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Combustion of Pulverized Coconut Shell in Lab-Scaled Incinerator Rig using CFD

Nurhazwani Hazman[1], Norasikin Mat Isa[1,*], Nurul Fitriah Nasir[1], Normayati Nordin[1]

[1] Department of Mechanical Engineering, Faculty of Mechanical and Manufacturing Engineering, University Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia

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ABSTRACT

In power generation, particle size distribution (PSD) of pulverized coal used in a power plant was 65%-70% passing 200 mesh or known as 76 microns. Since coal took hundreds of millions of years to form, it is not renewable energy and coal will release harmful gases after-burn. Thus, biomass has become an alternative fuel for reducing the consumption of coal and the emission of harmful gases. Coconut shell has the potential to substitute coal as fuel. In this study, Computational Fluids Dynamics (CFD) is used for simulating the combustion process in the lab-scaled incinerator rig (LSIR). The behaviours of pulverized coconut shells and the effect of excess air during combustion are studied. The results showed that the average carbon monoxide (CO) and carbon dioxide (CO_2) mass fraction was calculated at 0.0196 and 0.257 respectively. The combustion efficiency was determined as 92.94%. The percentage of excess air (EA%) was increased by increasing the velocity of inlet air for investigating the responses of combustion efficiency. The EA with 39% was predicted as the most suitable EA for the combustion because the heat generated at 39% EA was the highest and its volume average temperature was recorded as 1198.7K. Besides, the combustion efficiency was increasing when the EA% is increased by calculating from every volume average of mass fraction of CO and CO_2.

1. Introduction

Coconut shell, one of the biomass sources, has the potential to substitute coal as a fuel for combustion. Combustion of coal will produce greenhouse gases that cause climate change while coconut shells from the source of biomass, which is also a renewable energy resource that could contribute zero greenhouse gas emission to the atmosphere. Biomass is used as a substitute for coal because its regrow rate is relatively faster than fossil fuels, which need hundreds of millions of years to form. No net emissions and carbon would be neutral in both the short and long term if forests were regulated where the annual harvest equals the annual net growth [1]. Besides, biomass's carbon and nitrogen content were lower than coal [2]. The lower the carbon content, the lower the emission

* *Corresponding author.*
E-mail address: sikin@uthm.edu.my

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of CO_2 during combustion. The emission of harmful gases such as NOx and ammonia will also have reduced since the nitrogen content was low in biomass.

Biomass is carbon neutral, which only emits carbon to the environment that was absorbed during its life cycle and generated no new carbon. The high volatile content and low char content of the biomass is one of the keys to biomass substituting coal as fuel because, with these characteristics, biomass can become a highly reactive fuel. For instance, Table 1 shows the proximate and ultimate analyses representing the properties of coal and common biomass. As can be seen in Table 1, the volatile content of biomass is higher compared to coal. The lower carbon content of biomass over coal can reduce carbon dioxide emissions during biomass conversion and slow down global warming. The low nitrogen content helps reduce harmful emissions such as NOx, N_2O and ammonia. In addition, Riaza *et al*., explained that biomass showed relatively shorter burnout time compared to coal due to higher volatile content but possible to have the exact burnout times as long as a larger size has been supplied [3]. Besides, Shiehnejadhesar reported that biomass can release higher volatile gases than coal up to 75 wt% during the devolatilization phase [4].

Table 1
Proximate and ultimate analysis of fuel

Sample	Proximate (%)				Ultimate (%)		
	Moisture	Volatile	Ash	Fixed Carbon	C	H	N
Coal [2]	0.4 – 20.2	12.2 – 44.5	5.0 – 48.9	17.9 – 70.4	62.9 – 86.9	3.5 – 6.3	0.5 – 2.9
Biomass [2]	2.5 – 62.9	30.4 – 79.7	0.1 – 34.3	6.5 – 35.3	42.2 – 60.5	3.2 – 10.2	0.1 – 12.2
Coconut Shell [5]	N/A	48.25	1.2	50.55	64.8	4.66	0.84

To be more specific, coconut shell has a high calorific value which is suitable to use as a fuel with low ash content and waste can be utilized. Based on the element analysis the solid coconut shell has a gross calorific value of 22.83 MJ/kg which is considered a high calorific value carbon (C). Therefore, coconut shell has good fuel properties.

Samsuri *et al*., [6] conducted combustion test with different coals in an existing boiler furnace. The result show that the coal with highest fixed carbon content recorded the highest temperature value while lowest fixed carbon gave the lowest temperature value.

In another research done by Ganguli and Bandopadhyay [7], studied the combustion efficiency of pulverized coal for different particle size distribution. The result show that only small difference was recorded thus represented that particle size distribution of coal has no effect on the efficiency of combustion. But, they noticed that the CO produced by coarser pulverized coal was higher which may lead to decrease of efficiency. They added, the emission of CO can be reduced as long as more oxygen reacted with CO to form CO_2

Hani *et al*., [8] studied experimentally the mechanism of combustion of oil-palm biomass using fluidized-bed combustor. According to the findings of the studies, the best combustion efficiency was 95% when highest air flow rate applied resulting the lowest O_2 and the highest CO_2 among the others. They stated that these results indicate the biomass combustion process worked very well and air flow rate supplied to combustion chamber is very suitable.

Silva *et al*., [9] investigated the effect of secondary air injector on biomass furnace by simulating the gas phase reactions using CFD modelling. This research is used ANSYS Fluent 16.2 to simulate the gas phase reactions within the full geometry of a biomass furnace. Since the actual boiler was too large thus required more time to simulate and obtain the CFD results, the only modelled 1/13 of the full boiler geometry. The research results proved that the secondary air injector had improved the combustion efficiency. There is a sudden increase in temperature due to the penetration of secondary air injector in the right-side wall. Besides, the supply of air by secondary air injector was resulting the carbon monoxide almost completely oxidized into carbon dioxide which can be seen from the mass fraction of carbon dioxide and carbon monoxide inside the boiler. As can be concluded, there are many journals and papers discuss about the combustion of biomass but only few of them talking about potential of coconut shell as a fuel. The aim of this study is to focus on the combustion reaction of pulverized coconut shell and simulate using CFD. The utilization of pulverized coconut shell as a fuel is been evaluated in terms of combustion efficiency and emission of CO and CO_2.

