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Numerical Investigation of Co-Firing of Palm Kernel Shell
into Pulverized Coal CombustionDwika Budianto^{*1}, Muhammad Aziz^{*2†}, Cahyadi^{*1}, and Takuya ODA^{*2}

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Co-firing of palm kernel shell (PKS) into 7 MW existing pulverized-coal boiler has been modeled and analyzed using the computational fluid dynamics (CFD). Co-firing of coal and PKS is a complex chemical reaction involving both gas and solid phases with turbulence effect along the combustor. In numerical simulation, two-steps global reaction mechanisms for homogeneous (volatile matter) and heterogeneous (char) combustion, turbulence and radiation heat transfer are considered. Moreover, five different mass fractions of PKS to coal are observed: 0 (fully coal), 10, 15, 25 and 50 %, respectively. In this study, the analysis is focused on the comparative prediction related to the distribution of temperature, velocity and produced gases of CO₂, CO, SO₂. As the result, higher PKS mass fraction leads to a favorable combustion in terms of combustion temperature and produced gases exhausted from the combustor.

7 MW 級の微粉炭を用いる既存の燃焼炉でパーム椰子殻 (PKS) を混焼することを想定し、数値流体力学 (CFD) によるモデル化と解析を行った。石炭と PKS の混焼は気固相を含む複雑な化学反応であることに加えて、燃焼炉内の乱流の影響もある。数値シミュレーションでは、均質相 (揮発性物質) と不均質相 (チャー) を含む2段階の反応メカニズム、乱流、放射伝熱を考慮した。また、PKS と石炭の質量分率として、0 (全量石炭)、10、15、25、50%の5種を与えて評価した。本研究では主に、混焼に伴う燃焼炉内での温度分布、速度分布、CO₂、CO、SO₂ 等の生成ガスに着眼した。その結果、PKS 質量分率が高いほど、燃焼温度が上昇して生成ガスの構成も良くなることを明らかにした。

Key Words

PKS, Coal, Co-firing, CFD, Temperature, Gas emission

1. Introduction

Recently, the fast economic growth in some developing Asian countries, especially in Indonesia, has led to a significant increase of electricity demand. In Indonesia, this demand grows about 7 % per year or equal to about 6 GW. Currently, nearly 60 % of the available power generation is supplied by coal¹⁾. Moreover, coal reserve in Indonesia is largely dominated by a low rank coal which is characterized by low sulfur content, ash yield and mineral matter^{2) 3)}. Unfortunately, it also has very high moisture content (40-50 wt% on wet basis) leading to some difficulties during its utilization⁴⁾. In fact, it leads to some problems including environmental issues and sustainability of the coal

combustion process in the boiler plant which produces large amount of greenhouse gases.

On the other hand, Indonesia also has very high biomass potential including palm tree (*Elaeis guineensis*). The growth rate of palm plantation continues to increase, especially in the last decade which was recorded at 7.67 %. In addition, the production of palm oil and its products also increases by 11.09 % per year⁵⁾. Unfortunately, the increase of palm oil production also causes an increase of wastes including empty fruit bunch, palm kernel shell (PKS) and fiber⁶⁾. Compared to other wastes, PKS has some beneficial characteristics including lower moisture content, higher heating value and lower ash content. The amount of PKS among the produced wastes is about 5-7 %. In Indonesia, it is predicted that the total potential of PKS is very high, which is about 6.65 Tg year⁻¹ (6.65 Mt year⁻¹). These characteristics and potential of PKS lead to the idea of

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broader utilization of PKS including fuel.

Currently, the utilization of wasted biomasses as fuel alternatives substituting the fossil fuel has gained higher attention. Co-firing of biomass to the existing combustion boilers fired by fossil fuel is also a feasible technology which does not only significantly reduce CO₂ emission but also increases the share of renewable energy sources in the overall energy systems. Biomass co-firing has been successfully performed in over 200 plants worldwide in various fuel combinations and scales (pilot and full-scale commercial plants)⁷⁾. The consideration on the characteristics of each biomass is very important to be made in accordance with the design and selection of the operating conditions for the combustor and boiler⁸⁾. Some typical biomasses co-fired with coal include cattle manure⁹⁾, saw dust, sewage sludge¹⁰⁾, switch grass¹¹⁾, wood chips¹²⁾, straw¹⁰⁾, and bagasse¹³⁾.

