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COMPARISON OF TEMPERATURE, RADIATION RATE, HEAT LOSS, FURNACE AND THERMAL EFFICIENCIES OF DIFFERENT PLATES IN THE FBC COMBUSTION CHAMBER

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ABSTRACT

The conversion of solid biomass waste into energy continues to be developed at this time to reduce dependence on fossil energy. Energy conversion can be carried out using several technologies commercialized by several industries, including the fluidized-bed combustor (FBC). This FBC technology has also been developed in several ways, such as the modification or unique modelling. In particular, the perforated plate modelling applied in this study is to provide excess air supply so that complete combustion can be achieved. In addition, modifying the perforated plate increases efficiency and radiation and reduces heat loss in the FBC combustion chamber. This research was conducted with combustion experiments using palm kernel shell (PKS), oil palm midrib (OPM), and empty fruit bunches (EFB) against different plates. Experimental results show that the maximum temperature achieved on the modified four guide plates is 975°C for PKS fuel, 850°C OPM, and 883°C EFB with 20% -70% excess air. The results of the highest furnace efficiency on the four guide plate modifications were 91.44% PKS, 73.48% OPM, and 77.63% EFB. Meanwhile, the highest efficiency recorded from modifying the four guide plates for each fuel was 84% PKS, 73% OPM and 74% EFB. The highest radiation rates were recorded at 7745.21 W/sec PKS, 5971.17 W/sec OPM, and 6356.12 W/sec EFB. The perforated plate modification applied in the FBC combustion chamber can reduce heat loss significantly compared to when implementing standard plates.

Keywords: *Biomass, Temperature, Furnace efficiency, Thermal efficiency, Radiation, Heat loss.*

1. INTRODUCTION

The conversion of solid biomass waste into energy in various countries continues to be carried out to produce power to overcome the problem of dependence on fossil energy. The abundant availability of solid biomass waste in different regions allows it to be converted into energy (Erdiwansyah, Mahidin, et al., 2019; Erdiwansyah et al., 2020; Erdiwansyah, Mamat, Sani, & Sudhakar, 2019). The technology for converting solid biomass into power has been widely commercialized, both on a small, medium and large scale. One of the most commonly used small-scale biomass-to-energy conversion technologies is the fluidized-bed combustor (FBC).

The FBC technology can convert solid biomass and liquid waste energy. Several studies have widely used experiments using FBC technology, including (Banerjee, Shahnam, Rogers, & Hughes 2023; Erdiwansyah, Mahidin, Husin, Faisal, et al., 2021; Erdiwansyah, Mahidin, Husin, Nasaruddin, et al., 2021; Erdiwansyah et al., 2022; Zhou, Wang, Luo, & Fan, 2022; Erdiwansyah et al., 2023). Combustion tests with different biomass fuels with FBC technology have also been carried out (Sher, Pans, Sun, Snape, & Liu, 2018). Research is being carried out for future commercial applications with stationary combustion power plants. Experiments with oxy-circulating fluidized-bed combustion and fluidized-bed oxy-circulating were carried out to facilitate the reduction of O_2 supply requirements (Ju Kim et al., 2023). While in a different study, combustion experiments in the FBC combustion chamber were carried out to investigate the effect of oxidant staging and the addition of limestone on reducing NO, N_2O, and SO_2 emissions that circulate 25% oxy and 31% oxygen input (Baek et al., 2022; Liu, Zhong, Yu, & Wang, 2022; Rahman et al., 2019). At the same time, research through numerical simulation of reactive flow with gas-solid in the FBC combustion chamber has also been carried out (Wan, Yang, Wei, Hu, & Wang, 2020). Simulation via CFD is carried out to validate experimental data and hydrodynamics of various operating components. Combustion experiments using palm oil solid waste biomass fuel in recent years have begun attracting the attention of researchers worldwide.

Experiments on burning using palm shell fuel with FBC technology in 2014 were carried out in Thailand (Ninduangdee & Kuprianov, 2014a). The size of the energy used is 30 kg and 40 kg, with variations in the air between 20% and 80%. Combustion efficiency from their research reached 99%, with CO and NO levels below the established quality standards. While burning with FBC technology using oil palm shells and empty palm oil fruit bunches has also been

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discussed (Kuprianov, Ninduangdee, & Suheri, 2018; Ninduangdee & Kuprianov, 2013; Suheri & Kuprianov, 2015). While in a different study burning palm shell fuel with FBC technology with a blazing speed of 45 kg/s and excess air of around 20% -80% has also been carried out (Ninduangdee & Kuprianov, 2015). Combustion efficiency from the test reached 98.6-98.9% by producing CO and NO below the established quality standards. Combustion using FBC technology using palm shell fuel at a 45 kg/hour speed has also been discussed (Ninduangdee & Kuprianov, 2014b). The average particle size used in the burning is between 1.5 mm, 4.5 mm, 7.5 mm, 10.5 mm and 5 mm for empty palm oil bunches with an air velocity of between 20% -80%. The results of experiments carried out can produce a level of combustion efficiency reaching 99.4-99.7%. Of the many studies that have been carried out previously, there has not been a specific investigation regarding plate modification in the FBC combustion chamber. Modification of the plate in the FBC combustion chamber floor can also be carried out to provide excess air supply with the aim of achieving maximum combustion efficiency.

Based on the results of the review of several studies described above, many energy conversions from solid biomass waste have been carried out. However, we are still looking for methods to reach the optimal point of producing energy. Several technologies for converting biomass into energy have also been commercialized for various scales. The study carried out in this paper investigates the comparison of the results of several tests carried out on different fuels. This work examines the highest temperatures when adding plate modifications to the FBC combustion chamber. In addition, plate modifications were modelled to investigate the efficiency level of the furnace and the thermal efficiency of each fuel used. Radiation rates and heat loss rates from applying plate modifications are also discussed. The plate modifications involved in the study were tested using palm kernel shell (PKS), oil palm fronds (OPM), and empty fruit bunches (EFB) as fuel. Three modifications to the modelled perforated plate and one standard plate are added to compare the initial results.