2. Methodology

2.1 Description of the Problem and Equation Involved

A selection of the CFD simulation studies on pulverized coconut shell combustion is studied, which includes the sub-models of lab-scale incinerator rigs. This study involves several limitations which are flow field, thermal field, mass fraction and combustion efficiency. Furthermore, the relationship between excess air and the combustion efficiency is identified. A combustion simulation is carried out using the Computational Fluid Dynamics (CFD). By inserting the parameter and properties of coconut shell, CFD will simulate the combustion reaction in the combustor with the exact dimension and parameter of the combustor. From the simulation data, the efficiency of combustion strongly depends on the concentration of the air. The efficiency of combustion can be measured by the heat losses such as heat loss due to incomplete combustion and heat loss due to unburned carbon during the combustion reaction. Complete combustion produces higher carbon dioxide than carbon monoxide, while incomplete combustion produces higher carbon monoxide. The unburned carbon was the ash content after the combustion reaction.

There are a few parameters that need to be considered when designing the lab-scale incinerator rig using CFD modelling, incorporating the applicable criteria that follow

i. The geometry model of the incinerator rig is equipped with a fuel inlet, air inlet and pressure outlet.
ii. The boundary conditions of the system are aligned with the experimental value.
iii. The quality of the CFD solution is depending on the mesh generated that can minimize the errors in the solvers for obtaining accurate results.
iv. Grid independent study usually started with the coarse mesh and continues with the finer mesh until a suitable result was obtained. In this case, three simulation results are compared and the most suitable mesh is chosen

According to the TSI incorporated, the equation for combustion efficiency was presented in percentage and determined by subtracting the heat losses. The equation of the combustion efficiency is as follows [10]

$$\eta_{comb} = 100 - \left(q_{ic} - q_{uc}\right) \tag{1}$$

$$q_{ic} = \frac{CO\%}{CO\% + CO_2\%} \times 100\% \tag{2}$$

$$q_{uc} = \left[\frac{U * A\% * 33810}{100 - U}\right]\frac{1}{HHV} \tag{3}$$

where the flying ash or bottom, U, percentage of ash content, A%, and higher heating value of coconut shell, HHV.

2.2 Lab-Scaled Incinerator Rig

Figure 1 shows the illustration of a lab-scaled incinerator rig in the real application. The system consists of five main components which are material input, screw feeder, blower, combustion chamber and exhaust pipe. The pulverized coconut shell biofuel product is supplied through material input as shown in Figure 1. Next, the screw feeder works as transporting the fuel in the pipe and then being blown by a blower that acts as primary air.

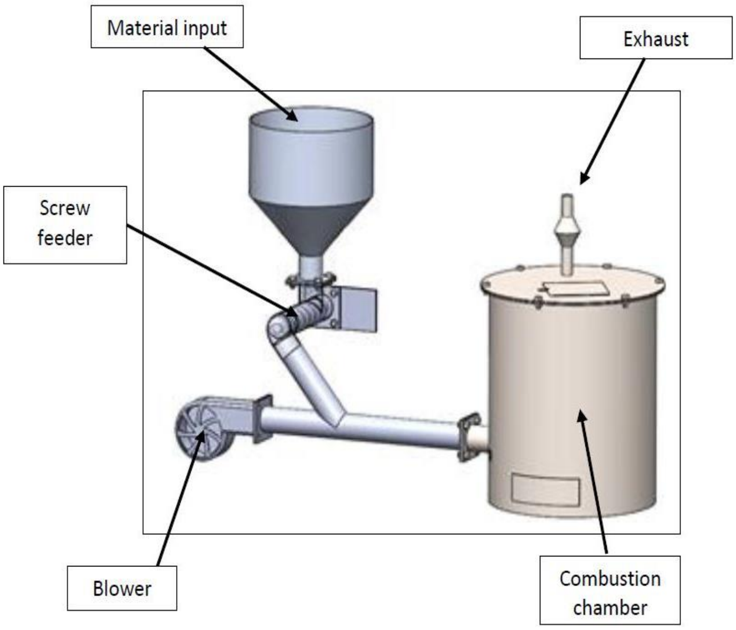


Fig. 1. Illustration diagram of lab-scaled incinerator rig

The scope of the research is more focused on the combustion that occurs in the chamber or also known as the combustor. The combustion behaviours of pulverized coconut shells were studied in terms of the flow field, thermal profile and mass fraction of carbon dioxide (CO_2) and carbon monoxide (CO_2). In addition, to improve the combustion efficiency in the system, the effect of excess air during combustion has also been studied.

2.3 CFD Simulation Software

ANSYS FLUENT 18.1 Workbench Software was used in this study to investigate the combustion of the coconut shell in a combustor. ANSYS fluid dynamics is a comprehensive software suitable for modelling fluid flow and other related physical phenomena.

2.3.1 Number of components

The number of the fuel injector, air injector, particles injector, pressure outlet, and fluid body should be determined. In this study, the air injector and particle injector are sharing the same inlet.

2.3.2 Parameter of fluid

The parameter of fluid should be determined such as the density, viscosity, speed of injected air, the properties of the coconut shell and other related parameters that are needed in the simulation.