In addition, some researchers also have investigated the behavior of biomass co-firing to existing conventional coal combustion system using the computational fluid dynamics (CFD) with different biomasses including pinewood¹⁴⁾, switch grass¹⁵⁾, sewage sludge¹⁶⁾ and olive waste¹⁷⁾. In addition, CFD modeling for co-firing of other different materials also has been performed for mixture of biomass and natural gas¹⁸⁾ and mixture of coal and solid recovered fuels¹⁹⁾. In addition, CFD modeling for oxy-fuel co-firing of coal and biomass also has been performed by Bhuiyan and Naser²⁰⁾. Unfortunately, to the best knowledge of the authors, there is no study dealing with the effort to clarify the co-firing behavior of PKS into coal-fired boiler, especially the low rank coal.

CFD is considered as a very helpful tool to measure and predict the behavior of combustion, including co-firing. This work focuses on the investigation of co-firing of PKS into the existing coal-fired boilers for 7 MW scale of power plant using CFD. This power plant is selected in consideration of the increase of small scale coal-fired power plants to supply the electricity in Indonesia. Both geographic and demographic conditions of the country have led to the trend of increasing the small scale and distributed power plants. In addition, this study deals with the combustion behavior especially the distribution of temperature, gas velocity, CO₂, CO and SO₂ across the combustor. Five different co-firing conditions in terms of mass fraction of PKS to coal are observed: 0 (fully coal, base condition), 10, 15, 25, and 50 %.

CFD is recognized as an efficient and appropriate tool to measure the performance of co-firing. Existing coal combustion model is modified to include the effects of biomass co-firing on the overall combustion behavior.

In the developed model, coal and biomass co-firing is approximated through numerical solution using the time-averaged conservation equations for the gas and solid (particle) phases. The gas flow is mathematically modeled using a volume-averaged Eulerian system, whereas the solid phase is evaluated by the Lagrangian trajectory analysis procedure. For the gas phase, the flow is calculated by solving the steady-state Reynolds-averaged Navier-Stokes equations (RANS). In addition, the motion of solid fuel particles and dispersed phase are tracked by the discrete phase model. In the dispersed phase, momentum, mass, and energy are mutually influenced by one in the fluid phase. CFD-based co-firing model usually consists of various sub-models including turbulent fluid mechanics, gaseous combustion, particle dispersion, particle drying, particle devolatilization, heterogeneous char reaction, pollutant formation and radiation²¹⁾. Moreover, to simplify the mathematical calculation, particle sub-models including particle dispersion, particle drying, particle devolatilization and heterogeneous char reaction are separated from the gas phase sub-models (turbulence, radiation, and gaseous combustion).

2. Mathematical modeling

In this study, CFDSOF ver. 3.4 developed by AIR Group in University of Indonesia is used to simulate the co-firing of PKS in the combustion zone of existing 7 MW coal-based power plant. The computation of the developed model is performed in a two dimensional structure consisting of 2,400 cells. The CFD codes solving the appropriate transport equations for Eulerian-Lagrangian approach are used to calculate the particle trajectories throughout the calculated gas field. The turbulence model and heat transfer radiation are employed to model the dynamics of the flow. In addition, the simplest approach to determine the devolatilization process is the empirical approach in which the global kinetics are employed. In this case, the Arrhenius expressions are adopted to correlate the rates of weight loss with temperature.

2.1 Governing equations

Co-firing is typically modeled as a dilute two-phase (solid-gas) reacting flow using an Eulerian-Lagrangian approach. In the Eulerian-Lagrangian approach, the gas phase is described by the Navier-Stokes equations, while the solid phase is treated as a discrete phase. The trajectory of each particle is calculated by Newton's laws of motion, and the collisions between particles are described by the model of sphere²²⁾. Other variables such as temperature and gas concentration are computed by the equations of energy and

mass transfers for each particle. Since each particle in the system is tracked, the accuracy of simulation result can be improved. The mass, momentum and energy interactions between the gas phase and the solid particles are calculated using the particle source-in-cell method while updating the particle state along a set of particle trajectories²³⁾.

