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Numerical Analysis of the Co-firing Combustion of Coal and Palm Shell Kernel In Stoker Boiler

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ABSTRACT

The United Nations Framework Convention on Climate Change (UNFCCC) states that Indonesia is committed to contributing to global climate change solutions. The government will also continue to encourage the development of a number of renewable energy (EBT)-based power generation projects. This is based on the use of renewable energy which is still low, namely around (1.9%) 8215.5 MW. Meanwhile, the potential for EBT to become energy can be around 443,208 MW. One source of EBT in Indonesia that can be utilized is Biomass. Co-firing of biomass is a relatively cheaper option and does not require investment in new power plants. However, Co-firing combustion has several aspects that need to be studied, such as temperature combustion and the generation of gas emissions. Therefore, this study aims to determine the temperature and the emissions resulting from co-firing of palm kernel shell biomass. This research was conducted using the Computational Fluid Dynamics method on stoker boiler model. The test parameters of the research was the maximum and average temperatures in the furnace, and the average and maximum fractions of CO_2, SO_2 in the stoker boiler furnace. From the research conducted, it was found that the resulting combustion temperature decreased as the co-firing fraction of the biomass increased. However, CO_2 gas emissions increased and SO_2 decreased with increasing fraction of co-firing biomass which showed a decrease in harmful gas emissions and complete combustion that occurred in the furnace.

1. Introduction

The energy sector has a significant impact, most of which have a negative impact on the environment. Dominant dependence on conventional energy sources is a real threat to the sustainability of the current economy. The need for energy will continue to increase along with the population and technological development of a country [1]. Renewable energy sources are increasingly important in the energy sector worldwide, and are recognized as a relevant alternative to fossil fuels [2-4].

In addition, to control global warming, it is very important to reduce carbon dioxide (CO_2) emissions in various fields globally [5, 6]. There is potential to reduce CO_2 emissions from coal-fired

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boilers in thermal power plants which generate more CO_2 emissions than other power generation methods. Various methods have been proposed to achieve this, one of which is by applying co-firing to the boiler [7]. Co-firing in boilers generally utilizes biomass fuel as one of the fuel materials. Co-firing of biomass is a low-cost method for creating environmentally friendly energy [8].The physical and chemical properties of biomass fuel have an important influence on combustion performance.

Biomass fuels have a larger range of structures and compositions in terms of waste products and amount of fuel. In addition, biomass is an identical type of fuel with a higher amount of volatile and ash content than fossil fuels [9].

The analysis of coal contents is an extremely important procedure for combustion and other coal utilization, which helps to improve the conversion efficiency and reduce the pollutant generation [10]. Analysis of coal content is divided into two types. The first is the ultimate analysis which provides information about the chemical constituents of coal such as carbon, hydrogen, oxygen, nitrogen and sulfur. Then another analysis is proximate analysis which shows the proportion of coal composition such as volatile content, fixed carbon, moisture, and ash [11]. Moisture content mainly consist of H2O which increasing moisture content significantly increases the combustion delay period for both coals [12]. Volatile matter consist of combustible components: CH_4, C_2H_2, CO, H_2, etc.; and non-combustible components such as CO_2, H_2O, N_2, NH_3, NO_X (NO, NO_2), N_2O, etc.; [13]**.** Fixed carbon is one of coal combustible content in which the amount of fixed carbon in a coal affects the calorific value or calorific value of the coal, where the higher the carbon content in the coal, the greater the calorific value of the coal [14]. Coal ash is the residue from coal burning which consists of two types, namely fly ash and bottom ash.

The content of carbon, oxygen and hydrogen, is the element that determines the rank of coal [15]. The carbon content in the ultimate analysis is the carbon element which evaporates at combustion temperatures and will form new compounds such as carbon monoxide (CO) and carbon dioxide (CO_2). The hydrogen content in the coal will come out or evaporate from the coal particles at the combustion temperature where the hydrogen will be attached to volatile substances. The amount of hydrogen content in the ultimate analysis of coal will affect the heat produced by burning coal where hydrogen binds with oxygen to form water [16]. The oxygen content in unburned coal is tied to the water content of the coal. Therefore, coal with high oxygen content is identic with low quality coal. Coal contains abundant nitrogen, and the form of nitrogen in coal is very complex. The mechanism of nitrogen transfer during pyrolysis and coal combustion is highly dependent on the type of coal and reaction conditions [17]. The sulfur content in coal will carry over to the volatile substances that are released from the coal at the combustion temperature. Temperature greatly affects the process of releasing sulfur content in volatile matter [18].

One of the biomass fuels that can be used as an alternative to the use of fossil fuels in boiler combustion is palm kernel shell. The oil palm tree is considered among the world's leading crops. Producing crude palm oil results in about 70% of solid wastes from post-processing products such as trunks, fronds, leaves, empty fruit bunch, and shells, which is the most promising biomass energy source because of the highest heating values (HHV). Indonesian palm kernel shell HHV ranges from 17.95 to 19.07 MJ/kg. Thus, Palm Kernel Shell (PKS) is a favorite feedstock renewable energy source in the country [19].