2.3.3 Geometry of combustor chamber

There are plenty of types of combustors used for combustion. The CAD model was created for the volume of fluid inside the system. The CAD model of the system can be seen in Figure 2. For further analysis, the parameter of the lab-scale incinerator rig was ruled by these steps

i. Boundary Condition – At the fuel inlet, it was defined as a mass flow inlet with a feeding rate of 2.82 kg/hr according to the experimental value [11]. The parameters set up for CFD modelling can be seen in Table 2. The mean mixture fraction in species was set to 1 while the discrete phase model (DPM) was set as an escape. The air inlet was treated at 1 m/s of velocity while discrete phase model DPM was set to reflect. For the outlet, the flow leaves the atmosphere was set to 0 Pa and 300K for pressure and constant temperature respectively.
ii. Mesh generation − During this stage, the element was set to 0.02m with fine meshing, the skewness was at 0.7 and the smoothing was set to high. The mesh model was created with total nodes of 22613 and 114748 elements. The applied meshing was shown in Figure 3.
iii. Grid independence test – Before running the simulation, the grid independence test was simulated for determining the most suitable meshing that provided the most accurate result. The fine mesh was selected with acceptable results shown although taking a long time.

Table 2
Pulverized coconut shell experimental value

Parameter	Value
Particle Size (microns)	100
Air Velocity (m/s)	1.0
Density of air (kg/m^3)	1.164
Inlet Diameter (m)	0.075
Inlet Area (m^2)	4.418×10^{-3}
Mass flow rate (kg/hr)	2.82
Average molecular weight of dry, CO_2- free air (g/mol)	29
Volume ratio of component (oxygen/air)	0.232

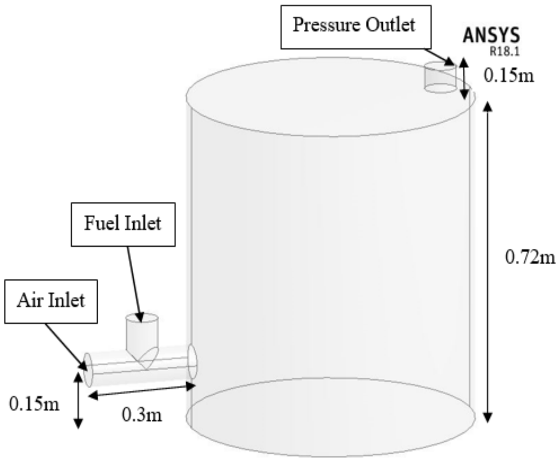


Fig. 2. Geometry modelling of combustor

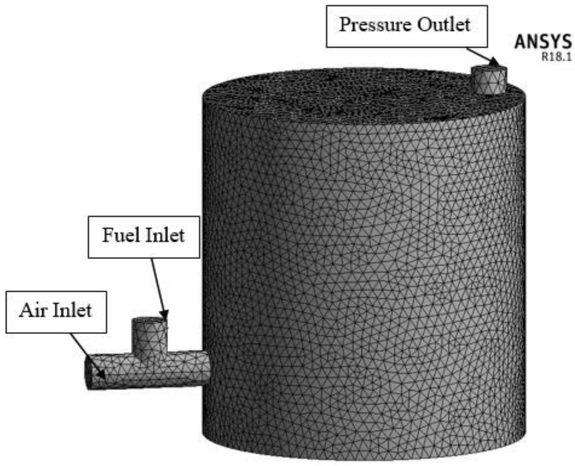


Fig. 3. Mesh model

3. Results

3.1 Flow Field

As presented in Figure 4, the velocity profile on the cut plane of the combustor. The velocity magnitude ranged from maximum which was from 4.124 m/s to zero velocity. The velocity at both inlet and outlet of the combustor were higher compared to the velocity inside the combustor. The trend of the velocity is decreasing away from the inlet and then increases toward the outlet. The volume average of the velocity is 0.449295 m/s. Meanwhile, Figure 5 shows the velocity vector on the cut plane of the combustor. It clearly shows that the airflow is swirling due to reflection when it hit the wall of the combustor. The swirling effect will influence the combustion reaction.

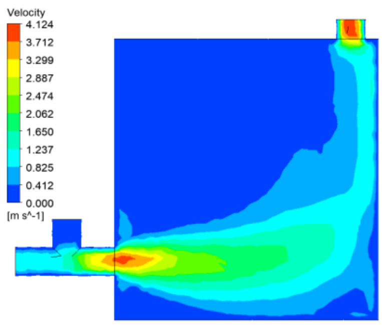


Fig. 4. Velocity profile

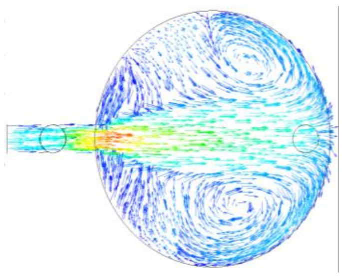


Fig. 5. Velocity vector

3.2 Thermal Field

Figure 6 represents the thermal profile on the cut plane of the combustor. The temperature magnitude was distributed between room temperature and 1361.46K. The temperature from the inlet to the inside of the combustor was increase rapidly due to the process of combustion reaction occurred. It is visible that the high-temperature regions were located at the bottom of the combustor which means the combustion reaction occurred in those regions. In addition, the temperature distribution at the inlet region shows that when the fuel contact with the air, the combustion reaction has begun. The temperature distribution of the wall was a range between 406.15K and 618.44K while the temperature distribution at the outlet was a range between 618.44K and 936.87K. The volume average of the temperature of the combustor is 890.12K.

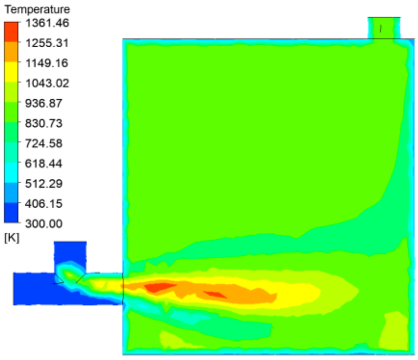


Fig. 6. Thermal profile

3.3 Mass Fraction of Species

The mass fraction of carbon monoxide (CO) and carbon dioxide (CO_2) inside the combustor can be seen in Figure 7 and Figure 8 respectively. The range of the CO mass fraction is 0 to 0.2404 while the CO_2 mass fraction is 0 to 0.2764. It is shown that the CO mass fraction is much lower than the CO_2 mass fraction by comparing both figures. This is due to the most of the carbon and CO are completely oxidized into CO_2. Similarly, this happens due to the air supply was enough for the complete combustion reaction. However, there were some incomplete burned CO were still inside the combustor. The CO mass fraction volume average is 0.034 while the CO_2 mass fraction is 0.258. Unlikely, the mass fraction of CO_2 has zero value at the wall as the streamlined flow mass fraction.