In CFD calculation, mathematical processes are governed by fluid flow equations. The equations of fluid properties involve mass conservation, density, temperature, specific mass fraction, enthalpy, turbulent kinetic energy (k) and turbulent dissipation rate (ϵ). Assuming that the fluid dynamics represents a viscous flow^{24) 25)}, the transport governing equations can be written as follows:

● Mass (continuity equation)

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{U} = 0 \quad (1)$$

● Momentum equation in x component

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \quad (2)$$

● Momentum equation in y component

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad (3)$$

● Momentum equation in z component

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \quad (4)$$

● Energy equation

$$\begin{aligned} \rho \frac{D}{Dt} \left(e + \frac{U^2}{2} \right) &= \rho \dot{q} + \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) \\ &+ \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) - \frac{\partial (up)}{\partial x} - \frac{\partial (vp)}{\partial y} - \frac{\partial (wp)}{\partial z} + \frac{\partial (u\tau_{xx})}{\partial x} \\ &+ \frac{\partial (u\tau_{yx})}{\partial y} + \frac{\partial (u\tau_{zx})}{\partial z} + \frac{\partial (v\tau_{xy})}{\partial x} + \frac{\partial (v\tau_{yy})}{\partial y} + \frac{\partial (v\tau_{zy})}{\partial z} \\ &+ \frac{\partial (w\tau_{xz})}{\partial x} + \frac{\partial (w\tau_{yz})}{\partial y} + \frac{\partial (w\tau_{zz})}{\partial z} + \rho f \vec{U} \end{aligned} \quad (5)$$

2.2 Turbulence

In this study, a k - ϵ turbulence model is adopted to solve the RANS equations for co-firing of PKS to pulverized coal combustion. k - ϵ model is commonly employed in predicting the swirling combustion flows^{26) ~ 30)}. The equation for each k and ϵ can be written as follows:

● Turbulent kinetic energy (k)

$$\begin{aligned} \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) &= \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \\ &+ P_k + P_b - \rho \epsilon - Y_M + S_k \end{aligned} \quad (6)$$

● Turbulent dissipation rate (ϵ)

$$\begin{aligned} \frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) &= \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] \\ &+ C_{1\epsilon} \frac{\epsilon}{k} (P_k + C_{3\epsilon} P_b) - \rho C_{2\epsilon} \frac{\epsilon^2}{k} + S_\epsilon \end{aligned} \quad (7)$$

where, P_k , P_b are the generation of turbulence kinetic energy due to mean velocity gradient and buoyancy, respectively. Moreover, μ_t and β represents turbulent viscosity and coefficient of thermal expansion, correspondingly. Each of them can be expressed as follows:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \quad (8)$$

$$P_k = -\overline{\rho u_i u_j} \frac{\partial u_j}{\partial x_i} \quad (9)$$

$$P_b = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (10)$$

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right) p \quad (11)$$

In addition, g_i , T and Pr_t are the gravitational acceleration in the i th direction, temperature, and turbulent Prandtl number, respectively. The value of Pr_t is 0.85 for the standard and realizable k - ϵ model. Moreover, $C_{1\epsilon}$, $C_{2\epsilon}$, $C_{3\epsilon}$, C_μ , σ_k , and σ_ϵ are some coefficients adopted in this study. A general fluid flow problem can be solved in one dimensional model, while two and three dimensional problems are solved with parabolic, elliptic and hyperbolic equations.

2.3 Radiation

Radiation heat transfer has an important role in solid particle combustion including process heating, ignition and char combustion. Radiation heat transfer has a strong impact throughout the overall combustion process because it determines the overall involved subsequent steps. Hence, it is crucial to know the rate and amount of volatiles released in the devolatilization step as a function of temperature. In this work, P-1 radiation model for solving radiation heat transfer is adopted. This model is not only valid for small scale model but also appropriate for large scale combustion³¹⁾.

2.4 Particle phase sub-models

Modeling particle phase and dispersion particle in co-firing is conducted through numerical particle tracking in Lagrangian approach³²⁾. Particles of coal and PKS are modeled separately as two discrete phase models. For particle distribution model, Rosin-Ramler distribution approach is adopted³³⁾. Combustion of coal char is different with one of PKS char. PKS char is more reactive and has higher heating rate than the coal char. Furthermore, the combustion in air environment is usually approximated using one-step global heterogeneous reaction. Therefore, this one-step global heterogeneous reaction for each coal and PKS char is adopted to estimate the mechanism of char combustion which can be expressed as follows²⁶⁾:

