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A pilot-scale investigation of ash and deposition formation during oil-palm empty-fruit-bunch (EFB) combustion

T. Madhiyanon [a],*, P. Sathitruangsak [a], S. Sungworagarn [a], S. Pipatmanomai [b], S. Tia [c]

[a] *Department of Mechanical Engineering, Mahanakorn University of Technology, Bangkok 10530, Thailand*
[b] *The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand*
[c] *Department of Chemical Engineering, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand*

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ABSTRACT

In Thailand, oil-palm empty-fruit-bunch (EFB) a by-product of the crude-palm-oil milling process is currently one of the most promising potential energy resources. However, the ash-forming potassium, chlorine, silicon, and calcium constituents of EFB fuel can cause severe fouling, slagging, and ash meltdown, during combustion. This study is aimed to investigate EFB firing in a pilot-scale reciprocating grate-fired combustor with a 150 kW_{th} capacity. The study included chemical analyses of fuel and fuel ash, and samples of bottom ash, fly ash, and deposits derived from laboratory combustion tests. Experiments were conducted at temperatures of ≈800 °C (low-temperature) and 900–950 °C (high-temperature).

Deposits mainly formed on the upstream side of the probe, and comprised two distinct layers, i.e., a thin white inner layer, and a gray outer layer. A swift growth of deposits on the cooled deposit probe, simulating superheater conditions, was evident, with significant retardation of heat transfer. Heat uptake by the probe appeared to reduce to 70% of the initial value within a 19-h period. The deposit mass flux was 167 g/m^2 h, which corresponded with a fouling thermal resistance of 0.023 $m^2 \cdot K/W$. Following initial deposit formation of KCl condensate, particle impaction entailed deposit formation for incorporating Si- and Ca-rich fly ash particles into the deposits. XRF (X-ray fluorescence spectrometer) and SEM/EDX (scanning electron microscopy/energy dispersive X-ray) analyses revealed that not only did KCl mainly exist in the inner deposit layer, but also dominated the entire deposit mass (60–80 wt.%), suggesting a crucial role for alkali condensation in deposit formation. If the bulk flue gases were sufficiently cooled, the KCl deposited on the probe by the transport of small solidified KCl particles. Corrosion attack was apparent near the metal surface and involved the deposition of KCl. SEM–EDX mapping exhibited that silica in combination with potassium led to the formation of low-melting-point compounds, which readily melted at high-temperature combustion. ICP-AES (inductively coupled plasma-atomic emission spectroscopy) analysis indicated that the potassium in the deposits had high mobility; the results were consistent with the XRF and SEM–EDX analyses.

1. Introduction

Biomass-fired power plants are becoming increasingly promising potential options, as energy shortages and climate change affect many parts of the world. In Thailand, biomass-fired power plants are typically small (<10 MW_e) and rely on agricultural residues and energy crops. One of the most serious barriers to the development of a biomass-fired electric-power industry is the inadequacy of technologies employed to solve the fireside problems, such as fouling, slagging and erosion. For biomass, alkali and alkaline earth metals are important to the formation of fireside deposits. Chlorine is essential to the vaporization of alkali species and is a facilitator in generating deposits, associated with the condensation of KCl on heat-transfer surfaces in the boilers. The most abundant elements in the biomass are K, Si, Ca and Cl; therefore, biomass firing commonly concerns severe fouling of the boiler heat-transfer surfaces and slagging or sintering on the grates of grate-fired boilers.

Straw is an attractive offset fuel for use in Europe, but burning straw in power station boilers will involve the inevitable problems of fouling and slagging. These problems derive from the high potassium (0.2–1.9 wt.% dry basis) and high chlorine (0.1–1.1 wt.% dry basis) content of the straw [1]. Previous investigations have been performed in both field-biomass power plants [2–9] and lab-scale reactors [10–13] in examining the deposit formation during straw combustion. Deposits can grow to such an extent that they apparently bridge across the superheater coils of a straw-fired boiler [5]. This may lead to restricted gas flow, and eventually, unscheduled plant shutdown. In straw-fired power plants, air-cooled probes were basically utilized to explore deposit build-up in furnaces and superheaters [2,6–9]. In these studies, the deposit probe surface temperature was normally kept close to

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* Corresponding author. Tel.: +66 0 2988 3666x3107; fax: +66 0 2988 3655x3106.
E-mail address: thanid_m@yahoo.com (T. Madhiyanon).