2. EXPERIMENT SETUP AND MATERIAL

2.1 Material

The experiment in this study was burning palm oil solid biomass waste using FBC fluidized-bed combustor technology with a modified perforated plate. The schematic diagram of the FBC technology used for the combustion experiment is shown in Figure 1. Temperature data measurement using FBC technology uses a thermocouple cable with a measurement range between 100-1000°C and a digital thermometer that can read up to 1300°C, as shown in Figure 2 (b). Five thermocouples for data collection are marked with T01, T02, T03, T04, and T05. Two thermocouples are placed in the combustion chamber (T01 and T02), two pieces on the freeboard (T03 and T04) and one for recording temperature data on the outer wall. The whole place for recording temperature data for each test is shown in Figure 1, where the thermocouples T01 and T02 are placed in the combustion chamber. At the same time, T05 also records the temperature on the outer wall of the reactor.

Furthermore, the tool used to support this research is a blower fan which supplies air into the combustion chamber, as shown in Figure 2.a. The function of the blower fan is to provide more perspective into the combustion chamber so it can produce complete combustion. The fuel in the combustion chamber is solid waste that does not burn quickly like liquid fuel. Therefore, excess air is needed for the combustion process to achieve complete combustion. At the same time, the thermocouple and digital cables for recording combustion temperature data are shown in Figure 2.b. Descriptions and physical-chemical properties of the tested fuels are shown in Table 1.

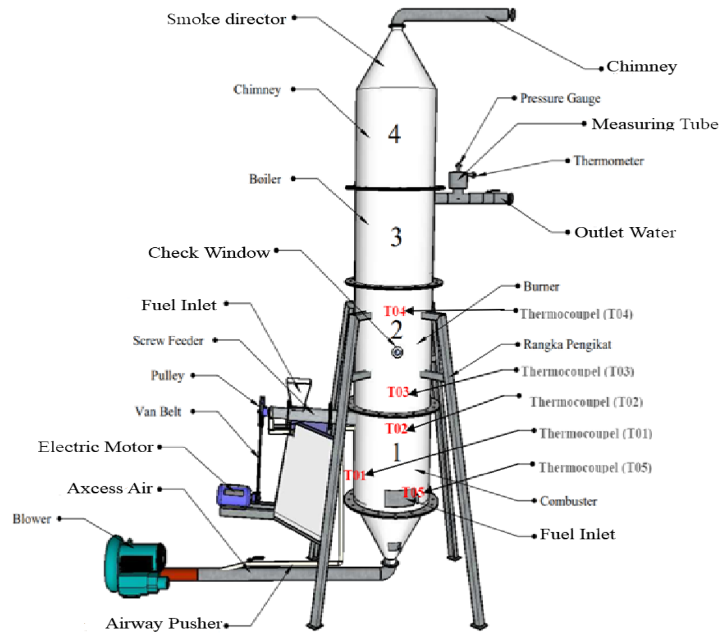

Fig. 1 Schematic Diagram (fluidized-bed combustor)

Table 1. The description and physical-chemical properties

No	Content	Palm Kernel Shell (CKS)	Palm Oil Midrib (POM)	Empty Fruit Bunches (EFB)	Unit
Analysis of Ultimate					
1	C	68.15	55.43	63.35	%
2	H	10.51	9.25	6.55	%
3	N	16.25	14.35	10.97	%
4	S	0.67	0.53	0.25	%
5	O	17.35	21.05	22.15	%
Analysis of Proksimat					
1	Air Content	5,01	9.25	2.09	%
2	Volatile Matter	69.53	75.45	75.69	%
3	Fixed Carbon	21.25	13.04	15.30	%
4	Ash	1.10	3.15	5.03	%
5	Calorific Value	23.45	15.01	17.95	MJ/kg
Analysis of Lignin, Cellulose and Hemicellulose					
1	Cellulose	31.55	39.45	53.25	%
2	Hemicellulose	16.15	27.55	27.15	%
3	Lignin	47.43	22.10	24.20	%

(a) Blower Fan

(b) Digital and Cable Thermocouple

Fig. 2. Blower-Fan and Thermocouple

Table 2. Blower fan specifications

Parameter	Measurement Rank
Type Blower	HG-750 Whirl Charging Aerator
Voltage	220V/50Hz
Power	750W
Pressure	14.7 k Pa
Output	75 m³/h

Combustion experiment by applying a modification of the perforated plate in the FBC combustion chamber using solid palm oil fuels such as palm kernel shell (PKS), oil palm midrib (OPM), and empty fruit bunches (EFB). The amount of energy for each experiment was 3 kg for each experiment. The type of fuel used for the combustion experiments in this study is presented in Figure 3. The FBC technology used in this study was carried out by modelling a plate that aims to provide excess air supply into the combustion chamber. The modelled perforated plates are three types plus one standard plate, used as a comparison result. The modified perforated plate has two, three, and four guides plus a small hole between the primary air guides, as shown in Figure 3. The plate modelling in the FBC combustion chamber functions for air passage supplied by the blower far from the bottom pipe, so the combustion air requirement is sufficient. The combustion test was repeated for each fuel on each plate. The blower fan, thermocouple and digital thermometer specifications are presented in Table 1 and Table 2. The temperature data measurement point with a thermocouple is also shown in Figure 3.