Table 1 Kinetics of reaction mechanism

Reaction	A (s ⁻¹)	Ea (J kmol ⁻¹ K ⁻¹)
12	2 x 10 ¹¹	4.4 x 10 ⁷
13	6.8 x 10 ¹⁵	1.67 x 10 ⁸
14	3 x 10 ⁸	1.26 x 10 ⁸
15	1.9 x 10 ¹⁵	1.27 x 10 ⁸
16	2.75 x 10 ⁹	8.47 x 10 ⁷

2.5 Gas phase sub-models

Homogeneous reactions of volatile matters is approximated using two-steps global reaction mechanism. It is assumed that each volatile matter of coal and PKS are considered as two different components³⁴. The amount of activation energy and pre-exponential factor are determined from proximate and ultimate analyses of each of coal and PKS. These mechanisms can be expressed as follows (Westbrook and Dryer mechanism³⁵):

The kinetic parameters considered in these reactions are given in Table 1.

3. Materials

In this work, the coal used in the existing power plant is originated from Kalimantan, Indonesia. This coal is classified as low rank coal which has typically high moisture content. It can be considered as the representative of fuel being used in coal-fired boiler for small scale power plants in Indonesia. On the other hand, the sample of PKS is delivered from palm mills in Sumatera, Indonesia. Both proximate and ultimate analyses and calorific value were measured by Energy Technology Centre, Agency

for Assessment and Application of Technology (BPPT, Indonesia) and shown in Table 2. As-received and as-used represent the un-pretreated raw material entering the dryer and treated material used as fuel fed to combustor, respectively.

4. Boundary Condition

Fig. 1 shows the geometry of combustor used for co-firing. Air is used as the reactant supplying O₂ required for combustion. Air and fuel are input to the combustor through each inlet distributed at lower part of the combustor. Air is divided into primary and secondary flows. The former is fed together with fuel injecting the fuel to the combustor. While the rest of air which is required for combustion is additionally supplied in the secondary air flow

Fig. 1 Geometry of the combustor

Table 2 Coal and PKS biomass analysis

Component	Coal		PKS	
	As-received	As-used	As-received	As-used
<i>Proximate analysis</i>				
FC	24.93	40.23	20.80	24.35
VM	25.76	41.57	57.05	66.77
Moisture	48.76	17.30	17.86	3.86
Ash	0.56	0.90	4.29	5.02
<i>Ultimate analysis</i>				
C	35.30	56.98	37.02	43.77
H	2.29	3.69	4.95	5.85
O	11.23	18.13	35.79	42.32
N	1.75	2.83	0.75	0.89
S	0.11	0.17	0.00	0.00
CV (Kcal/kg)	3307	5337	3573	4225

Table 3 Composition of used mixed coal and PKS

PKS mass fraction	Coal			PKS		
	Char	Volatile	Moisture	Char	Volatile	Moisture
0 % (fully of coal)	0.25	0.26	0.49	-	-	-
10 % PKS	0.23	0.23	0.44	0.02	0.06	0.02
15 % PKS	0.21	0.22	0.42	0.03	0.09	0.03
25 % PKS	0.19	0.20	0.37	0.05	0.14	0.05
50 % PKS	0.13	0.13	0.25	0.11	0.29	0.09

until the designated air-to-fuel ratio (AFR) is reached. The total amount of primary and secondary air is calculated considering the stoichiometric condition for combustion with additional excess air of 80 % on mass basis. Therefore, as the feeding rate of coal for the existing 7 MWe power plants is 6.1 Mg h^{-1} (6.1 t h^{-1}), the required AFR and total amount of air are 10.2 and $52.7 \times 10^3 \text{ Nm}^3 \text{ h}^{-1}$ (under ambient condition), respectively. This amount of air is fixed for all evaluated conditions. Moreover, air inlet temperature is fixed at 373 K. Turbulent intensity and length scale for the primary air are assumed to be 10 % and 0.125 m, respectively. While for the secondary air, they are 40 % and 0.125 m, respectively.