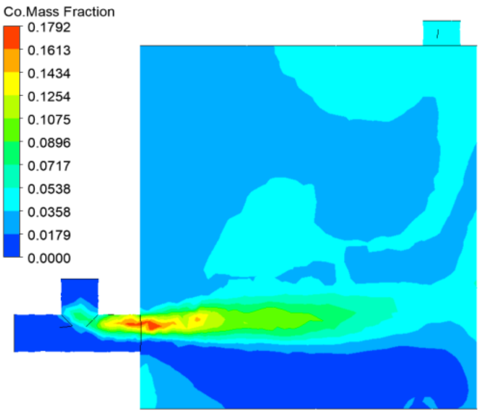


Fig. 7. CO mass fraction

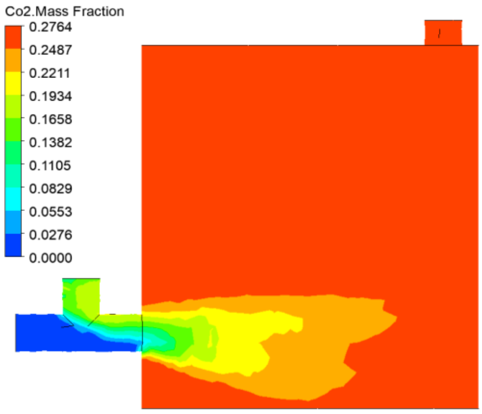


Fig. 8. CO_2 mass fraction

3.4 Improvement of Combustion Efficiency

The combustion efficiency is expressed in percentage and can be determined by subtracting the percentage of heat losses. The combustion efficiency for air inlet velocity 1m/s was calculated as 92.94%. The suggestion for improvement is to increase the mass fraction of air in the combustion reaction to boost the efficiency of combustion by expecting more carbon and CO can burn completely into CO_2. Theoretically, the mass fraction of air is increased when the mass flow rate of air is increased, and the mass flow rate of air is directly proportional to the air fuel ratio (AFR). Therefore, AFR will increase when the mass fraction of air increases and if AFR is less than 1 it means the combustion is rich-mixture. From the equation of mass flow rate of air, the velocity of the air inlet is only the adjustable variable since the density of air and area of the inlet are fixed.

The combustion of coconut shell was modelling by several air inlet velocities with an increment of 0.2 m/s from 1 m/s until 2 m/s. The simulation result was compiled, analyzed and compared. Table 3 shows the EA for every air inlet velocity. From Table 3, excess air percentage was increased when the air inlet velocity increased. However, there was the optimum value of excess air percentage for the combustion depends on the type of fuel. The typical excess air required for various combustion systems is in the range of 5 to 50 percent, depending on the fuel characteristics and the system configuration [12]. It was stated that the increase of primary air makes the CO_2 emission arise until the peak value and gradually falls after a further increase of primary air [13].

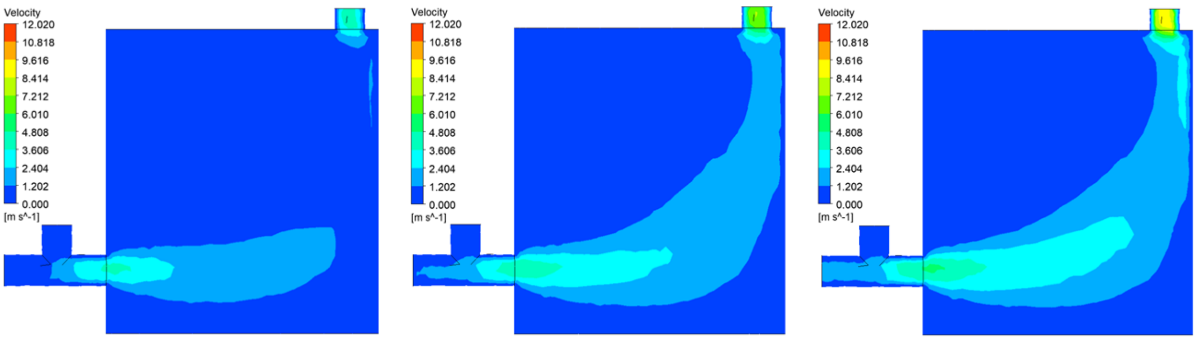
As we all know, excess air is the most important parameter in the definition of the efficiency of the combustion process. Nonetheless, the complexion of chemical and fluid dynamics phenomena evolving into the combustion chamber makes the reference parameter given by the rate of air mass fed is not directly related to the excess air of combustion as stated by Meghini [14]. As a result, to get the optimal trends of efficiency at a certain excess air, it is necessary to get a correct evaluation of the dependence between fuel consumption rate and air mass flow rate, unburned combustible loss and heat release rate.

Table 3
EA% for each stage

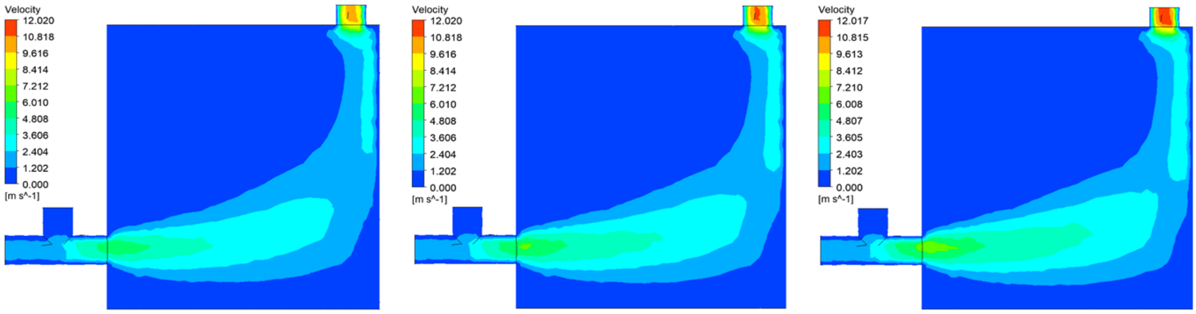
Parameters	Readings					
Air Inlet Velocity (m/s)	1.0	1.2	1.4	1.6	1.8	2.0
Volumetric Air Supply (m^3/s)	0.005	0.006	0.007	0.008	0.009	0.010
Excess Air (%)	0	19	39	59	79	99