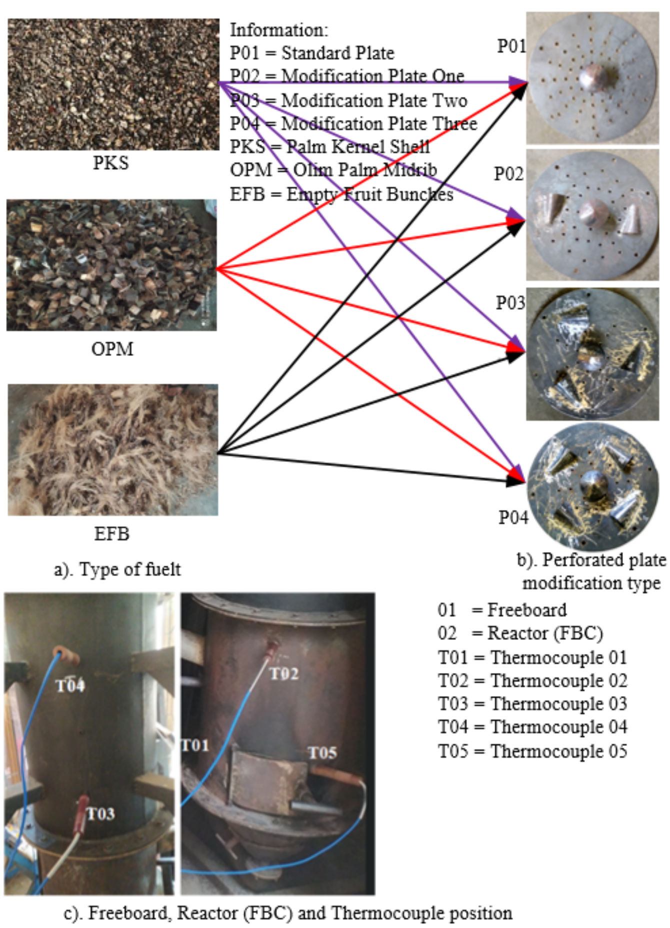

Fig. 3 Fuel type of biomass palm oil, plate, and positions for thermocouple

Table 3. Specifications for the HT-306 digital thermometer

Component	Output
Model HT-306	Dual Channel Input
Input Sensor	Thermocouple Type "K"
Data Hold Function	
Resolution	HT-306:1ºC/1ºF
Response Time	15 Seconds
Wide Measuring Range	-50ºC ~ +1300ºC (-58ºF ~ +1999ºF)
Low Battery Indication	-
Celsius (ºC) or Fahrenheit (ºF) for Selection	-
Offset Adjustment	-
"OL" Display When Overload or No Signal Input	-
Constructed of Durable ABS Plastic/Neoprene with Rubber Holster & Stand Rack	-
Wide Range of Specialized Probes Available	-
Power Supply	Baterai 6F22 9V

2.2. Method and Analysis

During the combustion experiment with solid biomass waste, not all elements could break down with oxygen (O_2), especially nitrogen (N_2), because this element would come together with the smoke gas. The amount of N_2 depends on the combustion air requirement and the fuel's nitrogen. The chemical composition contained in the energy when complete combustion occurs, which can be broken down by oxygen, is C and H_2 as the following reaction:

$$C + O_2 \rightarrow CO_2 \quad (1)$$
$$12kg\ C + 32kg\ O_2 \rightarrow 44kg\ CO_2$$
$$1kg\ C + 2.66kg\ O_2 \rightarrow 3.667kg\ CO_2$$

Thus, burning 1 kg C requires 2.66 kg of O2 oxygen, so burning 1.2 kilograms of fuel requires 0.454475 kg C x 2.66 kg O_2. Meanwhile, burning 1 kg of H_2 requires 8 kg of oxygen or 0.04 kg x 8 = 0.32 kg of fuel. At the same time, the amount of oxygen O_2 in the energy is 0.30 kg. The furnace efficiency of the FBC combustion chamber used for the experiments in this study is calculated by Eq. (2). This calculation is carried out to determine how far the furnace's efficiency is during the combustion process from the beginning to the end of the test.

$$Ef = \frac{T_{int}}{T_{out}} \quad (2)$$

where:
Eph = Efficiency
Q_{int} = inside temperature (°C)
Q_{out} = outside temperature (°C)

The ratio of heat obtained from burning fuel to heat increases the temperature. The combustion process's thermal efficiency in the combustion chamber uses Eq. (3) (Indonesia, 2013).

$$\text{Thermal efficiency} = \text{x } 100\eta_T \frac{m_a Cp\Delta T + \Delta m_a L}{\Delta m_k LHV} \quad (3)$$

where:
η_T =Thermal Efficiency
m_a =Mass of Water (kg)
$C_{p.s}$ =Specific Heat of water (4180 J/kg °C)
ΔT =Difference in Water Temperature (°C)
Δm_a =Evaporator Water Mass (°C)
L =Heat of Evaporation of Water (J/kg)
Δm_k = Mass of fuel that has been burned (kg)
LHV =Fuel calorific value (cal/gr)

The radiation rate for each experiment's combustion chamber was measured in the FBC combustion chamber by applying for perforated plates. Different fuels were calculated using equation (4), modelled by JP Holman (Indonesia, 2013).

$$q = \epsilon_t \, \sigma A_1 (T_1^4 - T_2^4) \quad (4)$$

where:

ϵ : Emissivity
σ : Stefan-Boltzmann constant
A: Cross-sectional area
T1: Burners (chamber burn)
T2: Tongue of Fire (Flame)

Calculating the heat transfer rate in combustion needs to be done so that the required energy requirements can be known. The heat transfer calculation used in this study adopts the JP Holman equation (Holman, 1988). In this case study, the equation used is adopted from JP Holman (Holman, 1988). The equation is then adjusted to the cases and results of this study Eq. (5).

$$q = \frac{2\pi l (T_I - T_O)}{\frac{1}{h_o A_o} + \frac{\ln\left(\frac{r_{o1}}{r_{i1}}\right)}{k_1} + \frac{\ln\left(\frac{r_{o2}}{r_{i2}}\right)}{k_2} + \frac{1}{h_i A_i}} \quad (5)$$

