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Coal Co-firing with Hydrothermally-Treated Empty Fruit Bunch Using Computational Fluid Dynamics

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Biomass co-firing into the existing pulverized coal boilers has economic and environmental advantages, such as reduced slagging inside the furnace and lower GHG emissions. Compared to other pre-treatments, hydrothermal treatment has high conversion efficiency, capability to eliminate the energy-intensive drying process, and relatively low operating temperatures. In this study, a simulation study using computational fluid dynamics (CFD) has been performed to explore the potential of coal co-firing with hydrothermally treated empty fruit bunch (HT-EFB) into an existing coal power plant. In the co-firing process, it is important to predict the combustion performance for all stages of the combustion. Furthermore, an empirical investigation is performed to clarify the result of simulations. In the findings, an HT-EFB mass fraction in the range of 10–25 % seems to be the most preferable co-firing condition.

1. Introduction

Agricultural waste from the palm oil industry is increasing due to massive expansion of this industry, especially in South-East Asia. There are many problems caused by improper disposal practices of the wastes. It is expected that about 90 % of the whole palm tree has no significant utilization, consisting of empty fruit bunch (EFB), palm kernel shell (PKS), and fiber (Aziz et al., 2015a). Among these wastes, EFB has the largest share, which is about 24.82 Mt per year, and the lowest economic value due to its characteristics (BPS, 2014). To overcome the economic and environmental problems, EFB can be utilized efficiently for energy generation purposes. Shahlan et al. (2017) reported EFB utilization for hydrogen production in Malaysia. Nyakuma et al. (2017) investigated the gasification of pelletized EFB in fluidized bed reactor. Furthermore, Mahmood et al. (2017) evaluated bioelectricity generation from palm oil empty fruit bunch (EFB).

One of technologies to harvest the energy from EFB is co-firing with coal. It offers some merits such as less expensive and more efficient compared to other techniques. Unfortunately, most biomass, including raw EFB has relatively high moisture content, up to 70 wt % on wet basis (wb) and low bulk density (Aziz et al., 2015a). Some pre-treatments have also been investigated to increase the co-firing rates to desired levels for EFB including drying (Aziz et al., 2015b), hydrothermal treatment (HT), carbonization (Zaini et al., 2017), and pelletization (Garcia-Nunez et al., 2016). Among these techniques, HT treatment which is performed as a pretreatment process prior to other thermo-chemical conversion of biomass has relatively high conversion efficiency (Lokahita et al., 2017), higher efficiency, and relatively low operation temperature compared to the other thermal processes (Mu'min et al., 2017). However, to the best of authors' knowledge, the studies dealing with the effort to evaluate the effect of hydrothermally-treated EFB (HT-EFB) co-firing to coal-fired combustor are very hard to find. A new approach is urgently required to estimate the potential of retrofitting an existing coal power plant to co-fire with HT-EFB.

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Therefore, this study focuses on coal co-firing behaviors with HT-EFB in a drop tube furnace (DTF). Co-firing is 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).

2. Proposed integrated system

The conceptual diagram of the overall process is shown in Figure 1. Hydrothermal treatment is initially conducted, converting the lignocellulosic material into coal-like solid carbon with lower moisture. The HT-EFB product is subsequently ground to achieve smaller and uniform size of particles. Similarly, coal particles are ground initially before being fed to the dryer for water removal. Both HT-EFB and dried coal particles are then fed together to combustor for co-firing process. The heat from combustion then is used to generate steam in order to generate power via a steam turbine. The rest of heat from co-firing is utilized for hydrothermal treatment and coal drying. On the other hand, a part of generated electricity is consumed internally for drying (steam compression) and others, while the larger part of electricity can be sold to the grid. To optimize the system in terms of energy efficiency, the principles of exergy recovery (Liu et al., 2014) and process integration (Darmawan et al., 2017a) are adopted in the developed system.