3.5 Comparison of Flow Field

The trend of the velocity is increasing when excess air percentage increases since the velocity of the air inlet are increasing as shown in Figure 9. As can be observed from the contours of the velocity profile, it shows the region at the bottom of the combustor becomes bigger which means the velocity of the airflow at those regions is increasing. The airflow at the inlet and outlet of the combustor is observed to increase when the excess air increases. For EA= 0%, the maximum velocity is only 4.12 m/s while for the EA= 99%, its maximum velocity is up to 12.02 m/s which is roughly 3 times of EA= 0%.



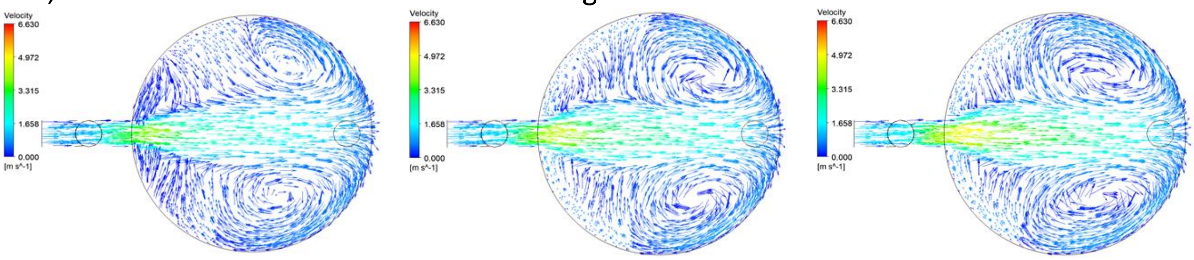
Excess air = 0 % | Excess air = 19% | Excess air = 39%



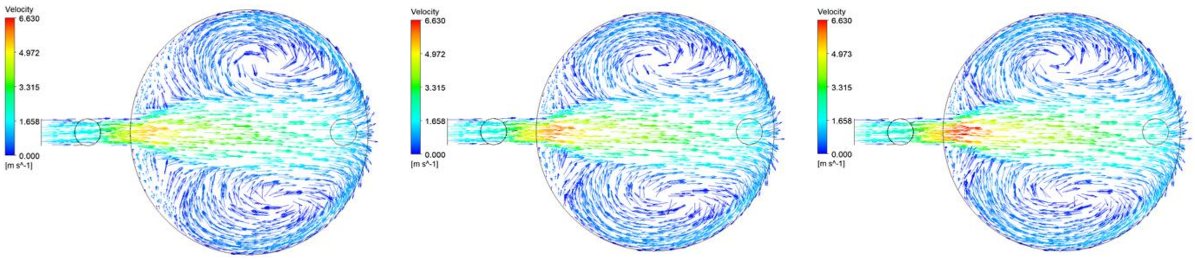
Excess air = 59% Excess air = 79% Excess air = 99%

Fig. 9. Velocity profile of combustion for each case

Also, the volume average velocity obtained are 0.449 m/s, 0.635 m/s, 0.715 m/s, 0.787 m/s, 0.846 m/s and 0.920 m/s respectively. The trend of the volume average velocity is also increasing. Meanwhile, every velocity vector shows there are swirling effect inside the combustor as can be seen in Figure 10. This is because of the airflow reflection when it hits the combustor wall. The velocity of the airflow is increasing which is also shown in the velocity vector diagram. Observing the high-speed region of the velocity vector shows the high-speed region is increasing when the EA increased. Besides, the airflow swirl is more obvious and larger when EA increases.



Excess air = 0 % Excess air = 19% Excess air = 39%



Excess air = 59% Excess air = 79% Excess air = 99%

Fig. 10. Velocity vector of combustion for each case

In terms of the swirl's shape, the shape of two swirls in EA= 0% is not equal in size and is smaller compared with the EA= 99%. Additionally, the swirl improves the mixing of fuel and air, accelerating the combustion at optimal values [15]. Besides, swirl also improves combustion stability. However, the high intensity of the swirl will tend to increase the emission of total hydrocarbons (THC) and CO which are affecting the combustion's efficiency. Therefore, the selection of optimal swirl values is important for obtaining a beneficial impact on combustion and emissions performance. In this section, the EA= 99% is selected as it gave the best result on the velocity profile and showed the acceptable swirling effect. The higher velocity of the airflow can improve the mixing of the fuel and air which lead to a more stable combustion reaction and increase the efficiency of the combustion and emission performance.

3.6 Comparison of Thermal Field

The temperature profile at different percentages of excess air also was observed. The EA= 0% was acted as a reference temperature profile and using for comparison with EA= 19%, 39%, 59%, 79% and 99%. The temperature profile of combustion of each case are presented in Figure 11. The highest temperature obtained in each temperature profile in every excess air was 1361.46K, 1582K, 1767K, 1871K, 1880K and 1862K respectively. The trend for the highest temperature is increasing when EA is increasing and decreasing when EA= 99%. The volume average temperature obtained for every excess air was 890.12K, 1177.22K, 1198.7K, 1163.66K, 1108.81K and 1073.37K respectively. The volume average temperature is increasing at first and decreases after EA=39%. By observing the temperature contour for every EA, it was observed that the temperature contour was getting larger and its temperature was getting higher. The most significant increase in temperature was shown at the temperature profile for EA= 0% and EA= 19%. There was a large increase in the temperature contour in EA= 19% compared to EA= 0%. It means the temperature increased rapidly when the EA was increased. Besides, it was observed that there was a peak value either for the highest temperature obtained or the volume average temperature when the EA was increasing.

