stages of biomass combustion at different operating temperatures. A strong correlation was found between the onset of agglomeration and increase in the slip resistance, especially near the onset of agglomeration, due to the build-up of molten biomass ashes, presence of liquid bridges between particles and formation of incipient agglomerates. With further validation, the method developed in the present study can potentially be used to quantify agglomeration tendency in a fluidized bed reactor and characterize the dynamic process of agglomeration.

1. Introduction

Fluidized bed combustion technology has many advantages, such as wide applicability of fuel, high efficiency, and low emissions. However, when it is used to combust biomass fuel, bed material particles are likely to adhere to one another, which may result in agglomeration and failure of fluidization because of the high alkali metal content and the low melting point of the biomass ash [1–3].

Related studies have shown that the possible cause of biomass agglomeration is the reaction of bed materials with biomass ash forming low melting point compound [3–5], or the adhesion of molten biomass ash to bed materials directly at a high temperature [6,7], which increases the adhesion force between bed material particles. Thus, fluidization failure occurs. Visser [8] proposed two types of agglomeration formation: melt-induced agglomeration and coating-induced agglomeration. In the melt-induced agglomeration formation process, molten ash particles between colliding bed material particles act as a glue to bind them together. In the coating-induced agglomeration formation process, a uniform coating layer is slowly generated which originates from accumulating deposits from gas phase inorganic compounds on the particle surface. Manzoori and Agarwal [9] have observed that temperature has a very strong effect on the agglomeration rate and the rate of ash deposition is dominated not by chemical, but by physical processes. The bond of agglomerates which is mainly composed of silicon and potassium, sometimes with a small amount of calcium, has been observed in many biomass fired fluidize beds [10,11].

Molerus [12] took the inter-particle force into account. For fine powders, the inter-particle forces mainly stem from the van der Waals force and electrostatic forces. The other sources of the inter-particle force are caused by the presence of a liquid phase

* Corresponding author. Tel.: +86 571 87952801; fax: +86 571 87951616.
E-mail address: chunjiang@zju.edu.cn (C. Yu).

http://dx.doi.org/10.1016/j.fuel.2014.03.002
0016-2361/

(liquid bridge). If one of the inter-particle forces is in the same order of magnitude as the gravitational force on the particle, the fluidization regime may be changed. It was illustrated by Seville [13] that the particles become sticky when liquid bridge is present. As the amount of liquid increased, the bed material became difficult to fluidize. Moreover, the particles tend to adhere upon collision when the inter-particle forces are strong enough [14].

Forecasting the trend of agglomeration is necessary because agglomeration often leads to a non-normal shutdown. Many detection and counteraction methods have been studied [15–19]. One way to predict the agglomeration tendency during fluidized bed combustion of biomass is to test the ash melting behavior using standard methods, such as ASTM and TMA methods [19–22].

Research [23] showed that the force exerted from the gas or liquid between particles has a relatively low effect on the particles compared with the inter-particle force when the particle phase compacted to a certain degree. The particles of dense-phase zone in fluidized bed may have similarities in some degree with the compacted particles. Measuring the inter-particle slip resistance in dense-phase zone may provide a new method to conduct research on agglomeration in fluidized bed. Agglomeration is mainly caused by the changes in the adhesion force between bed material particles during combustion. Based on the above analysis, this study focuses on the changes in the mechanical properties of particles in dense granular system at different combustion conditions. A double-cylinder test device is employed to measuring the slip resistance between the particles at different conditions for the agglomeration study, and this method has not been reported before for the use of determining agglomeration tendency.