Palm kernel shell is a waste product of palm oil processing in the form of shells which are then crushed in an oil palm mill. A study shows that palm kernel shell has high thermal and combustion reactivity despite having a complicated structure and high density. Palm kernel shells resulting from processing of oil palm have an average density of around 1500 kg/m^2 [20]. In terms of proximate content, palm kernel shell has a significant volatile content compared to other biomass, while other proximate contents such as fixed carbon, moisture, and ash have average levels [21]. From the results of testing the ultimate content of several palm kernel shell samples, it was found that palm kernel shells had a carbon (C) content of 45%-55% which is lower than the carbon content possessed by coal in general, and a hydrogen (H) content of 5%-7% while the oxygen (O) content is 30%-45% which is greater than the oxygen content of coal in general, and also the palm kernel shell has a very low nitrogen and sulfur content of 0.05%-2.0% and 0.05%-0.2% [22].

Stoker Boiler is a type of boiler burning coal and solid waste with the disadvantage of having low energy efficiency [23, 24] but it has simple construction, simple handling and very good flexibility. However, stoker boilers are still used in several power plants in Indonesia. From the various facts described previously, Co-firing combustion has several aspects that need to be studied, such as temperature combustion and the generation of gas emissions. Therefore, this study aims to determine the temperature and the emissions resulting from co-firing of palm kernel shell biomass. However, numerical approaches gained importance by developing relevant mathematical models because of the high costs and time requirements of experimental method [25], so this study used computational fluid dynamics method to solve the problems.

2. Model Description

2.1 Physical Model

Figure 1 shows the stoker boiler geometry used in the simulation which is taken from the original geometry of the stoker boiler at one of the power plants in Indonesia. In the simulation, the geometry modeled as fluid in the stoker boiler which make the geometry design affect the boundary layer in the stoker boiler. The boundary layer is the area where viscosity predominates and most of the drag that a body submerged in a fluid experiences is produced [26].The stoker boiler has several parts which in the simulation are modeled as boundary conditions. To simplify the modeling of the simulation geometry, heat transfer areas such as the superheater and steam drum in the boiler furnace are modeled as walls similar to those section areas in the simulation.

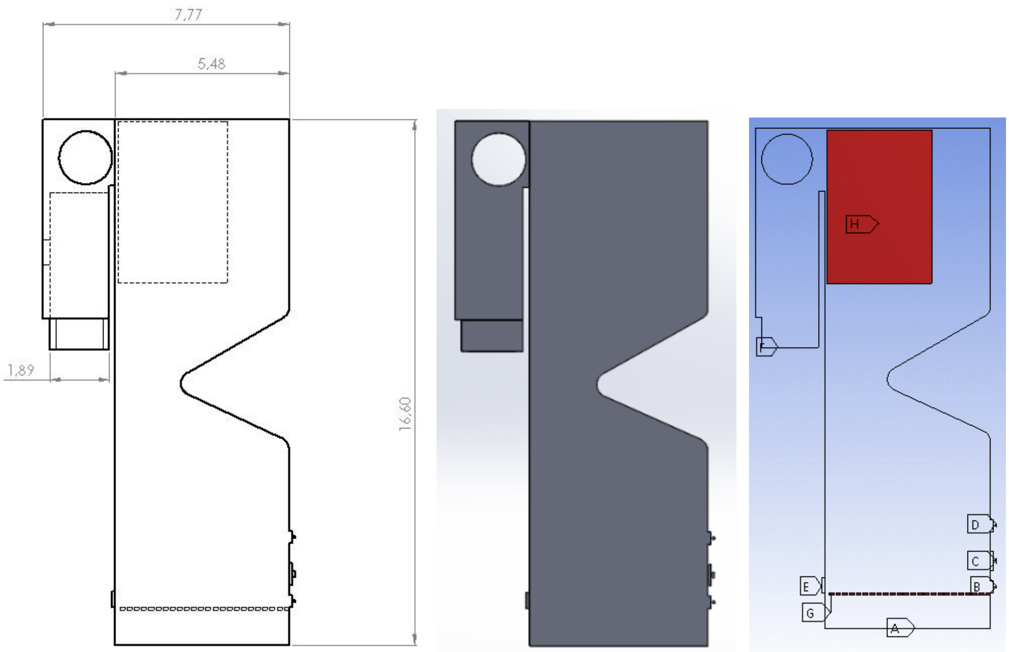


Fig. 1. (A) *Furnace*, (B) *Over fire air* 1, (C) *Ash re-Injection*, (D) *Over fire air* 2, (E) *Spreader*, (F) *Exhaust*, (G) *Coal bed*, (H) *Superheater*

2.2 Coal and Palm Kernel Shell Properties

Palm kernel shell and coal consists of ultimate content and proximate content. The proximate content is the content present in the fuel based on the form of the content. Proximate analysis is a test that includes analysis for moisture content, ash content, volatile matter. While the Ultimate content is the content that is in the fuel based on the type of element of the content. The ultimate analysis includes the analysis of determining the content of carbon, hydrogen, oxygen, nitrogen, total sulfur and calorific value. The ultimate and proximate analysis of palm kernel shell and coal used as research materials are shown in the Table 1 and Table 2.