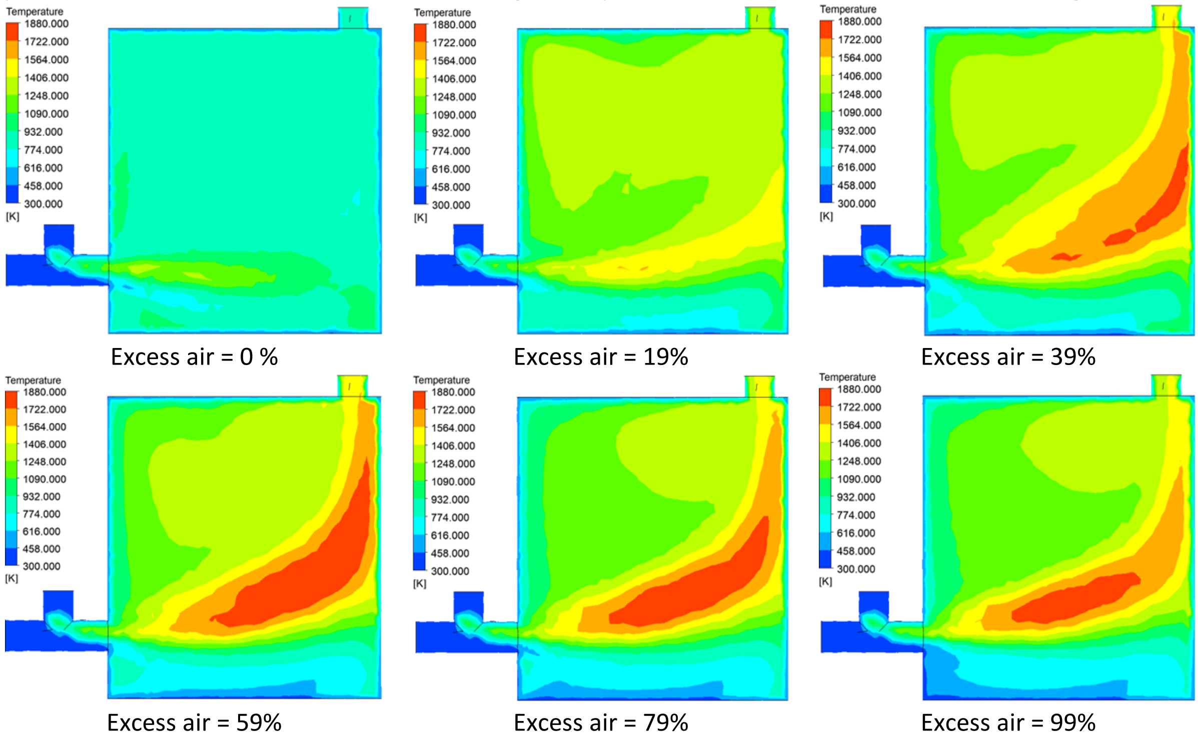


Fig. 11. Temperature profile of combustion for each case

The excess air improved the combustion efficiency by allowing more oxygen reaction with the fuel but too much excess air led to a drop in the heat generated. Thus, the selection of excess air is paramount for obtaining the best heat generation. According to the TSI Incorporated [10], the high intensity of the excess air brought a bad impact on the combustion reaction as it will decrease the heat generation. Furthermore, the nitrogen in the air which occupied about 80% of air composition played no role in generating the heat. However, it increased the absorption rate of the heat energy. In this section, EA= 39% was selected as the most suitable excess air for heat energy generation. This was because the average volume temperature obtained was the highest among the others.

3.7 Comparison of CO Mass Fraction

The result of CO mass fraction at different percentages of excess air are shown in Figure 12. The highest mass fraction of CO at EA= 0% was recorded as 0.1792 which was obtained from the simulation result. The highest CO mass fraction for the following excess air was 0.1929, 0.2198, 0.2318, 0.2349 and 0.2354 respectively. The trend of the highest CO produced was increasing according to the data obtained. Nevertheless, the trend for the volume average CO mass fraction was decreasing when EA was increasing. The volume average CO mass fraction data obtained was recorded as 0.0342, 0.0079, 0.0029, 0.0015, 0.0011 and 0.00088, respectively.

By observing the contour of the CO between EA= 0% and EA =19%, it shows a massive drop in the CO mass fraction at EA =19%. This was due to the entered air being increased and improved the combustion performance. This phenomenon can also be observed from the data recorded, the volume average of the CO at EA= 19% was much lower compared to EA= 0%. The EA= 99% was selected as the best excess air for the combustion reaction because the volume average of CO mass fraction produced was the lowest among the excess air percentage. The lower the emission of CO, the higher the efficiency of the combustion as more complete combustion occurred.

