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Combustion of palm kernel shell in a fluidized bed: Optimization of biomass particle size and operating conditions

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ABSTRACT

This work presents a study on the combustion of palm kernel shell (PKS) in a conical fluidized-bed combustor (FBC) using alumina sand as the bed material to prevent bed agglomeration. Prior to combustion experiments, a thermogravimetric analysis was performed in nitrogen and dry air to investigate the effects of biomass particle size on thermal and combustion reactivity of PKS. During the combustion tests, the biomass with different mean particle sizes (1.5 mm, 4.5 mm, 7.5 mm, and 10.5 mm) was burned at a 45 kg/h feed rate, while excess air was varied from 20% to 80%. Temperature and gas concentrations (O_2, CO, C_xH_y as CH_4, and NO) were recorded along the axial direction in the reactor as well as at stack. The experimental results indicated that the biomass particle size and excess air had substantial effects on the behavior of gaseous pollutants (CO, C_xH_y, and NO) in different regions inside the reactor, as well as on combustion efficiency and emissions of the conical FBC. The CO and C_xH_y emissions can be effectively controlled by decreasing the feedstock particle size and/or increasing excess air, whereas the NO emission can be mitigated using coarser biomass particles and/or lower excess air. A cost-based approach was applied to determine the optimal values of biomass particle size and excess air, ensuring minimum emission costs of burning the biomass in the proposed combustor. From the optimization analysis, the best combustion and emission performance of the conical FBC is achievable when burning PKS with a mean particle size of about 5 mm at excess air of 40–50%. Under these conditions, the combustor can be operated with high (99.4–99.7%) combustion efficiency, while controlling the gaseous emissions at acceptable levels. No evidence of bed agglomeration was found in this conical FBC using alumina as the bed material for the entire time period of experimental tests.

1. Introduction

In Thailand, the palm oil industry is an important sector of the national economy. In 2013, the palm oil production in this country is estimated to be about 2 million tons, the third largest in the world [1]. Crushed shell of oil palm seed, commonly referred to as palm kernel shell (PKS), is one of the biomass residues from the processing of palm oil. Taking into account the substantial availability and rather high calorific value of PKS, the domestic energy potential of this biomass is roughly assessed as 60 MW_e [2]. Due to highly suitable physical and chemical properties, this oil palm residue shows the potential to be used as a feedstock in all major thermo-chemical conversion processes (pyrolysis, gasification, and combustion) involved in the production of biofuels, heat and power [2–4].

Fluidized-bed combustion technology has been proven to be one of the most effective technologies for energy conversion of different kinds of biomass [5–10]. However, the combustion efficiency and emission performance (the latter being mainly represented by CO, C_xH_y, and NO emissions) of a fluidized-bed combustion system (furnace/combustor) fuelled with biomass are reported to depend on fuel analysis and particle size, as well as on the system design features and operating parameters, particularly excess air [6,9,11–15].

When burning biomass in a well-designed combustion system, the CO and C_xH_y emissions from this system can be effectively decreased via increasing the amount of excess air within a reasonable range. Along with a decrease of unburned carbon content in the fly ash (generally observed with increasing excess air), a reduction in the CO and C_xH_y emissions leads to the improvement of the system combustion efficiency [5–8]. On the contrary, the emission of NO shows a substantial increase with a higher level of excess air [5,7,9].

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As reported in a study on the combustion of shell-type biomass with hard structure in a fluidized-bed combustor, the feedstock particle size has significant (proportional) effects on the emissions of products of incomplete combustion (CO and C_xH_y) as well as on unburned carbon in fly ash, and consequently, on the combustion efficiency of the reactor [12]. However, higher CO and C_xH_y in the flue gas lead to a substantial catalytic reduction of NO on the surface of char/ash particles transported by the gas inside the reactor [5]. Thus, via selecting optimal values of excess air and/or feedstock particle size, the combustion and emission performance of a system fuelled with this kind of biomass can be improved. A cost-based optimization model aimed at minimizing emission (or "external") costs of a combustion system can be a suitable tool for simultaneous optimization of a fuel property and a system operating parameter [15,16].

A serious operational problem, bed agglomeration, may likely occur in a fluidized-bed combustion system using silica (quartz) sand as the bed material when firing high-alkali biomass [5,17]. Due to the agglomeration, defluidization of the bed (containing silica grains, chars, and ash particles) occurs within a few hours, causing eventually an unscheduled system shutdown [18]. Pioneering studies elsewhere showed an occurrence of bed agglomeration and rather fast (within a few hours) defluidization during the combustion of PKS in a fluidized bed with silica sand [2,19]. To prevent bed agglomeration, alternative bed materials, such as alumina, dolomite, limestone, pre-calcined bauxite, ferric oxide and some commercial materials, can be used in fluidized-bed combustion systems fired with high-alkali biomasses [5,11,18,20]. A fluidized-bed combustor with a cone-shaped bed (referred to as 'conical FBC'), using a relatively small amount of the bed material [7,11,15], is a suitable fluidized-bed combustion technique for testing various alternative bed materials, particularly those of a high cost.