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500 °C. Zbogar et al. [2] revealed that the deposits formed in a Danish straw-fired boiler retarded the heat-absorbent capacity of air–water-cooled probes, which simulated superheater conditions. The average gas temperature at the probe position was around 1000 °C. The heat uptake by the probe in the first 6 days was found to have reduced by half the initial value.

Jensen et al. [6] conducted experiments in two straw-fired power plants with average flue gas temperatures of around 850 °C in the furnace and 650 °C in the superheaters. They found that the deposits were formed in the range 15–160 g/m^2 h in the furnace, and around 2–25 g/m^2 h in the superheaters, depending on variations in potassium content (0.5–2.5 wt.%). Jensen et al. [5] analyzed, by SEM/EDX, mature superheater deposits collected at two Danish straw-fired boilers operating under different superheater conditions. The superheated steam temperatures were 390–520 °C. The flue gas temperatures varied from 960 to 1020 °C. Deposits were in the range of a few centimeters to 15 cm in thickness. The mature superheater deposits from both plants consisted of three distinct main layers. The inner layer typically contained iron oxide, KCl, and K_2SO_4. The intermediate layer collected at one power station contained many Si- and Ca-based particles glued together by melted KCl, while at the other plant it was depleted in Cl. The outer layer had Si- and Ca-rich particles bound by melted KCl and K_2SO_4.

Hansen et al. [7] investigated mature deposits formed on the superheater tubes of a straw-fired boiler, and short-time deposits formed on air-cooled probes. The flue gases at the superheaters were around 1000 °C, while the superheated steam temperatures were 455–520 °C. Deposits on the probes can be characterized by two distinct layers: an inner layer of KCl and an outer layer of sintered fly ash. The mature deposits on the superheaters had a characteristic layer structure, with a thin dense layer of K_2SO_4 adjacent to the metal surface and a quite thick massive layer of KCl with fly ash particle inclusions. Michelsen et al. [8] measured deposition using an air-cooled probe installed at the secondary superheater of a 10-MW (3 MW_e and 7 MW_{th}) straw-fired boiler. The flue gas temperatures were in the range 725–750 °C. The superheated steam temperature was 450 °C, while the surface probe temperatures were 460–550 °C. The fly ash was rich in K and Cl, accounting for 45–55 wt.%. All of the K in the fly ash was water-soluble, while the bottom ash contained K, half of which was water-soluble. Only about 30 wt.% of the total K in the deposits was water-soluble. K and Cl made up 40–80 wt.% of the deposits. SEM/EDX analysis of the deposits demonstrated that they mainly consisted of Si–Ca-rich fly-ash particles and condensed KCl.

Oil palms are widely cultivated in tropical Asia, especially in Malaysia, Indonesia, and Thailand. Taking into account this enormously available and CO_2-neutral fuel resource, oil-palm-empty fruit bunch (EFB), a by-product of the crude palm-oil milling process, represents one of the most promising energy resources. In Thailand, EFB is annually generated approximately one million tons or equivalent to 1.07×10^7 GJ. However, due to the very high potassium content of EFB, typically 2.0 wt.% (dry basis), about double the potassium in straw, severe fouling and slagging of boiler heat-transfer surfaces can be expected when burning EFB. Many crude palm oil manufacturers in southern Thailand have experienced that even when blending only 20–30 wt.% EFB with the palm-fiber and palm-shell fuel mixture, grate-fired boilers were prone to unmanageable ash deposits running off the walls and accumulating on the grate, resulting in operational instability and subsequent shutdown of the boilers within a few months. They finally decided to discontinue utilizing EFB, so losing the benefits its energy value as an alternative fuel.