The fuel composition is varied in terms of mass fraction of PKS to coal during co-firing, which is listed in detail in Table 3 (under ambient condition, 343 K). The turbulent intensity and length scale of the fuel are 10 % and 0.325 m, respectively. In addition, Rosin-Rammler distribution is used to characterize the particle size distribution. The particle is assumed to be a solid sphere. The flowrate, mean particle size and bulk density

Fig. 2 Relationship of temperature and combustor height for each PKS mass fraction

Fig. 3 Graphical temperature distribution across the combustor for each PKS mass ratio: (a) 0 % (fully coal), (b) 10 %, (c) 15 %, (d) 25 % and (e) 50 %

of the pulverized coal are 1.69 kg s^{-1} , $70 \text{ }\mu\text{m}$ and 700 kg m^{-3} , respectively. On the other hand, the bulk density and particle size of PKS are 600 kg m^{-3} and $70 \text{ }\mu\text{m}$, respectively. The temperature of coal and PKS is assumed to be uniform when they are fed to the combustor. The heat loss from the combustor wall is considered due to convection and radiation heat transfers during combustion. The heat transfer coefficient, external temperature, external emissivity, and wall emissivity are $73 \text{ W m}^{-2} \text{ K}^{-1}$, 313 K , 0.9 , and 0.6 , respectively.

5. Results and Discussion

5.1 Temperature Distribution

Fig. 2 shows the relationship between the mean temperature and combustor height for all evaluated PKS mass fractions. In addition, Fig. 3 shows the detailed graphical temperature distribution across the combustor. Generally, the combustion temperature increases following the increase of PKS mass fraction co-fired with the coal.

The maximum difference of the highest temperatures achieved in the combustion among the evaluated conditions is about 200 K which is achieved between PKS mass fractions of 0 and 50% . Co-firing with higher PKS mass fraction leads to higher volatile contents producing high gas yields. Therefore, the produced gases are distributed in a larger volume across the combustor. Further, they are reacting with the oxidizing gas for combustion in gas phase. As the result, the combustion flame tends to be distributed in a larger volume inside the combustor^{(28), (36)}. In addition,

high gas yields also result in higher total calorific value earned during combustion leading to higher combustion temperature.

5.2 Velocity distribution

Figs. 4 and 5 show the mean velocity distribution in respect of combustor height and detailed graphical velocity distribution across the combustor for each PKS mass fraction, respectively. Generally, the velocity increases slightly following the increase of PKS mass fraction. PKS particles have higher volatile contents, lower moisture

Fig. 4 Mean velocity distribution across the combustor for all evaluated mass fractions

Fig. 5 Graphical velocity distribution across the combustor for each PKS mass ratio: (a) 0% (fully coal), (b) 10% , (c) 15% , (d) 25% and (e) 50%

content and lower particle density than coal particles. As the result, the particles, especially PKS, are distributed faster across the bed followed by faster devolatilization and combustion as the PKS mass fraction increases. Furthermore, higher temperature in case of higher PKS mass fraction is also considered to influence the change of velocity.

5.3 CO₂, CO and SO₂ distribution

Figs. 6 and 7 show the mean distribution of CO₂ mass fraction in relation to combustor height and its detailed graphical distribution across the combustor for

Fig. 6 Mean distribution of CO₂ mass fraction across the combustor for all evaluated mass fractions

all evaluated PKS mass fractions. CO₂ is produced during combustion and becomes the main content of flue gas exhausted from combustor. Higher PKS mass fraction leads to faster combustion, hence faster formation of CO₂ can be achieved. Moreover, as the amount of volatile matter of the fuel increases, larger amount of gas yields are produced.

As the devolatilization completed, highly reactive biomass char will participate in the oxidation process with the surrounding O₂ leading to the formation of CO₂. Moreover, a released volatile matter also reacts with O₂ through one-step reaction combustion converting perfectly all the components. As the result, the amount of CO₂ increases, while the concentration of CO decreases. For all evaluated cases, the maximum concentration of CO₂ takes place at the outlet of combustor.

In addition, at combustor height of about 10 m, there is any increase in CO₂ mass fraction. There are two possible mechanisms related to this increase: CO₂ dissociation and reverse water-shift gas reaction. In the former, CO₂ is transformed to CO under high temperature (Fig. 2) resulting in the slight decrease of CO₂ at the same level of combustor height. In the latter, a part of CO₂ reacts with hydrogen producing CO and H₂O.