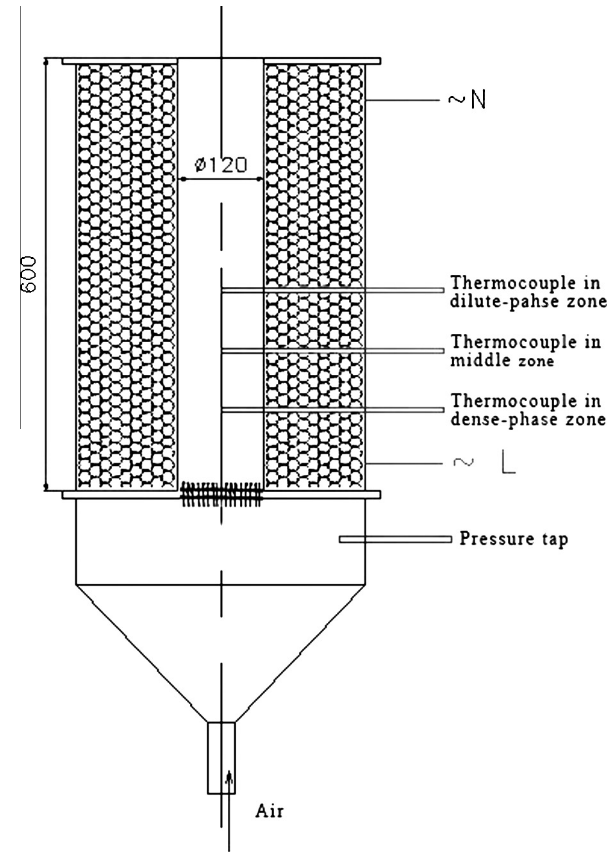

Fig. 1. Bubbling bed combustion test.

2. Experimental section

2.1. Fluidized combustion test

In bubbling bed combustion, the particle concentration is high in the dense-phase zone. The relatively low velocity of the fluidizing medium and the weak disturbance of the bed material particles make agglomeration occur more easily compared with CFB. In this experiment, the bubbling bed combustion mode was chosen for the combustion test. The test bench is shown in Fig. 1. The reactor has an inner diameter of 120 mm and a height of 600 mm. A distributor plate with 690 holes with diameter of 0.3 mm was fitted to the reactor. Three thermocouples were fitted at distances of 100, 200 and 300 mm from the distributor plate. An electric heater was used to start the ignition and to maintain the set temperature of the bed. The test was performed to observe the agglomeration phenomenon in specific fluidized combustion conditions and to obtain typical bed material samples in different conditions for the mechanical test. The fuel was uniformly poured from the top of the reactor. Air volume, combustion temperature, time, accumulated feeding amount of fuel and other parameters were obtained and the movements of particles can be observed from the top of the combustor. After the combustion test, the bed material was poured out from the top of the combustor and collected for the slip resistance test.

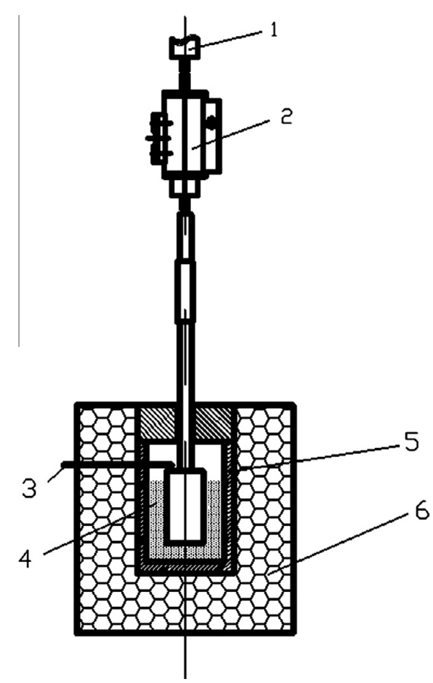

Fig. 2. Bench-scale apparatus for determining slip resistance of solid materials 1 – high-precision variable frequency motor; 2 – torque sensor; 3 – thermocouple; 4 – bed material; 5 – outer cylinder; 6 – insulation material.

2.2. Testing of the mechanical properties of the dense granular system

A double-cylinder test device was designed to measure the slip resistance characteristics of the bed material particle system. The test platform is shown in Fig. 2. The inner cylinder was driven by a CL-01A high-precision variable frequency motor, produced by Beijing Times Brilliant Technology Co., Ltd. The highest maximum output frequency of the motor is 42.5 KHz and the frequency resolution is 1 Hz. A WDH-TX1 torque sensor from Beijing Wodehang Century Technology Co., Ltd. was used to measure the torque. It has a range of 0 NM to 5 NM and an accuracy of 0.2% and the sample frequency was 5 Hz. The container was an outer cylinder that