In previous studies, extensive attention has been drawn to the formation of deposits while firing straw, but experience of firing EFB is minimal. It is attractive to improve our understanding of the consequences of firing EFB on the formation of fireside deposits and the aggregation of bottom ash. If managed correctly, EFB may become economically viable in the future. This study presents systematic and detailed analyses of the fuel, fly ash, bottom ash, and deposits, associated with the combustion of EFB. The analyses encompassed the appearance, structure, and chemical composition of the laboratory samples, to understand the mechanisms, quantitative nature (considered as arising from potential combinations of specific elements to form problematic compounds) of deposit formation, and ash aggregation. The study was conducted by constructing a pilot-scale reciprocating grate-fired combustor (150 kW_{th}) and the deposit probes that could measure heat uptake and deposit mass changes. Temperature variations at different positions in the combustor were also described.

2. Experimental set-up

2.1. Grate-fired combustor and deposit probe

The experiments were performed in a pilot-scale reciprocating grate-fired combustor, with slopping grate dimensions of 680 × 1700 mm and a thermal capacity of 150 kW_{th}. A scheme of the combustor showing temperature-measurement and deposit-probe positions is shown in Fig. 1. Oil-palm empty fruit bunch (EFB) was fed into the combustor via two screw conveyers equipped with a variable-speed drive. As combustion proceeded, the fuel was transported downwards sequentially along the combustor by the operation of the reciprocating movements of the moving grates, located just above the stationary grates. The bottom ash and combustion residues were conveyed to the end of the combustion chamber, then they fell into the ash screw conveyer carrying them out of the combustor. The combustion air was divided into two parts: (1) The primary air (under-fired air) was distributed beneath the grates through three air pipes, of which each of them diverted the air into the front, middle, and end of the combustor zones. (2) The secondary air was supplied via three nozzles at the upper-front of the furnace.

Deposits were collected on a 35 mm O.D. carbon steel tube simulating the superheater tubes. The deposit probe was situated horizontally across the combustor exit flow. It was constructed as a double annular pipe, cooled by water and compressed-air flows, as shown in Fig. 2. The probe was designed to measure (1) heat uptake by the probe, calculated from the measured temperatures and the fluid flows, (2) fouling resistance due to deposition, and (3) changes in deposit mass. The probe surface temperatures were measured by two thermocouples placed on the upstream side of the outer probe metal tube (at two ends of the measurement zone) with small guards for shielding them from direct exposure to flue gases. To trace changes in mass due to deposition, the probe was hung on two load cells fixed in position by two supports placed adjacent to the flue-gas duct walls. To investigate the adverse heat-transfer effects on the probe, we allowed probe-surface temperatures to vary with time as deposition proceeded, by keeping the flow of both fluids constant throughout the testing period.

Probe heat uptake at any recorded time (t), $Q(t)$ [W], was calculated by Eq. (1) where m [kg/s] was the mass flow rate, c_p was the specific heat determined at the mean temperature of a cooling fluid, and $T_{in}(t)$ and $T_{out}(t)$ [°C] were the inlet and outlet temperatures of the cooling fluids (w = water, a = air).

$$Q(t) = m_w c_{p,w}\left(T_{w,out}(t) - T_{w,in}(t)\right) + m_a c_{p,a}\left(T_{a,out}(t) - T_{a,in}(t)\right) \tag{1}$$

Conduction resistance of the deposit changing with time (t), $R_f(t)$ [K/W], was calculated sequentially from Eqs. (2.1)–(2.3).

At initial time; $t = t_0$ (or at $t = 0$)

$$R_g(t_0) = \frac{T_g(t_0) - T_{wall}(t_0)}{Q(t_0)} \tag{2.1}$$

where $T_g(t_0)$ was the upstream-gas temperature (at the probe) at initial time (t_0), and $T_{wall}(t_0)$ the mean temperature of the probe surface