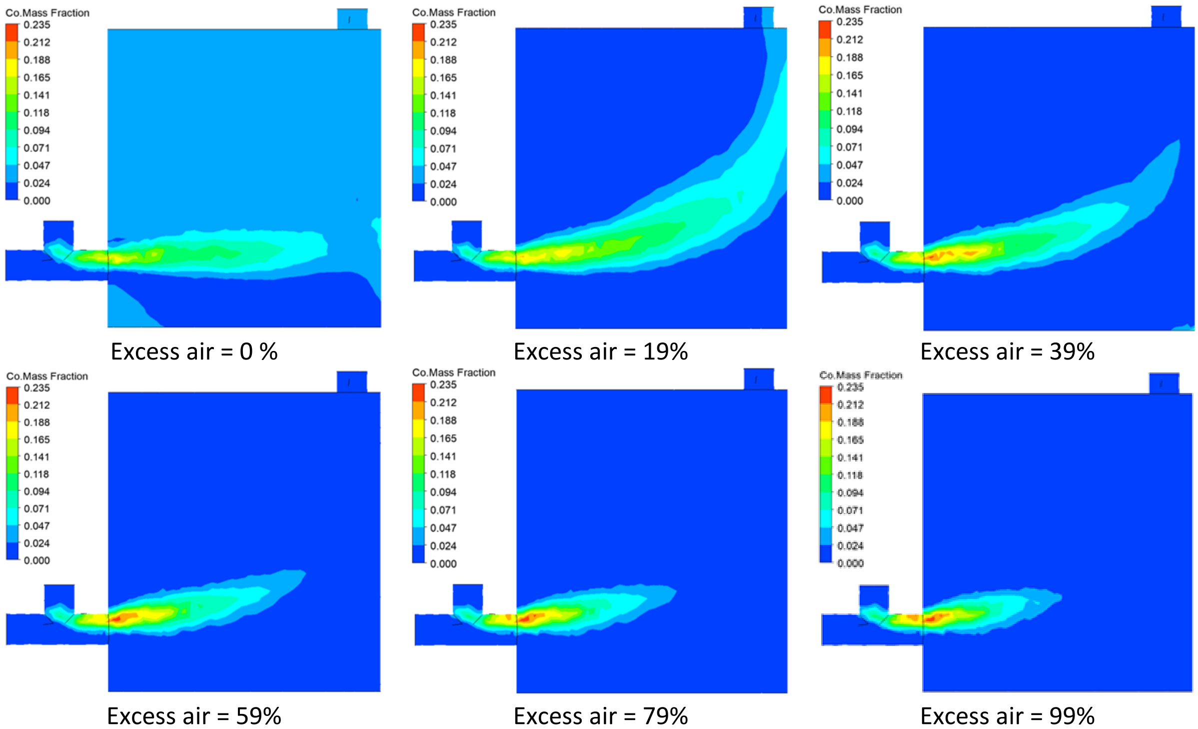


Fig. 12. Mass fraction of CO at different excess air (%)

3.8 Comparison of CO_2 Mass Fraction

CO_2 mass fraction at different percentages of excess air are presented in Figure 13. CO_2 mass fraction at EA= 0% was acted as a reference for comparing with the other excess air percentage. In the EA= 0%, the highest CO_2 mass fraction was recorded as 0.2764. The CO_2 mass fraction for the following excess air was 0.2718, 0.2708, 0.2625, 0.2569 and 0.2504 respectively. The trend of the CO_2 mass fraction was observed to decrease. It was the same reported by J. E. Eduardo, CO_2 values were opposite of CO because CO_2 molecules were dissociated and formed CO and O where the CO concentration was higher [16]. Besides, the volume average CO_2 mass fraction obtained for all the excess air are 0.2582, 0.2507, 0.2196, 0.1896, 0.1709 and 0.1583 respectively. The trend of the volume average also showed decreasing.

By comparing the CO_2 mass fraction contour, it showed that the mass fraction of CO_2 was also decreasing. It can be observed that the high-intensity region was decreasing. According to the TSI Incorporated, the concentration of CO_2 was diluted by the air which caused the decrease in the mass fraction of CO_2 [17]. The EA=99% with the lowest CO_2 produced was selected as the most suitable excess air for the combustion system. This is because the lower the CO_2 produced, the lower the emission of CO_2 to the surrounding which can decrease the emission of GHGs for reducing global warming.