This work was aimed at studying the combustion of PKS in the conical FBC using alumina sand as the bed material to prevent bed agglomeration. Effects of excess air (a key operating parameter of the combustor) and feedstock particle size on the behavior of major gaseous pollutants (CO, C_xH_y, and NO) in different regions inside the conical FBC, as well as on the emission of these pollutants from the combustor, were the focus of experimental tests. To facilitate the interpretation of combustion behavior inside the reactor, a thermogravimetric analysis of PKS with different particle sizes was performed prior to the combustion tests, with the aim to investigate the effects of biomass particle size on thermal and combustion reactivity of PKS. Optimization of the biomass particle size and excess air, ensuring the minimum emission costs of the combustor, was also among the main objectives of the study.

2. Materials and methods

2.1. Experimental set up

Fig. 1 shows the experimental set up with the conical FBC and auxiliary equipment, as well as the design features and geometrical characteristics of the combustor. At the specified fuel feed rate (45 kg/h), the combustor was operated with heat input of about 200 kW_{th}. It consisted of two steel sections assembled coaxially: (1) a conical section of 0.9 m height with 40° cone angle and 0.25 m inner diameter at the bottom plane, and (2) a cylindrical section comprising five cylindrical modules of 0.5 m height and 0.9 m inner diameter. Both sections had 4.5-mm thick metal walls lined internally with refractory-cement insulation of 50 mm thickness.

Besides the combustor, the experimental set up included: a diesel-fired start up burner for preheating the bed material prior to combustion tests, a screw-type fuel feeder for delivering biomass into the conical section, a 25-hp blower for air supply to the reactor (through the air pipe of 0.1 m inner diameter), a cyclone for collecting particulates from the flue gas, and facilities for recording experimental variables. An air distributor with nineteen bubble caps closely arranged on the distributor plate was employed to generate a fluidized bed in the conical section of the combustor. Fig. 2 shows the general view of the distributor and the design details of an individual bubble cap (stand pipe). Each stand pipe had 64 holes of 2 mm in diameter evenly arranged over the pipe surface as well as six vertical slots (15 mm × 3 mm in sizes) at the top of a pipe. Net cross-sectional area of airflow at the distributor exit (calculated as the difference between area of the 0.25-m-diameter distributor plate and total area occupied by the caps) was 0.016 m^2. The proposed design of the air distributor ensured rather uniform distribution of airflow over the bed (i.e., avoiding bed spouting) at an insignificant pressure drop across the air distributor [21].

To measure temperature and gas concentrations inside the reactor, the conical FBC was equipped with stationary Chromel–Alumel thermocouples (of type K) and gas sampling ports located at different levels above the air distributor as well as at the cyclone exit. Using the stationary thermocouples, flue gas temperature was monitored inside the combustor during its start up.

2.2. The fuel and bed material

Table 1 shows the ultimate and proximate analyses, as well as the lower heating value (LHV) of Thai palm kernel shell used in this study as fuel. It can be seen in Table 1 that the biomass included a significant amount of volatile matter, whereas fuel moisture and ash were at quite low levels, which resulted in a substantial heating value of the shell. Compared to other agricultural residues, the solid density of this biomass fuel was found to be rather high, about 1500 kg/m^3.

Chemical structure is another important biomass characteristic, basically affecting the thermal and combustion reactivity of fuel. Like any other agricultural waste, PKS used in this study consisted mainly of hemicellulose (14.4 wt.%), cellulose (33.4 wt.%), lignin (46.3 wt.%), and some minor extractives (all on dry ash-free basis), determined according to the method described in Ref. [22]. Similar proportions between the constituents of the PKS chemical structure have been reported elsewhere [23–25]. At an early stage of biomass combustion (i.e., during fuel devolatilization), hemicellulose and cellulose are generally responsible for formation of biomass volatile matter, whereas lignin is reported to be a major contributor to the fuel char formed during the biomass degradation [26]. With a substantial content of lignin in this shell-type biomass, the formation of the fuel char is expected to depend on fuel particle size [27,28], and thus may have an important impact on combustion efficiency of the combustor.

To investigate the effects of biomass particle size on combustion and emission performance of the conical FBC, combustion tests were carried out for four groups of PKS particle size: 1–3 mm, 3–6 mm, 6–9 mm, and 9–12 mm. In the discussion below, each test series for the particular size group is labeled by the corresponding mean particle size (MPS) of the shell. The above-mentioned size groups of the shell were characterized by MPSs of 1.5 mm, 4.5 mm, 7.5 mm, and 10.5 mm, respectively.

Note that the ash analysis (wt.%, as representative oxides) of PKS exhibited a predominant proportion of silicon (SiO_2 = 54.12%), followed by calcium (CaO = 23.21%), potassium (K_2O = 8.12%), and iron (Fe_2O_3 = 6.14%). An elevated potassium content in the fuel ash can indicate at a potential problem (tendency to bed agglomeration) that would occur during the combustion of this biomass in a fluidized bed if silica sand had been used as the bed material.