Where:

Q_I = Temp. Flame (*Flames*)
Q_O = Temp. Outer Wall
ro1 = *Outer radius of a cylinder*
ri_1 = Inner radius of a cylinder
ro_2 = Outer radius of insulation
ri_2 = Fingers in isolation
k_1 = Thermal conductivity of the plate
k_2 = insulation conductivity
ho = Convection heat transfer coefficient on the outer wall cylinder
hi = *Convection* heat transfer coefficient inside the cylinder
Ao = Outside cross-sectional area
Ai = Inner cross-sectional area

$$q = \frac{T1 - T5}{\frac{1}{hoAo} + \frac{\ln\left(\frac{ro1}{ri1}\right)}{k1} + \frac{\ln\left(\frac{ro2}{ri2}\right)}{k2} + \frac{\ln\frac{ro3}{ri3}}{k1} + \frac{1}{hiAi}} \quad (6)$$

Where:

*T*1 = The temperature flame
*T*5 = The temperature outer wall
*ro*1 = The outer radius of the combustor
*ri*1 = The mine radius of the combustor
*ro*2 = The outer radius of insulation
*ri*2 = The inner radius of insulation
*ri*3 = The radius of the cylinder
*k*1 = The thermal conductivity of the plate
*k*2 = The thermal conductivity of the insulation
ho = The coefficient heat transfer rate from outer wall to air
hi = The coefficient in the wall from the combustor chamber to the inner wall
Ao = The outer cross-sectional area
Ai = The inner cross-sectional area

Table 4. Experimental operating conditions

Type of Plate	Type of Fuels	Total Fuels
Plate Standard (P01)	PKS	3 kg
	OPM	
	EFB	
Plate Modification (P02)	PKS	
	OPM	
	EFB	
Plate Modification (P03)	PKS	
	OPM	
	EFB	
Plate Modification (P04)	PKS	
	OPM	
	EFB	

The experimental operating conditions carried out in the study are presented in Table 4. Where each fuel was tested on a different plate. The weight of the fuel for each test is the same, 3 kg. This is done to make it easier to analyze each result obtained from each plate with a different fuel.

3. RESULT AND DISCUSSION

This study's combustion experiments with FBC technology aim to analyze the temperature comparison of plates and different fuels. Based on the analysis results, it can be explained that modifying the perforated plate designed in FBC can increase the combustion temperature. The increase in combustion temperature for each plate reaches 10% to 15%, as shown in Figure 4.a. The highest temperature recorded when testing the standard plate for PKS fuel came to 859°C. At the time of testing using a modification of the two guide plates, the temperature increased by 66°C to 925°C compared to the standard plate. The combustion temperature recorded from modifying the three guide plates in the FBC reaches 935°C. The test results of the three guide modifications experienced a slight increase compared to the two guide plate modifications. At the same time, the experimental results in the FBC combustion chamber with four guide plate modifications can produce a temperature of 971°C. 112°C significantly increased the combustion temperature recorded on the four guide plate modifications compared to the standard plate test. At the same time, the increase in combustion temperature from testing the two and three guide plate modifications was 46oC and 36°C, respectively. The combustion temperature obtained from this test is also higher than in previous studies 112oC significantly increased the combustion temperature recorded on the four guide plate modifications compared to the standard plate test. At the same time, the increase in combustion temperature from testing the two and three guide plate modifications was 46°C and 36°C, respectively. The combustion temperature obtained from this test is also higher than in previous studies 112oC significantly increased the combustion temperature recorded on the four guide plate modifications compared to the standard plate test. At the same time, the increase in combustion temperature from testing the two and three guide plate modifications was 46°C and 36°C, respectively. The combustion temperature obtained from this test is also higher than in previous studies (Erdiwansyah, Mahidin, Husin, Faisal, et al., 2021; Erdiwansyah et al., 2022).

Based on the graph in Figure 4.a above, it can be seen that the application of the four guide plate modifications in the FBC combustion chamber shows slightly slower combustion than the two, three guide and standard plate modifications. However, when the burning time was 50 seconds, it significantly increased compared to the other plates. While the combustion temperature with the application of a modification of the three guide plates so that the combustion time reaches the optimum point is slightly faster, namely at 50 seconds. Meanwhile, the modification temperature of the four guide plates reaches the optimum moment when the combustion time is 60-70 seconds.

Based on the experimental results from each test carried out with OPM fuel, it can be explained that the design of the perforated plate in the combustion chamber can affect the combustion temperature. In addition, implementing perforated plate modifications can also increase the burning time. The combustion temperature resulting from the OPM fuel test for standard plates reaches 789°C. While the test results were done by modifying the two air guide plates, the temperature reached 815°C. The increase in temperature when testing the two guide plate modifications was around 36°C compared to the standard plate test. The temperature obtained from the modification of the three guide plates reaches 830°C. Meanwhile, the combustion temperature recorded from the modified test of the four air guide plates is 850°C shown in Figure 4.b. The increase in combustion temperature that occurs in changing the perforated plate is due to sufficient air entering the chamber. In addition, modification of the perforated plate in the FBC combustion chamber can provide better combustion and more perfect results than the standard plate.