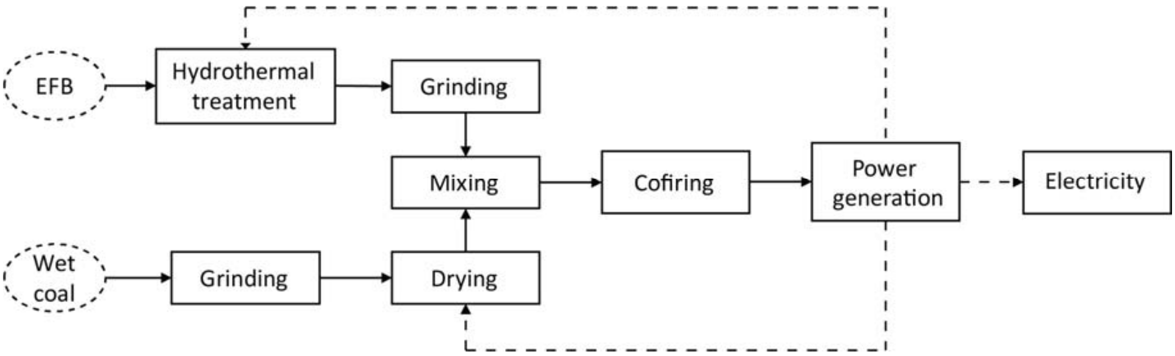

Figure 1: Conceptual diagram of the proposed integrated system of biomass co-firing with coal. The material flow and electricity/heat are represented by solid and dashed lines, respectively (Darmawan et al., 2017b)

3. Process modeling and analysis

In this section, DTF reactor, materials and simulation conditions will be discussed. The first step in the cofiring evaluation through CFD is determining the combustor dimension and its layout of the meshing. Composition and enthalpy formation for both biomass waste and coal are determined based on both proximate and ultimate analyses

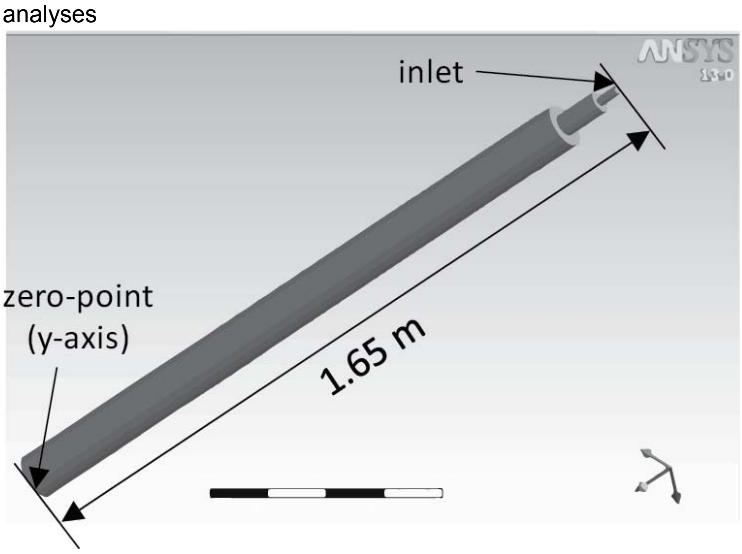

Figure 2: Geometry model of drop tube furnace

3.1. Drop tube furnace

To observe the co-firing performance and its feasibility, co-firing using DTF is modeled and evaluated in terms of temperature distribution and produced gases composition. The detailed geometry of used small drop tube furnace (DTF) is shown in Figure 2. A 1 kWth capacity laboratory scale tubular DTF with dimensions of 1.5 m in height and 0.07 m in diameter is modeled. The furnace uses an electric heater which is divided into three zones to maintain isothermal conditions along the furnace. A screw feeder equipped with a vibrator is used to feed coal into the furnace. The coal feeder is also equipped with water coolers to prevent premature ignition of the fuel. The combustion process takes place inside the tubular furnace with combustion draft downward flow direction. Combustion air supply consists of primary and secondary air with volumetric flow rates of 3 and 4 L/min, respectively, which is supplied to the furnace. Feed rate of coal particles is set to 45–60 kg/h which is fed through the injection probe carried by the primary air. The combustion products are later sampled by a gas sampling probe to analyze the emission gases concentrations by means of a gas analyzer.

