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Retrofitting existing coal power plants through cofiring with hydrothermally treated empty fruit bunch and a novel integrated system

Arif Darmawan [a,b,*], Dwika Budianto [b], Muhammad Aziz [c], Koji Tokimatsu [a]

[a] Department of Transdisciplinary Science and Engineering, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226-8503, Japan
[b] Agency for the Assessment and Application of Technology (BPPT), Puspiptek Serpong, Tangerang Selatan 15314, Indonesia
[c] Institute of Innovative Research, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

HIGHLIGHTS

- Cofiring of hydrothermally-treated empty fruit bunch with coal is analyzed.
- Computational fluid dynamics is performed to clarify the cofiring behavior.
- Integrated system covers coal drying, HT treatment, cofiring and power generation.
- High power generation efficiency, about 40%, is achieved.

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ABSTRACT

High-potential biomass residues from the palm oil industry such as palm kernel shells and empty fruit bunch (EFB) must be utilized with the appropriate technology to optimize its economic benefit and minimize the environmental impacts. In this study, the cofiring behavior of hydrothermally treated EFB (HT-EFB) with coal is analyzed in terms of thermal behavior including temperature distribution and the composition of gases produced (CO and CO_2) through computational fluid dynamics. Several HT-EFB mass fractions are evaluated, i.e., 0%, 10%, 25%, and 50%. To complement this research, an experimental study is conducted to validate the simulation results. In general, an HT-EFB mass fraction in the range of 10–25% seems to be the most preferable cofiring condition. In addition, an integrated system is also proposed and evaluated including coal drying, HT treatment of EFB, cofiring, and power generation. Very low energy consumption during coal drying and HT treatment of EFB can be achieved. Finally, the net power generation efficiency of the proposed integrated system is approximately 40% including coal drying and HT treatment of EFB processes.

1. Introduction

The demand for energy sustainability has encouraged researchers to study the use of renewable energy sources in replacement of fossil fuel. In Indonesia, among the numerous available energy sources, biomasses including agricultural wastes play a very important role in the energy matrix. Recently, palm plantations have been expanding significantly due to the high demand for palm oil products throughout the world [1]. According to data from the Indonesian Ministry of Agriculture, the total area of palm tree plantations was approximately $8 \times 104\ km^2$ in 2015 or twice as much as in 2000 ($4 \times 10^4\ km^2$). This number is projected to increase to $1.3 \times 10^5\ km^2$ by 2020 [2]. Annual production of crude palm oil in Indonesia was 27.78 Mt in 2013. This production is expected to reach 37 Mt in 2019 with an annual growth rate of 4.59% [3]. Palm oil production is mainly located in Sumatera (70%) and the Kalimantan (30%) islands [4].

The massive increase of palm oil production has led to the production of a significant amount of agricultural waste. It is assumed that approximately 90% of an entire palm tree has no significant utilization, including the empty fruit bunch (EFB), palm kernel shell (PKS), and fiber [5]. This leads to many problems associated with improper disposal practices of the palm oil wastes. Among these wastes, EFB has the largest share, representing approximately 24.82 Mt per year, and has the lowest economic value due to its characteristics [3]. Advanced utilization of EFB, including

* Corresponding author at: Department of Transdisciplinary Science and Engineering, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa 226-8503, Japan.

E-mail addresses: arifdarmawan33@gmail.com, arif.d.aa@m.titech.ac.jp (A. Darmawan).

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energy harvesting, is urgently required from both the economic and environmental viewpoints.

In the effort to harvest the energy from EFB, cofiring with coal has been identified as one of the least expensive and most efficient technologies for converting these palm oil wastes to electricity. According to the Electricity Power Supply Business Plan (RUPTL) 2016–2025 issued by State-owned Power Utility (PLN) [6] to meet the rapid increase in industrial demand for electricity due to accelerated economic growth, coal-fired power plants have become the major electricity supplier and will expand significantly until 2030. Unfortunately, although Indonesia produces coal, coal reserves are limited [7]. In addition, environmental awareness has encouraged citizens and policy makers to use environment-friendly energy resources and technologies. Cofiring of biomass and coal is believed to be an excellent solution for answering these problems as well as extending power plant lifetimes and coal reserves. Unfortunately, cofiring generally requires biofuels with a uniform quality and high energy density to allow for processing in the fuel handling and combustion equipment of existing coal-fired power plants.

Different to PKS, raw EFB has drawbacks of high moisture content, up to 70 wt% on a wet basis (wb) and low bulk density [5]. New techniques have been studied to increase the cofiring rates to desired levels for EFB including drying [8], hydrothermal (HT) [9], carbonization [10], and pelletization [11]. Among them, HT treatment, which is performed as a pretreatment process prior to the thermo-chemical conversion of biomass, offers significant merits such as high conversion efficiency, elimination of the energy-intensive drying process, and relatively low operation temperatures as compared to other thermal processes [12,13].