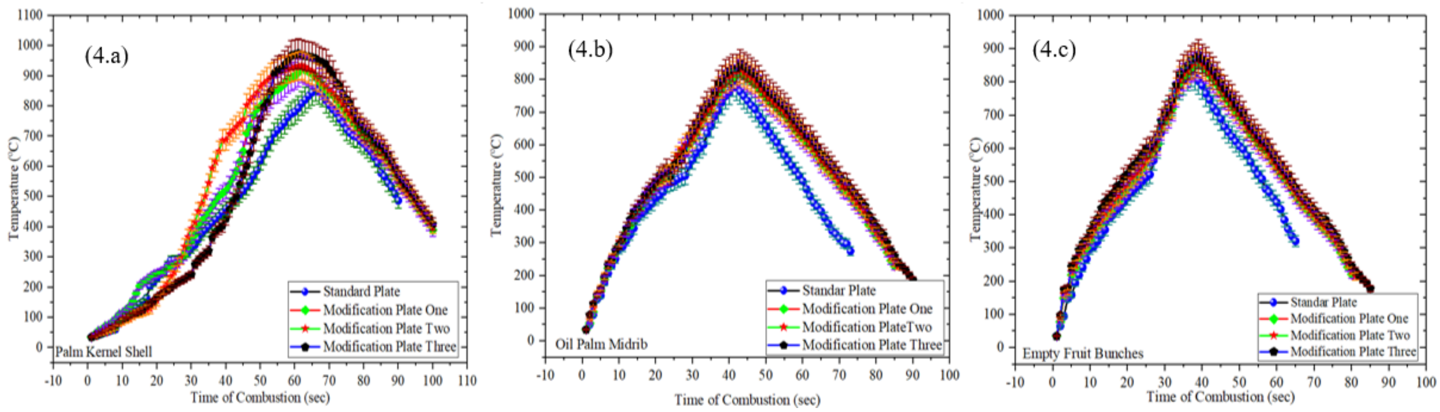

Fig. 4. Comparison of combustion temperatures in the FBC combustion chamber by applying different plates and fuels

Figure 4.b above compares the combustion temperature between each plate applied in the FBC combustion chamber using OPM fuel. The fuel used in each test has the same amount, namely 3 kg. The test results with OPM fuel for each tested plate showed different phenomena and combustion temperatures. The combustion temperature resulting from the standard plate test is slightly lower, and the burning time is shorter. While for each test, by applying plate modifications, it shows a varying increase. The burning time when testing the modification of the two guide plates with a fuel weight of 3 kg reached 85 seconds compared to 70 seconds with the standard plate. At the same time, the burning time when modifying the three and four guide plates got 90 and 100 seconds. Thus, it can be concluded that the plate modifications were designed to influence the temperature in the combustion chamber.

The final temperature comparison analysis was conducted on EFB fuel for standard plates and plate modifications. The measurement results of each test show an increase in temperature between 10% and 15%, as shown in Figure 4.c. The test results with EFB fuel on a standard plate can produce a temperature of 828^{o}C. Meanwhile, the temperature recorded from the combustion of EFB with a modification of the two guide plates reached 858^{o}C. Modifying the two guide plates has an increase of 30^{o}C compared to the standard plate. Experiments by applying modifications to the three air guide plates in the FBC combustion chamber can obtain a temperature of 868oC. Modifying the three guide plates used in the combustion chamber can increase the temperature by 10^{o}C compared to the modification of the two guides and increase 40^{o}C compared to the standard plate. At the same time, the test results by applying a modified four-direction plate obtained a temperature of around 883^{o}C. Combustion temperature resulting from testing the four pilot modifications increased by 15^{o}C from the three pilot modifications, 25^{o}C from the two and 55^{o}C from the standard plate. Based on the test results, modifying the plates in the combustion chamber can increase the combustion temperature. In addition, improving the plates in the combustion chamber can also increase the burning time (Vodička et al., 2021). Where was their research? They used a mixed fuel of solid biomass waste. The highest temperature achieved from the test only reached 800^{o}C.

3.1 Efficiency of Furnace

The furnace efficiency analysis was carried out to compare each plate tested against PKS, OPM, and EFB fuel. From the results of this comparison, it can be explained more clearly the extent to which the furnace's efficiency is produced. Based on the results shown in Figure 5, the increase in furnace efficiency from standard plates and different plate modifications can be seen.

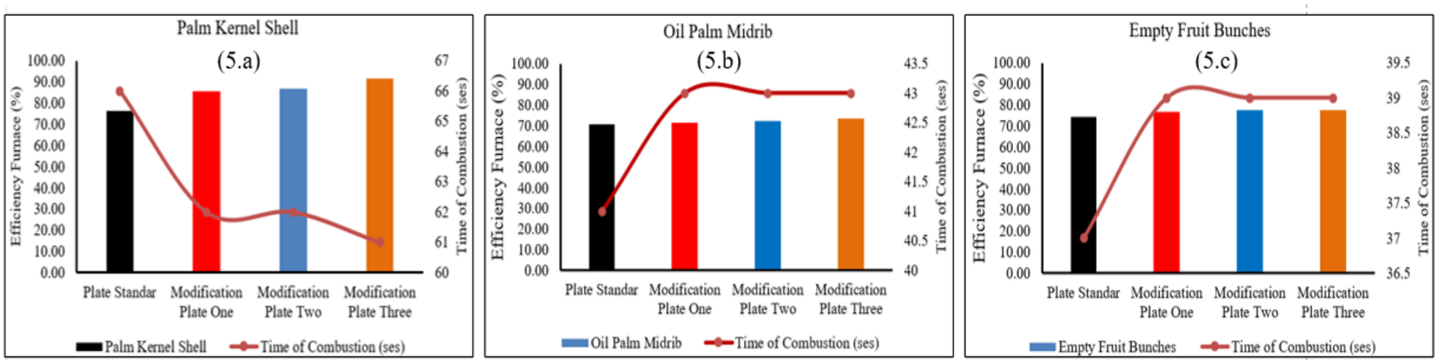

Fig. 5. Comparison of furnace efficiencies in FBC combustion chambers for different fuels and plates

Figure 5.a**,** above describes the results of comparing the efficiency level of the furnace from the results of the CKS fuel combustion test in the FBC combustion chamber against different plates. In addition, the time to reach the maximum efficiency point of the furnace also varies between the plates applied. Modifying the four guide plates allows for shorter firing times to achieve maximum furnace efficiency. Meanwhile, standard plates have more time to produce the top efficiency level of the furnace.