3.2. Materials

The coal used in the simulation was originated from Kalimantan, Indonesia (Aziz et al., 2016). This coal is classified as low rank coal which is typically high in moisture content. Both the proximate and ultimate analysis of the coal were done by Energy Technology Centre, Agency for Assessment and Application of Technology (BPPT, Indonesia). The raw EFB feedstock used in the experiment was obtained from Yonsei University, Korea (Novianti et al., 2014). EFB was selected as a representative waste biomass due to its high-power generation potential in Indonesia.

Table 1: Material composition of coal, EFB, and HT-EFB used in this study

Component	Coal		EFB		HT-EFB	
	As-received	Dry Basis	As-received	Dry Basis	As-received	Dry Basis
Proximate analysis						
Fixed Carbon	24.93	40.23	6.43	15.30	28.62	29.50
Volatile Matter	25.76	41.57	33.09	78.70	62.57	64.50
Moisture	48.76	17.30	58.00	0.10	3.00	0.00
Ash	0.56	0.90	2.48	5.90	5.82	6.00
Ultimate analysis						
C	35.30	56.98	17.58	41.81	52.74	54.37
H	2.29	3.69	2.48	5.73	5.33	5.49
O	11.23	18.13	19.22	45.71	31.95	32.94
N	1.75	2.83	0.71	0.84	0.85	0.88
S	0.11	0.17	0.00	0.00	0.00	0.00
Calorific Value (kCal/kg)	3307	5337	1877	4464	5308	5472

3.3. Simulation conditions

In the simulation, commercial CFD softwares, ANSYS Design Modeler and Fluent ver. 13.0 (ANSYS Inc.), were used to build 3D combustor model and to analyze the co-firing behavior, respectively. Co-firing simulation includes some considerations of dynamics equations, conservation of mass (continuity), momentum and enthalpy, turbulence (k-ϵ turbulence model), radiation heat transfer (P-1 model), and reactions in both particle (Eulerian-Lagrangian model) and gas (global 2-steps reactions) phases. Some additional boundary conditions include: (1) fuel and air inlet flow rates are 1.38×10^{-5} kg s^{-1} and 1.6×10^{-4} kg s^{-1} at 300 K, (2) furnace wall temperature, wall roughness and internal emissivity are set to 1,300 K (isothermal), 0.5 and 1, respectively, and (3) feeding wall is considered isothermal at 300 K.The combustion reactions for each coal char and HT-EFB char can be expressed as follows:

$$\text{Coal char (C)} + 0.5\ O_2 \rightarrow CO \tag{1}$$

$$\text{HT-EFB char (C)} + 0.5\ O_2 \rightarrow CO \tag{2}$$

During devolatilization, the volatile matters from both coal and HT-EFB are released rapidly, and then react with oxygen for further combustion. Furthermore, the oxidation reaction of volatile matter from both coal and HT-EFB is approximated as a global 2-steps reaction mechanism in which CO becomes an intermediate component (Yin, 2009). Each coal and HT-EFB is considered as different component and both composition and enthalpy of formation are derived from proximate and ultimate analyses of each material. The reaction mechanisms for the volatile matter in the gas phase can be expressed as follows (Westbrook-Dryer mechanism):

Coal volatile matter ($CH_{0.39}O_{0.24}N_{0.043}S_{0.0011}$) + $0.48O_2 \rightarrow CO + 0.195H_2O + 0.0011SO_2 + 0.022N_2$ (3)

HT-EFB volatile matter ($CH_{1.21}O_{0.45}\ N_{0.014xx}$) + $0.5775O_2 \rightarrow CO + 0.605H_2O + 0.007N_2$ (4)

$CO + 0.5\ O_2 \rightarrow CO_2$ (5)

4. Results and discussion

This section mainly consists of temperatures profile in the reactor of simulation and distribution of exhausted gases.