Table 1
Coal and palm kernel shell proximate analysis

Ultimate analysis	Coal	Palm kernel shell
carbon (C)	76.2416%	50.2597%
Hydrogen (H)	9.698%	6.044%
Oxygen (O)	10.8837%	43.1369%
Nitrogen (N)	1.7226%	0.4595%
Sulfur (S)	1.4541%	0.0999%
Calorific value (kJ/kg)	1.7×10^4	2.89×10^4

Table 2
Coal and palm kernel shell ultimate analysis

Proximate analysis	Coal	Palm kernel shell
Fixed carbon	35.61%	17.51%
Volatile	47.94%	71.15%
Ash	10.6%	1.87%
Moisture	5.85%	9.47%

3. Numerical Methods and Validation
3.1 CFD Model

The CFD model used in this study refers to the actual phenomena that occur in the combustion of fuel particles in the stoker boiler furnace. In this study the aim was to observe the co-firing process of palm kernel shell biomass in a steady condition which did not depend on the burning time. In this case, the simulation time model used is steady. In the stoker boiler furnace, heat transfer occurs between fluid particles and the walls around the stoker boiler furnace, so that in this simulation the Energy modeling is turned on in the simulation setup. The fluid in the stoker boiler furnace is a mixture of various chemicals, both flammable chemicals and combustion products, so this simulation activates species modeling with the Species Transport-Eddy Dissipation type. This model also enables turbulent flow modeling with the K-Epsilon-Realizable type because this type of turbulence modeling is accurate in areas far from the wall. k -ε Realizable is a type of turbulence model in Ansys Fluent where the transport model equation based on the kinetic energy of turbulence (k) and its rate of dissipation (ε) [27]. Then to model the combustion of particles in the stoker boiler furnace, this research simulation activates the Discrete Phase modeling. Coal and palm kernel shell particles in the Discrete Phase Model input are injected from the top side of the combustion bed. The fuel particles in the boiler furnace from any inlet should be arranged to the top side of the combustion bed for combustion process. With this, it is very natural that the palm kernel shell particles and coal are injected directly on the top side of the bed to simplify the combustion process [28].

3.2 Grid Independence Test

The grid independence test is intended to test validation data whether the validation data value depends on the number of meshing cells or not. The criterion for passing the grid independence test is if the error range between cells is less than 10%. The grid independence test in this study was carried out with 5 different numbers of cells with details on each number of cells and the simulation results of the grid independence test which can be seen in Figure 2 and Table 3.

Table 3
Grid independence test result

	Meshing 1	Meshing 2	Meshing 3	Meshing 4	Meshing 5	Error (%)
Furnace temp (C)	588.9454	610.4878	615.5047	615.5651	620.3891	1.61%
Flue gas temp (C)	267.5743	293.5514	291.2781	297.8159	308.8973	5.68%
Fraction of CO_2 flue gas	0.09454	0.09518	0.10092	0.1046	0.10453	9.00%
Fraction of O_2 flue gas	0.06219	0.06267	0.06408	0.06951	0.06877	9.80%