They compare the furnace's efficiency when testing combustion with OPM fuel. The analysis results show that the furnace's efficiency increases for each plate modification applied in the FBC combustion chamber. However, the increase in efficiency is not as significant as the result of burning PKS fuel. The highest efficiency increase from the results of the OPM fuel test was 73.48% for the four guide plate modifications, which only increased by about 3.06% from the standard plate. The overall increase in furnace efficiency from applying different plates in the FBC combustion chamber for OPM fuel is shown in Figure 5.b. While the maximum time to achieve optimal efficiency during the OPM fuel test shows the opposite results from the results of the PKS fuel test (Ninduangdee & Kuprianov, 2014a). The efficiency level of their research reached 99% compared to 91.44%, but the FBC technology and fuel used were more significant than this research.

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While the level of combustion efficiency with a combustion speed of 45 kg/s and excess air between 20% -80% reaches 98.6% -98.9% compared to 91.44% in this study.

Comparative analysis of the last combustion furnace efficiency was carried out by testing the EFB fuel. These results were obtained from each test as previously described. However, the results of the furnace's efficiency at this stage are to see the efficiency level of the different modified plates. Overall, the modification of the perforated plate modelled in this study shows improvement compared to the standard plate. Comparison of test results with EFB fuel for different plates as shown in Figure 5.c. The results show that the combustion time to achieve maximum furnace efficiency is longer when the plate modification is applied in the FBC combustion chamber. Longer burning time than plate modifications can provide perfect combustion.
Based on the results described above, it can be explained that modification of the perforated plate in the combustion chamber can provide perfect combustion because the supplied air can meet the required air demand during combustion.

3.2 Efficiency of Thermal

The results of the comparison of thermal efficiency with the PKS fuel combustion test on different plates are shown in Figure 6. It can be explained that the thermal efficiency increases as the incoming air increase through plate modification. This indicates that the plate modelling in the combustion chamber applied in this study can provide more optimal thermal efficiency results than standard plates. The increase in thermal efficiency of individual plates varies from that of traditional plates. Two guide plate modifications can increase efficiency by 7.18% from a standard plate. At the same time, testing the combustion in the combustion chamber by applying the modification of the three guide plates increased by 8.27% compared to the standard plate. It increased by 1.09% compared to modifying the two guide plates. While the increase in thermal efficiency during testing by applying a modification of the four guide plates is 12.29% compared to the standard plate, as shown in Figure 6.a. The results of the thermal efficiency of modifying the four-guide plate combustion also experienced a slight increase compared to the two and three-guide plates tested previously.

The burning time to reach the maximum point of each tested plate also shows a difference. Achieving thermal efficiency at the top end takes about 66 seconds for the standard plate and modification of the four guide plates, as shown in Figure 6.a. Meanwhile, the time required to modify the two and three guide plates is slightly faster at 62 seconds. Based on the analysis results, standard plates require more time to reach the highest thermal efficiency point. At the same time, the recorded efficiency of the four guide modifications has the same time as the standard plate. However, the thermal efficiency of the four guide plate modifications is higher.

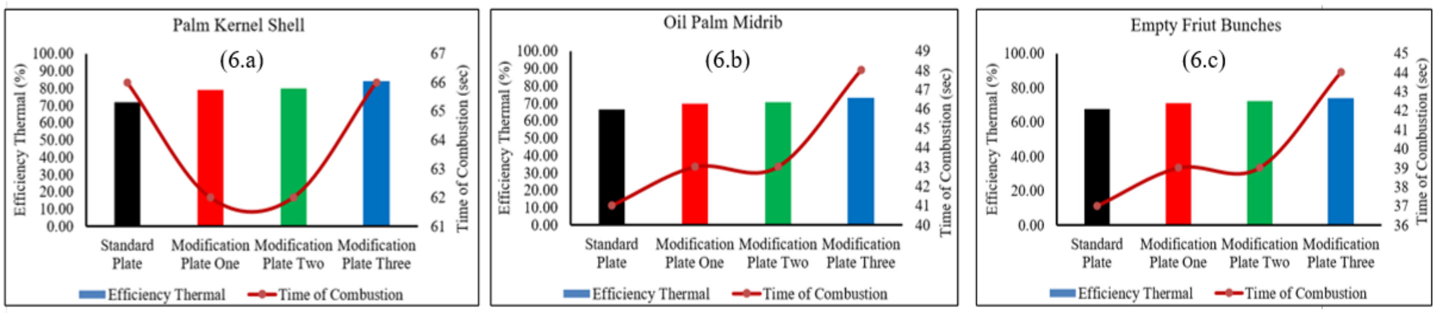

Fig. 6. Comparison of thermal efficiency in FBC combustion chambers for different plates and fuels

The results of the comparative analysis of thermal efficiency are then calculated from the results of the combustion test with OPM fuel on different plates. Based on the study and calculations from the combustion results, it was shown that the container modified with four guides experienced a significant increase compared to the standard plate. Overall, the modifications designed in the FBC combustion chamber with OPM fuel can improve thermal efficiency. When tested with a standard plate, the thermal efficiency was 66.15% and increased to 69.63% with a modified two-leader plate. At the same time, the calculation results from the combustion process by applying a modification of the three guide plates increased by about 4.60% compared to the standard plate.