Recently, researchers have performed studies and proposed the utilization of systems of wastes from palm oil milling, especially EFB, for energy production. Ninduangdee and Kuprianov [14] studied the combustion of EFB using fluidized bed technology with different bed materials. Diego et al. [15] conducted an experimental study of ethanol production using the EFB. Their results have shown that using only an alkaline pretreatment for the EFB is not a feasible technology. In terms of cofiring or co-combustion, Yan et al. [16] analyzed the influence of particle size distribution of coal on the co-combustion performance of sewage sludge and coal. They confirmed that decreasing the particle size of the fuel improves the combustion performance.

Luk et al. [17] proposed an integrated drying and power generation using EFB. Unfortunately, there was no significant effort to minimize the exergy loss in their system, hence, the energy efficiency was very low. Furthermore, Aziz et al. [18] developed a combined utilization of the EFB and palm oil mill effluent through gasification and digestion, respectively for power generation using a gas engine. Although their system looks feasible for application, it is designed as a standalone system at a milling site, thereby requiring new construction of a gasification system that leads to higher capital costs.

Considering the high potential of EFB and the number of coal-based power plants, especially in Indonesia, EFB utilization through HT treatment and cofiring with existing coal-fired power plants or ones being constructed or planned becomes very important. However, to the best of the authors' knowledge, studies dealing with the effort to evaluate the effect of hydrothermally treated EFB (HT-EFB) cofiring to coal-fired combustors are difficult to find. A new approach is urgently required to be developed in order to estimate the potential for retrofitting an existing power plant to cofire with HT-EFB.

Therefore, this study focuses on two important issues with the objective of proposing efficient EFB utilization, especially for cofiring with coal. First, coal-cofiring behaviors with HT-EFB in a drop tube furnace (DTF) are modeled and analyzed through computational fluid dynamics (CFD) in terms of thermal behaviors including temperature profiles and composition of exhausted gases (CO and CO_2). Secondly, an efficient integrated system model is developed to combine the CFD simulations with the entire plant processes including hydrothermal treatment, combustion system, and steam cycle.

2. Coal-cofiring of HT-EFB

Fig. 1 shows the conceptual diagram of an integrated coal-cofiring system with HT-EFB for power generation. Solid and dotted lines represent material and energy (electricity, heat) streams, respectively. Raw EFB is initially shredded to a smaller size before being hydrothermally treated. Generally, HT is performed under the subcritical region of water with a relatively low temperature of less than 250 °C [19]. Some researchers have evaluated the application of HT on several biomass processes to produce hydrochar [20,21]. To eliminate the drying process after HT, continuous HT using temperatures slightly higher than saturated one is adopted. Therefore, moisture inside the EFB is evaporated and exhausted together with the steam required for HT. The combined HT-EFB mixture is exhausted from the reactor with relatively low moisture content.

In parallel, coal is initially ground and dried to the lower moisture content before being mixed with HT-EFB. The mixed HT-EFB and coal is then cofired in a combustor producing high-temperature heat for steam generation using a boiler. Then, the generated steam expands in the steam turbine generating the necessary electricity. In addition, the exhausted flue gas from boiler is utilized mainly for HT and coal drying.

3. Numerical modeling and calculation for cofiring of HT-EFB and coal

3.1. Schematic diagram of coal cofiring with HT-EFB

To observe the cofiring performance and its feasibility when using a mixture of coal-HT-EFB, cofiring using a DTF is modeled and evaluated in terms of temperature distribution and composition of the produced gases. Fig. 2 shows the schematic diagram of a coal-cofiring system with HT-EFB in a DTF. The raw, wet coal is initially dried to a specified low moisture content and ground to achieve small and uniformly sized particles. Raw EFB is hydrothermally treated before being ground and fed together with the dried coal to the DTF. Hydrothermal treatment was based on the experimental results that were conducted at pressures of 2.4 MPa for 60 min [22].

In this study, four mass fractions of HT-EFB to total mass of mixed fuel are evaluated, i.e., 0 (100% coal), 10, 25, and 50%.

3.2. DTF and materials

Currently, despite the inherent differences in combustion behavior between a DTF and realistic combustion conditions, the DTF is still considered an effective component for evaluating certain combustion behaviors of fuel [23]. DTF is capable for facilitating an environment that simulates industrial conditions such as a fast heating rate, short residence time, and dilute particle phases [24]. In general, the DTF consists of a fuel feeding system, reactor, and particle collection system at the outlet side. HT-EFB is mixed initially with coal before being introduced into the feeding system.

In simulation, a laboratory scale DTF, which is a vertical tubular furnace, having dimensions of 1.5 m in height and 0.07 m in diameter and a capacity of 1 kW_{th} is used. Detailed geometry of the DTF is shown in Fig. 3. In addition, to facilitate isothermal conditions

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