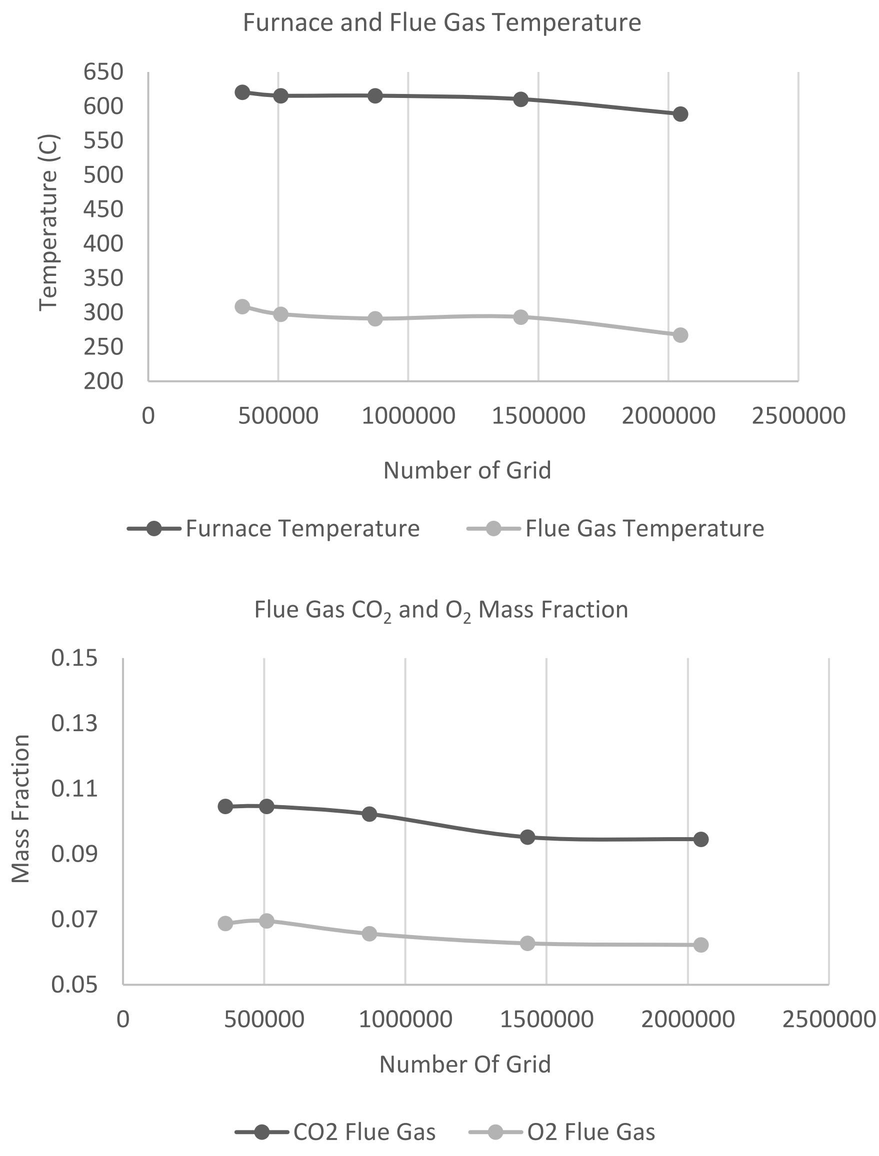


Fig. 2. Grid independence test result

3.3 Validation Test

Validation Test aimed to ensure the setup used in the simulation is correct. Validation data was taken from 100% palm shell burning in the stoker boiler at one of the power plants in Indonesia. Validation data includes furnace temperature, flue gas temperature, CO_2 mass fraction temperature, O_2 mass fraction temperature. The results of the validation test can be seen in the following Figure 3.

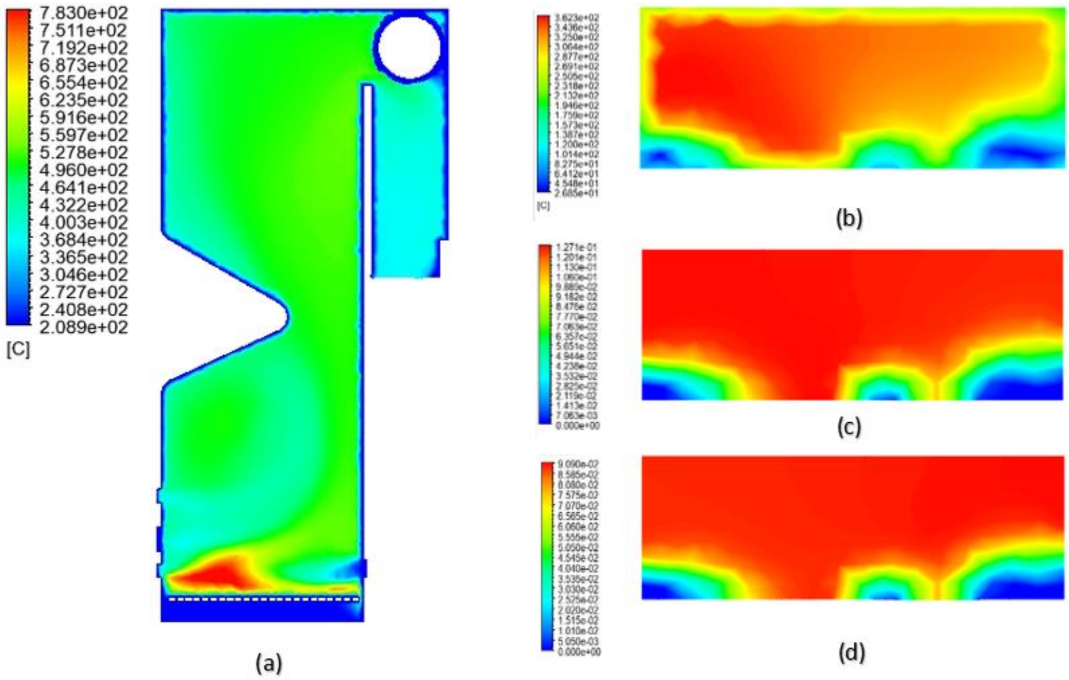


Fig. 3. Validation test result (a) Furnace temperature, (b) Flue gas temperature, (c) Flue gas CO_2 mass fraction, (d) Flue gas O_2 mass fraction

The error value of each validation data in Table 4 is less than 10% which indicates the maximum permitted error limit of 10% has been met [29].