Finally, the thermal efficiency analysis was carried out using EFB fuel for different plates. The combustion results in this stage show that the thermal efficiency obtained has increased with the modification of the perforated plate. This result is also the same as the previous test results. Where modification of the plate modelled in this study can increase thermal efficiency. Based on the results of the calculations performed for all the results tested, as shown in Figure 6.c. The thermal efficiency recorded from each plate modification test also showed an increase. Standard plate combustion results can provide a thermal efficiency of 67.75% and increase to 70.99% during the test by applying two guide plate modifications. At the same time, the experiments' results carried out using three driver modifications produced a thermal efficiency of 72.07%. Meanwhile, the thermal efficiency recorded during the last test by applying a modification of the four guide plates was 74%. The results that have been calculated and analyzed show that modifying the plates in the combustion chamber can increase thermal efficiency. The overall results for each different plate and fuel are presented in full in Figure 6. The results that have been calculated and analyzed show that modifying the plates in the combustion chamber can increase thermal efficiency. The overall results for each different plate and fuel are presented in full in Figure 6. The results that have been calculated and analyzed show that modifying the plates in the combustion chamber can increase thermal efficiency.

3.3 Radiation Rate

Next, an analysis was carried out to compare the radiation rates of each fuel against the different perforated plates. The radiation rate of PKS fuel for each plate used in the FBC combustion chamber is presented in Figure 7.a. These results show that the radiation rate when testing the modified four-direction plate significantly increases compared to the other plates. Meanwhile, the radiation rate from the test with the three-direction plate modification was slightly lower than the two-direction plate modification. In addition, the modification of the two guide plates shows that it reaches the maximum point earlier than the other plates. Overall, modifying the plate modelled in this study can significantly influence. The radiation rate increases because the combustion temperature also increases. Proper plate modification can provide sufficient air supply into the combustion chamber to increase the radiation rate.

Fig. 7.b below compares the radiation rate from the experimental results of burning OPM fuel against different perforated plates. The analysis results show that experiments in the FBC combustion chamber by modifying the four guide perforated plates can produce a radiation rate of 5971.17 W/sec. The obtained radiation rate increased significantly compared to the results using a standard plate of 1746.79 W/sec. The increase in the radiation rate of the standard plate reaches 60% more, which means that the modification of the applied perforated plate can give better results than the standard plate. While testing with

modified two and three guide plates used in the FBC combustion chamber can produce radiation rates of 2097.93 W/second and 2373, respectively. 51 W/s for OPM fuel. The results obtained from modifying the two and three guide plates also show an increase compared to the standard plate.

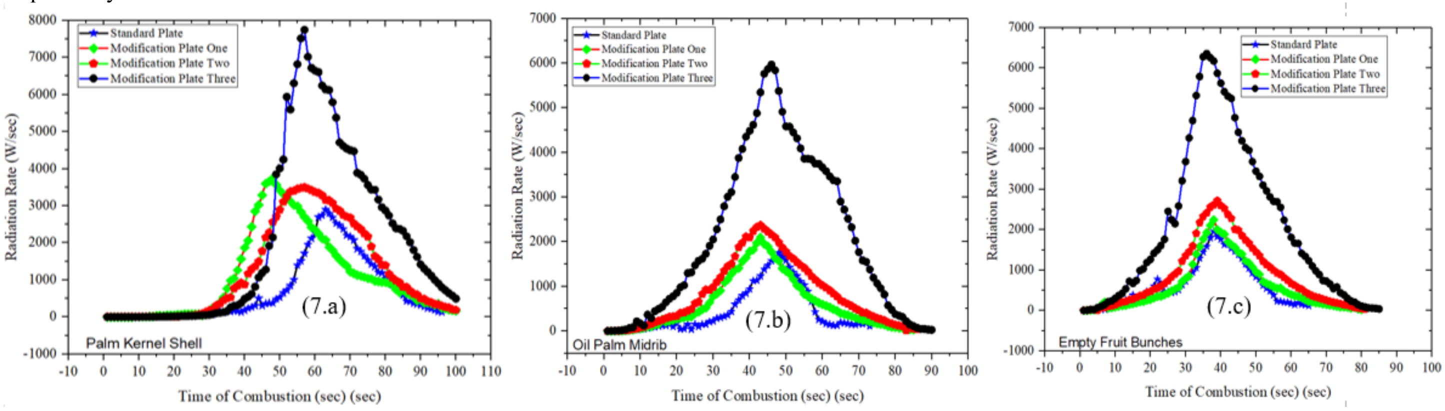

Fig. 7. Comparison of radiation rates in the FBC combustion chamber against different plates and fuels

A significant increase occurred when using the modification of the four-guide perforated plate because sufficient air was supplied, so the combustion temperature increased. The increased temperature also increases the rate of radiation. Thus, water heating in the boiler will reach the maximum point faster. The radiation rate from each plate test for OPM fuel during the experiment is presented in Figure 7.b. A significant increase occurred when using the modification of the four-guide perforated plate because sufficient air was supplied, so the combustion temperature increased. The increased temperature also increases the rate of radiation. Thus, water heating in the boiler will reach the maximum point faster. The radiation rate from each plate test for OPM fuel during the experiment is presented in Figure 7.b. A significant increase occurred when using the modification of the four-guide perforated plate because sufficient air was supplied, so the combustion temperature increased. The increased temperature also increases the rate of radiation. Thus, water heating in the boiler will reach the maximum point faster. The radiation rate from each plate test for OPM fuel during the experiment is presented in Figure 7.b.

The results of comparing radiation rates on different plates tested in the FBC combustion chamber using EFB fuel are shown in Figure 7.c. Based on the analysis and calculations for each test, when tested with a modification of the four guide plate holes, the radiation rate also showed higher results than the other plates. The radiation rate of the modified four-direction plate reaches 6356.12 W/sec compared to 1958.30 W/sec with the standard plate. The increase in radiation rate comes to 60% more than standard plates. The radiation rate obtained during the test by modifying the two guide plates only reached 2241.97 W/sec. At the same time, the test results with the modification of the three guide plates produce a radiation rate of 2720.07 W/sec. The increase in radiation rate on the modification of the two and three-directional plates is not too significant compared to the standard plate. However, modifying the perforated plate applied in this study can increase the radiation rate. The radiation rate per second generated during the combustion process for each different plate for EFB fuel is shown in Figure 7.c.