Figs. 8 and 9 show the mean distribution of CO mass fraction across the combustor and the graphical distribution for each corresponding PKS mass fraction, respectively. In general, CO mass fraction is higher at the bottom and decreases following the height of combustor. Based on two film reactions models, CO is formed due to oxidation of volatile matter and particularly at the surface

Fig. 7 Detailed graphical distribution of CO₂ mass fraction for each PKS mass fraction: (a) 0% (fully coal), (b) 10%, (c) 15%, (d) 25% and (e) 50%

Fig. 8 Mean distribution of CO mass fraction across the combustor for all evaluated mass fractions

Fig. 10 Mean distribution of SO_2 mass fraction across the combustor for all evaluated mass fractions

Fig. 9 Detailed graphical distribution of CO mass fraction for each PKS mass fraction: (a) 0% (fully coal), (b) 10%, (c) 15%, (d) 25% and (e) 50%

of carbon. PKS has high volatile matter content which tends to produce larger CO content. In addition, as CO is mainly produced from volatile matter, higher volatile matter content results in higher CO mass fraction. Moreover, PKS which has lower moisture content than coal is considered to be able to facilitate faster formation of CO from its volatile matter. The concentration of CO decreases following the combustor height due to combustion across the combustor.

Fig. 10 shows the result of the mean distribution of SO_2 mass fraction across the combustor for all evaluated mass fractions. SO_2 is produced and converted from sulfur compounds, especially in coal composition, during

the reaction with air in high temperature combustion. As shown in Table 2, almost no sulfur content is found in PKS particles. Hence, the addition of PKS particles in existing coal fired combustor can reduce the sulfur content of the fuel which leads to low amount of emitted SO_2 .

5.4 Required palm mill scale

Table 4 shows the correlation between each PKS mass fraction and required palm mill scale to supply PKS in case of PKS co-firing to existing 7 MW coal fired power plant. PKS is a by-product during palm nut recovery, specifically in the separation of palm nut and its shell³⁷. For

Table 4 The required palm mill scale to supply PKS

PKS mass fraction (%)	Amount of required PKS (Mg h ⁻¹)	Required palm mill scale (Mg-FFB h ⁻¹)
10	0.61	15
15	0.92	30
25	1.53	45
50	3.05	75

this case, following considerations are made: (1) the mass fraction of produced PKS to initially fed fresh fruit bunch (FFB) to the mill is 5 %, (2) palm mill scale is a multiple of 15 Mg-FFB h⁻¹ (15 t-FFB h⁻¹), and (3) the margin capacity required to buffer the fluctuation is 20 %.

Palm mills having production capacity of less than 30 Mg-FFB h⁻¹ (30 t-FFB h⁻¹) are generally considered as a small scale. In addition, larger mills having processing capacity up to 75 Mg-FFB h⁻¹ (75 t-FFB h⁻¹) are considered as middle scale. The consideration of available palm mill scale surrounding the power plants is very important. Moreover, in Indonesia, palm mills are widely distributed mainly in Sumatera and Kalimantan islands. Hence, considering the transportation cost, the co-firing of PKS into existing small scale coal-fired power plants seems to be applicable in those areas and their surroundings.

6. Conclusion

A numerical simulation using CFD analysis of PKS co-firing into existing small scale coal-fired power plants has been carried-out. Five different PKS mass fractions to coal are evaluated: 0 (fully coal), 10, 15, 25, and 50 %. In addition, the effect of mass fraction to the distribution of temperature, velocity and emitted gases during the combustion has been observed. Generally, higher PKS mass fraction leads to better performance of the combustion.

In addition, as PKS mass fraction increases, the amount of O₂ required for combustion increases. This is due to higher volatile matter content of PKS than coal. In current study with initial AFR of 10.2, the maximum PKS mass fraction which can be added and co-fired with coal is 50 %. Hence, it is very important to measure the O₂ demand for combustion during co-firing. Insufficient O₂ supply leads to incomplete combustion resulting in lower combustion performance.

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Nomenclatures

c_p	specific heat capacity (J kg ⁻¹ K ⁻¹)
e	internal energy (J)
f	body force per unit mass (N kg ⁻¹)
g	gravitational acceleration (m s ⁻²)
k	turbulent kinetic energy (J kg ⁻¹)
m	mass (kg)
p	pressure (kPa)
Pr	Prandtl number
$\dot{q}$	volumetric heat per unit mass (W m ⁻³ kg ⁻¹)
t	time (s)
T	temperature (K)
U	velocity (m s ⁻¹)

Greek letters

ε	turbulent dissipation rate (J kg ⁻¹ s ⁻¹)
μ	viscosity (Pa s)
ρ	density (kg m ⁻³)
τ	momentum (kg m s ⁻¹)

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