Table 4
Validation test result data

Validation data	Validation data value	Simulation result	Error
Furnace temperature	660.75 C	657.7 C	0.27%
Flue gas temperature	283.9 C	297.5 C	4.90 %
Flue gas CO_2 mass fraction	10.58 %	10.09 %	4.63 %
Flue gas O_2 mass fraction	6.46 %	7.03 %	8,82 %

4. Result and Discussion

4.1 Furnace Temperature

Figure 4 shows the temperature stoker boiler furnace in different palm kernel shell co-firing fraction. Combustion temperature is an indicator that shows the performance of the boiler where the greater the temperature produced indicates the better performance of the boiler. Combustion in boiler is caused by several processes between fuel and primary and secondary air. The content difference between palm kernel shell biomass and coal makes the temperature produced in the combustion of each co-firing fraction of palm kernel shell biomass are different. One of the characteristics of biomass fuel that has the most influence on combustion performance is the high content of volatile matter with a low heating value. Low calorific value will cause a decrease in the maximum combustion temperature.

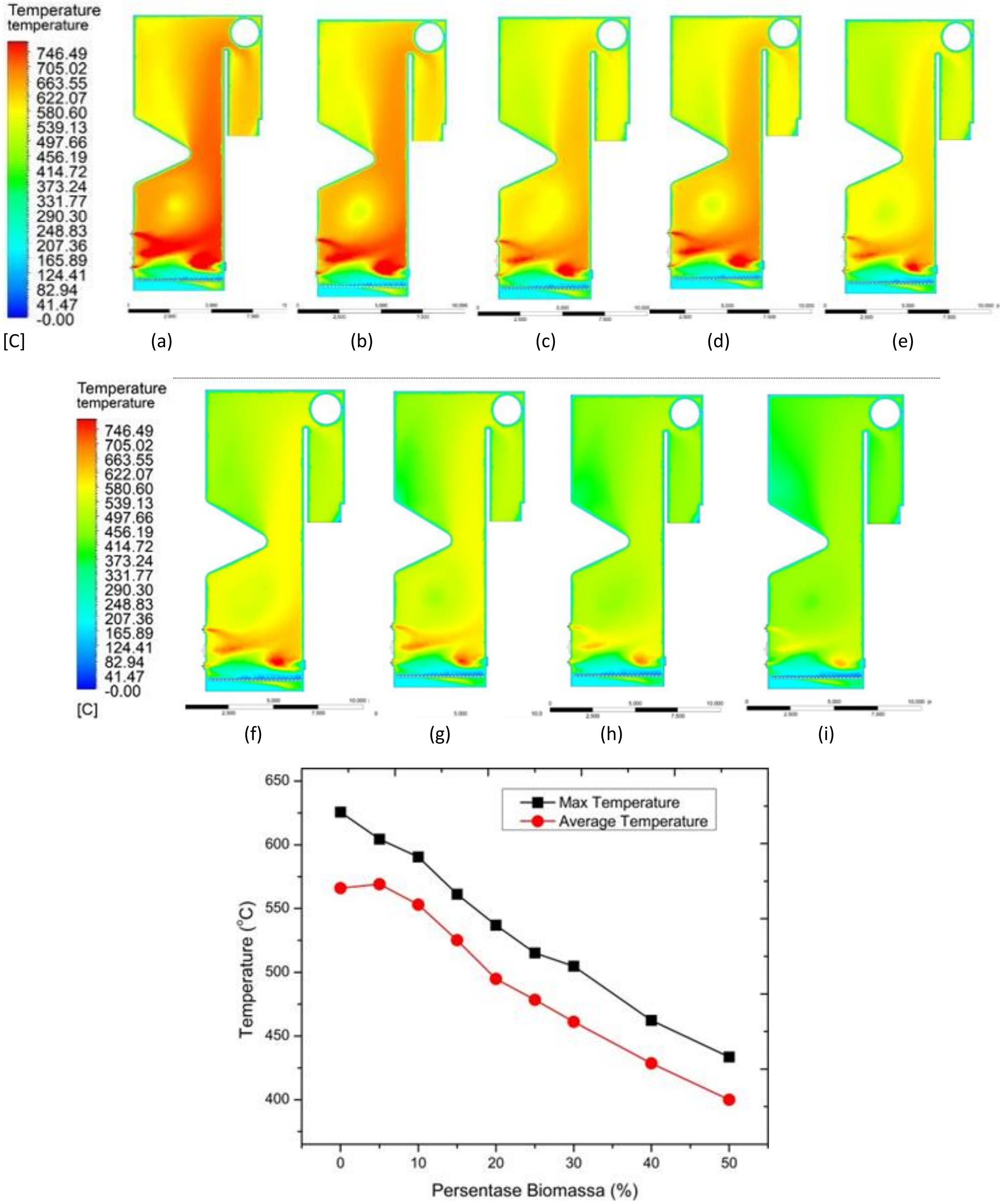


Fig. 4. Stoker boiler temperature profile in different co-firing fraction of palm kernel shell biomass (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%, (f) 25%, (g) 30%, (h) 40% and (i) 50%