4.1 Temperature distribution

In general, the results show that higher HTT-EFB mass fraction will increase temperature inside the combustor (Figure 3). Increasing HT-EFB proportion up to 50 % results in higher temperatures (maximum 1,536 K) compared to the coal only case (maximum 1,347 K). In this case, higher temperature also increases CO production level (Figure 4).

The mixed fuel configurations changes heating values, which consequently changes the flame shape and temperature profile within the combustor when significant quantities of HT-EFB are being co-fired. The important characteristic of HT-EFB is that it contains higher volatile matter and lower fixed carbon than coal (Table 1). These conditions affect the amounts of fixed carbon and volatile combustible matter of the mixed fuel; therefore, they directly contribute in the change of heating value. The location of the high-temperature region corresponds to the location of volatile matter’s combustion.

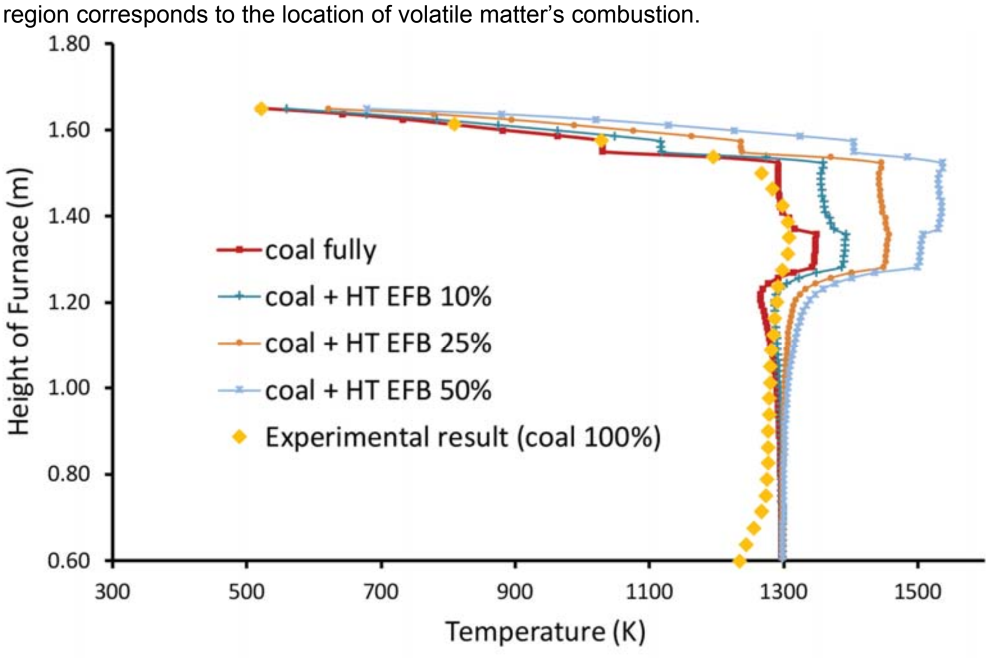

Figure 3: Temperature distribution profile along combustor

4.2 Distribution of CO and CO_2

Figures 4 and 5 depict the mass profiles of CO and CO_2 along the combustor, respectively. Regarding the produced CO concentration, higher mass fraction of HT-EFB leads to the increase of CO mass fraction during initial reaction of combustion. The volatile matter, especially from HT-EFB, is oxidized under high combustion temperature forming CO. Afterward, CO reacts further with O_2 (air) along the combustor forming CO_2. In addition, coal co-firing with HT-EFB results in lower CO_2 concentration following the increase of both HT-EFB mass fraction. The dots show the CO_2 pollutant observed during the experimental study; meanwhile, the lines show CO_2 emission based on a simulation model.