3.4 Heat Loss

This work also conducts a comparative analysis of heat loss during the combustion process in the FBC combustion chamber for each plate and different fuel. Based on the analysis results, it can be said that the plate modifications made can reduce the level of heat loss compared to when using standard plates. The experimental results of burning with PKS fuel for each tested plate are shown in Figure 8.a. The analysis results show that the decrease in heat loss recorded on the modification of the four-lead plate reaches 44.04 W/sec compared to the standard plate. While the reduction in heat loss during testing with the modification of the three guide plates can reduce by 14.07 W/sec compared to the standard plate. Temporary,

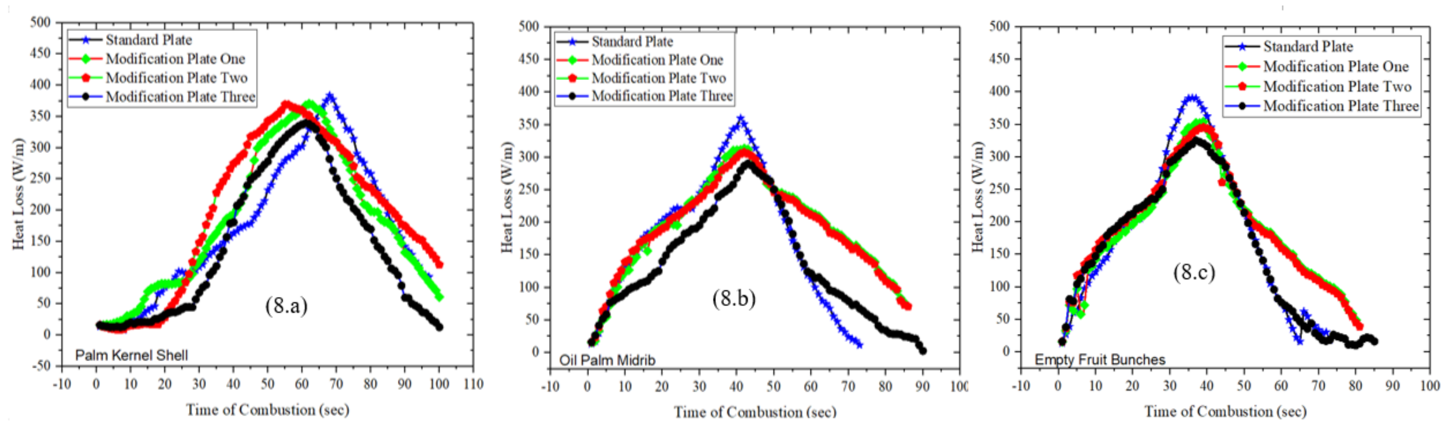

Fig. 8. Comparison of heat loss in the FBC combustion chamber against plates and different fuels

Comparative heat loss analysis was conducted during the OPM fuel combustion test. Each test obtains this analysis by applying a different plate in the FBC combustion chamber. Each test performed on each plate uses the same amount of energy. This facilitates the study of the amount of heat lost and the burning time needed to use the fuel.

Based on the analysis results, it can be said that with the modification of the plate that is applied with certainty, the heat loss can be reduced compared to when testing with a standard plate. The highest rate of heat loss recorded from the standard plate for OPM fuel is 359.82 W/sec. Meanwhile, when the two-leader plate was modified, it decreased to

313.22 W/sec. When tested with a modified three-pointer plate, the total reduction in heat loss was 307.48 W/sec or reduced by about 52 W/sec than the standard plate and 6 W/sec from a modified two-pointer plate. Meanwhile, the total heat loss recorded during the OPM fuel combustion test with four guide plate modifications reached 289.89 W/second. These results indicate a significant decrease compared to the application of standard plates. The total heat loss for each tested plate is presented in Figure 8.b.

The last comparative heat loss analysis was carried out from the experimental results of burning with EFB fuel on different plates. The testing process at this stage is also the same as the previous one. The analysis at this stage aims to investigate how effective the plate modification modelled in this study is, especially in using EFB fuel. The amount or weight of energy used in this test is the same as that of PKS and OPM fuel, namely 3 kg for each experiment.

Based on the analysis results, the perforated plate modelling applied in the FBC combustion chamber can reduce heat loss to increase the temperature and rate of radiation obtained. The total heat loss recorded during the test with a standard plate was about 390.60 W/s. However, after the modification of the two guide plates that were applied, it decreased by around 38.06 W/sec or 352.33 W/sec. Tests with modification of the three guide plates in the combustion chamber can produce a heat loss of 235.52 W/sec, a decrease of about 45.08 W/sec to the standard plate. A significant reduction in heat loss occurred during the test by modifying the four guides. The total heat loss recorded from the four-driver modification test is around 325.08 W/sec.

4. CONCLUSIONS

This study's combustion experiments with FBC technology apply modifications to perforated plates with PKS, OPM, and EFB fuel. Combustion tests were conducted to investigate the modified plates' highest temperature ratio, efficiency, radiation rate, and heat loss. Based on the experimental results that have been carried out, several conclusions can be drawn as follows:

1. The highest temperature recorded from testing the application of four guide plate modifications for PKS fuel was 975°C. Overall, the modelled perforated plate can provide up to 70% air supply and shows an increase compared to the application of standard plates.
2. Combustion efficiency obtained by applying a perforated plate modification reaches 91.44% by providing excess air between 20% -70%.
3. The thermal efficiency resulting from modifying the perforated plate reached 84% compared to 71.71% when tested with a standard plate.
4. When applying the modified four-direction plate, the highest radiation rate was 7745.21 W/s compared to the standard plate of 2895.67 W/s.
5. Modifying the perforated plate modelled in FBC technology can reduce the heat loss rate.

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CONFLICT OF INTEREST

All authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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