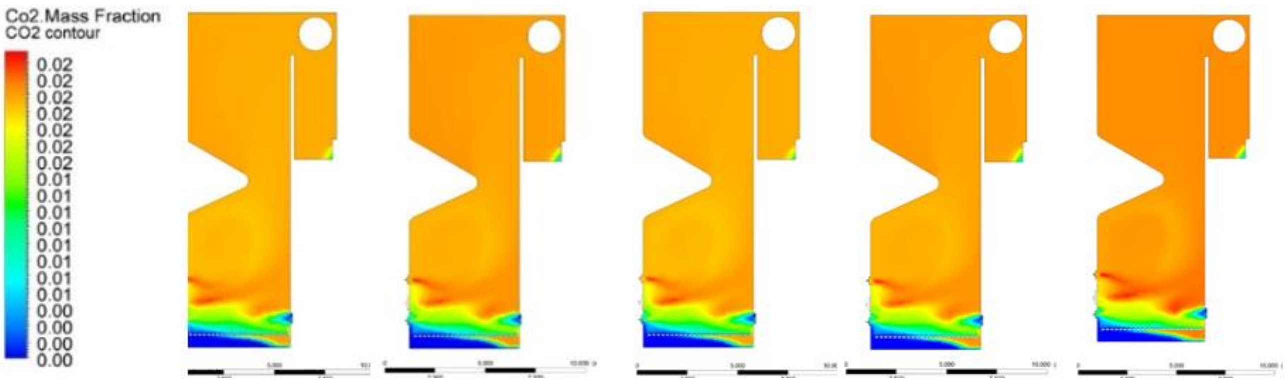
As the results of the co-firing temperature of palm kernel shell biomass simulation, it was found that the greater of fraction of palm kernel shell biomass, the lower the resulting combustion temperature. This is caused by the difference in the content in the palm kernel shell and coal, both proximate and ultimate content. The carbon content in ultimate and proximate content is the main factor in the temperature produced by fuel combustion where the higher of carbon content make higher the combustion temperature. The results of research conducted by Aziz *et al.,* [30] previously also showed that co-firing burning of palm shells produces lower combustion temperatures as the biomass co-firing fraction increases.

The largest temperature in furnace temperature profile indicates the place where fuel combustion occurs for the first time [25]. The largest Temperature occurs near the combustion bed, even though it does not occur directly above the bed. This is because in the combustion process it must go through a drying process, a pyrolysis process, and a gasification process. As the combustion occurs in the furnace, it occurs in the near secondary inlet. This indicates that the oxidation process of volatile matter is mostly caused by secondary air. This also shows the important reason for providing secondary air injection in the boiler furnace.

In addition, the temperature of the combustion products also decreases as it approaches the furnace outlet. This occurs due to heat transfer on the walls of the boiler, superheater, and steam drum furnaces, as well as heat transfer from the combustion gases and primary and secondary air which do not participate in combustion.

4.2 CO_2 Gas Emission of Combustion

Figure 5 shows the CO_2 mass fraction in gas emission of combustion in different shell biomass co-firing fraction. One of the gas emissions produced in the combustion of coal and biomass fuels is CO_2 gas. CO_2 gas from combustion is obtained due to complete combustion in the boiler furnace. Complete combustion occurs because the carbon content in the fuel can react perfectly with the oxygen O_2. Meanwhile, if in the combustion reaction the carbon content in the fuel does not react completely with oxygen it will produce carbon monoxide gas (CO). Thus, the O_2 content in the fuel and the O_2 content in the primary air greatly affect the CO_2 fraction that will be formed from the combustion of fuel.



(a) (b) (c) (d) (e)