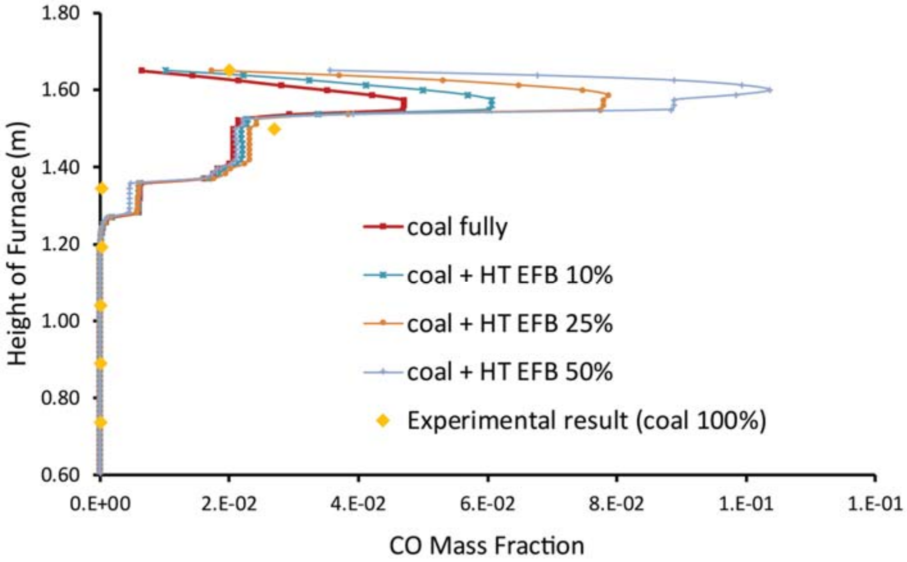

Figure 4: Concentration of CO along combustor

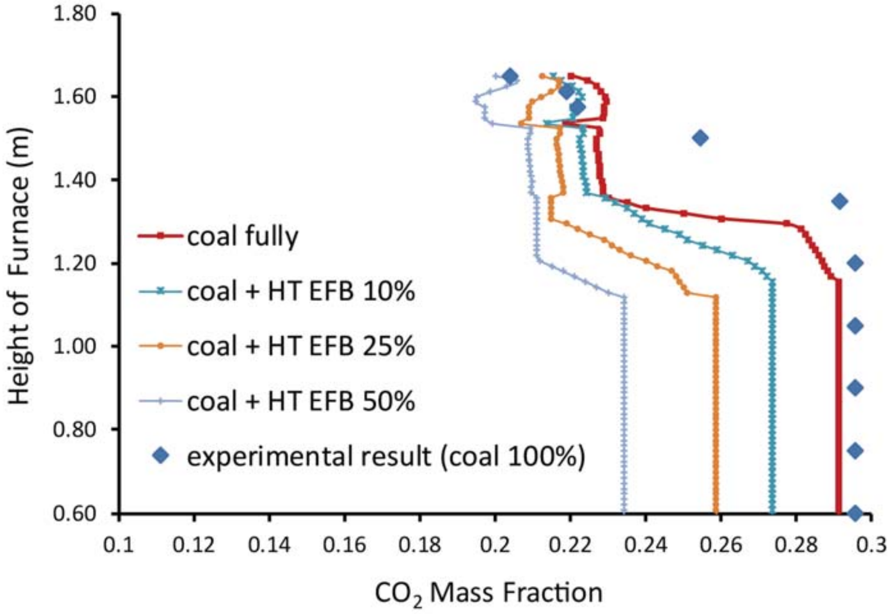

Figure 5: Concentration of CO_2 along combustor

5. Conclusion

Co-firing of biomass waste in a pulverized coal power plant was successfully simulated and studied using CFD. This study has discussed performance for all stages of the combustion including the combustion temperatures, kinetics behavior, and concentration of the produced gases especially CO and CO_2. In general, a HT-EFB mass fraction of 10–25 % appears to be the most preferable cofiring condition in terms of temperature and produced gas compositions.

Acknowledgments

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