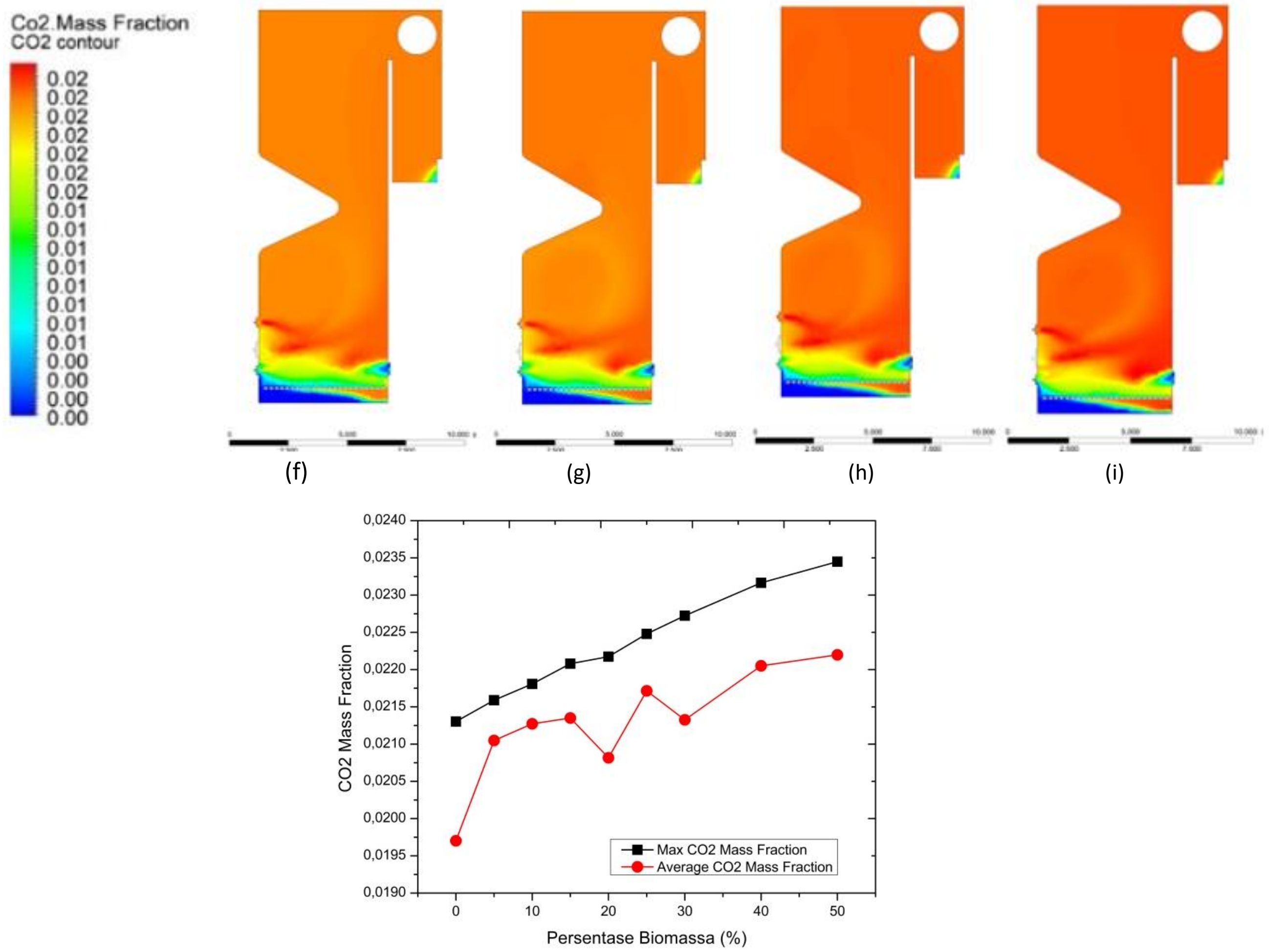


Fig. 5. Stoker boiler CO_2 gas profile in different co-firing fraction of palm kernel shell biomass (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%, (f) 25%, (g) 30%, (h) 40% and (i) 50%

Carbon dioxide and carbon monoxide are formed in volatile matter. Carbon monoxide is a flammable substance while carbon dioxide not. Fuels with a higher carbon and lower oxygen content such as coal will produce more carbon monoxide, while fuels with a lower carbon and higher oxygen content such as biomass fuel will produce more carbon dioxide, as shown in Figure 5.

Fuels that produce more carbon monoxide will produce a higher combustion temperature as well, while the carbon dioxide produced by the fuel has no effect on the combustion temperature. It is reasonable that coal with a higher carbon monoxide content will produce greater combustion temperature. From CO_2 distribution profile in the stoker boiler furnace as shown in Figure 5, the highest CO_2 mass fraction is in the combustion area. Thus, CO_2 is a gas produced by burning volatile matter.

Based on previous research by Suranani and Goly [31], the size of fuel particles affects the amount of CO_2 formed from combustion. Fuel with a smaller size tends to produce greater CO_2 gas emissions, which indicates more complete combustion.

4.3 SO_2 Gas Emission of Combustion

The content of SO_2 in flue gas contributes to environmental air pollution. In addition, the content of SO_2 is also dangerous for human health, especially children under 5 years to get pneumonia. Just like CO_2 and SO_2 gas is produced after the volatile matter is pyrolyzed for the second time. Figure 6 shows the SO_2 mass fraction in gas emission of combustion in different shell biomass co-firing fraction.

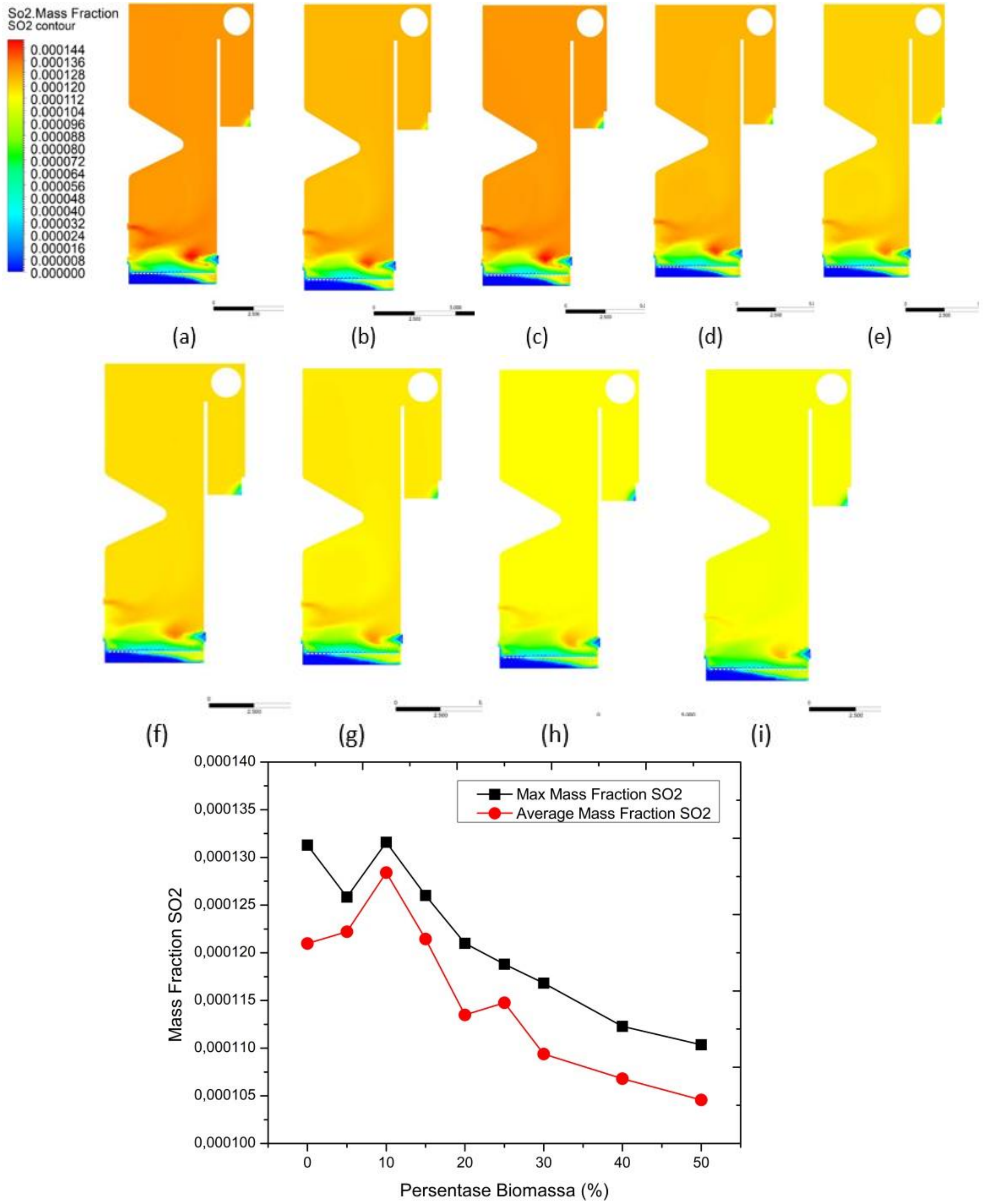


Fig. 6. Stoker boiler SO_2 gas profile in different co-firing fraction of palm kernel shell biomass (a) 0%, (b) 5%, (c) 10%, (d) 15%, (e) 20%, (f) 25%, (g) 30%, (h) 40% and (i) 50%

Sulfur oxide is a compound formed from the bond between sulfur and oxygen. Therefore, the sulfur content in the fuel greatly affects the SO_2 gas produced in fuel combustion. The sulfur content of coal is greater than that of palm kernel shell biomass, which causes coal combustion to produce more SO_2 than palm kernel shell biomass. Based on previous research conducted by Aziz *et al.,* [30] burning palm shell biomass produces lower SO_2 gas emissions. However, in fact the co-firing of palm kernel shell biomass at the 10% fraction produces the most SO_2 gas, exceeding the full coal combustion. The volatile matter content of the palm kernel shell biomass causes SO_2 gas production to increase in certain co-firing fractions.

5. Conclusion

This study aimed to determine the effect of palm kernel shell biomass co-firing in stoker boiler on combustion temperature and gas emission. Nine different co-firing fractions were used in this study. The result of this study can be summarized as follows:

i. The temperature produced by the palm kernel shell biomass co-firing burning decreases with increasing co-firing fraction. The lower carbon content of palm kernel shell biomass is the main factor in decreasing the combustion temperature as the co-firing fraction increases.
ii. CO_2 gas produced by co-firing palm kernel shell biomass increases with increasing co-firing fraction because palm kernel shell biomass has a higher oxygen content with lower carbon compared to coal.
iii. The SO_2 gas produced in the co-firing of palm kernel shell biomass decreased and increased as the co-firing fraction increased with the peak of SO_2 gas production at the 10% co-firing fraction. The factor of lower sulfur content and higher volatile matter content is a factor for the increase and decrease of SO_2 gas produced.

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