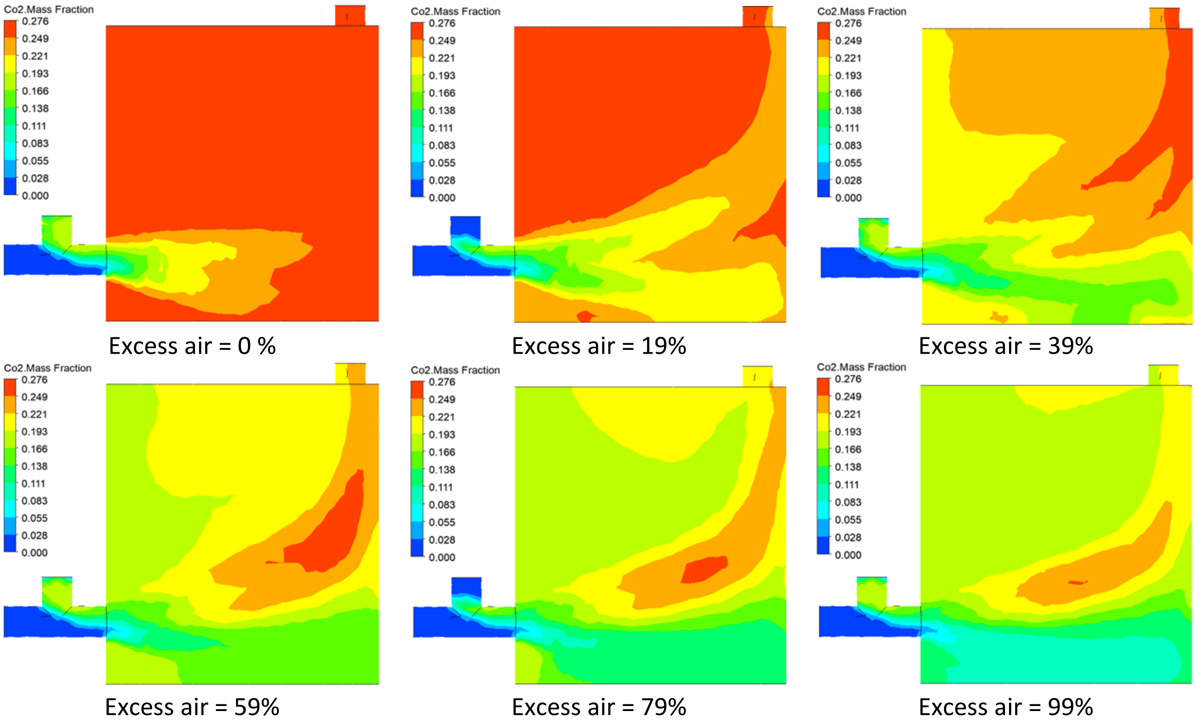


Fig. 13. Mass fraction of CO_2

3.9 Combustion Efficiency of Plotted Graph

The graph of the combustion efficiency versus excess air can be seen in Figure 14. The data for the combustion efficiency was calculated by obtaining the volume average mass fraction of CO and CO_2. The efficiency at each excess air should be less than or equal to the point because the unburned carbon was not calculated in this simulation. The efficiency of the combustion increased rapidly from 0% to 20%. This was because more air entered the combustor, improving the combustion reaction and efficiency. The combustion efficiency trend increased when excess air increased, and it was approaching 100%. However, it was impossible to efficiently reach 100%. In this case, the CFD simulation cannot generate or obtain other heat losses. Therefore, the efficiency of the combustion was lower than the graph plotted. In this section, the higher the combustion efficiency obtained, the more suitable the excess air used in the combustion system. So, EA=99% was selected as the most suitable excess air used for the combustion reaction.

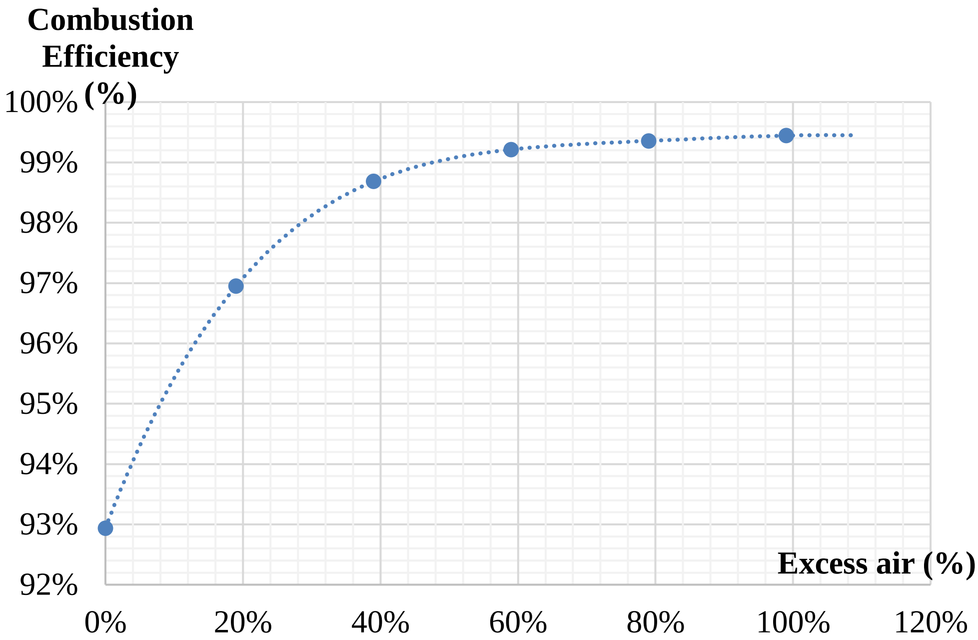


Fig. 14. Trend of combustion efficiency against excess air (%)

3.10 Data Validation

To ensure the validity and accuracy of this simulation analysis, a comparison with the actual experiment performed by Joseph [18] was made. The result obtained from simulation was compared to experimental result in term of the emission of CO_2 and CO mass fraction and also combustion efficiency. The comparison of results is presented in Table 4 below.

Table 4
Comparison between experimental and simulation results

Parameters	Experimental Result	Simulation Result	Error %
CO Mass Fraction	0.02	0.0195587	2.21%
CO2 Mass Fraction	0.19	0.257295	35.42%
Combustion Efficiency	90.48%	92.94%	2.72%

From the Table 4, it was observed that the CO mass fraction for experimental and simulation results were 0.02 and 0.0196 respectively which only differences in 0.0004. The error percentage of the CO mass fraction was only 2.21%. However, for the CO2 mass fraction, the simulation result was quite larger compared to the experimental result and the percentage of the error was up to 35.42%. The high percentage error of CO2 mass fraction was because the simulation result was always based on the theoretical model, while the experimental result represented the object's real behaviour and was always influenced by unexpected errors. Furthermore, the simulation combustion reaction was done in a perfect region with only air and fuel which will lead to a more perfect combustion reaction or more CO2 was formed. For experimental results, the combustor may not had sealed perfectly which could have leakage of air and caused the formation of CO2 was less.

For the combustion efficiency, both results were recorded as more than 90%, and their percentage of error was less than 3%. The error percentage was in the acceptable range. In conclusion, the simulation result was better than the experimental result due to simulation was based on the theoretical model while the experiment was based on real behaviour.

4. Conclusions

In this study, Computational Fluid Dynamics was used to simulate the combustion reaction for investigating the coconut shell's burning process in a lab-scale combustor. The simulation was successfully run, and the results were obtained. The simulation was using ANSYS-Fluent 18.1 and the species model was using the non-premixed combustion model to predict or simulate the combustion reaction of the coconut shell in the combustor. The coconut shell particle size was 100 microns and the combustion simulation results were successfully obtained.

The CFD simulation used as a reference was done by using the 100-micron size of the coconut shell for combustion and the primary air was set to 1 m/s. The velocity magnitude, static temperature, mass fraction, and combustion efficiency results were obtained and analysed. The combustion efficiency of the coconut shell was obtained as 92.94% which had fulfilled the first objective of the study. The simulation results were validated with the experimental results. Next, the increase of the primary air was used to compare with the reference results. In terms of the flow field, the velocity of the mixture was observed to increase when the excess air was increasing. Increasing the velocity of the mixture will create a more significant swirl inside the combustor where the swirl can improve the mixing of the mixture to improve the combustion reaction and its performance. EA=99% was created at the highest velocity of the mixture (12.02 m/s) and the most significant swirl. For the thermal field, the heat generated was increasing with the excess air. However, the temperature reached a peak value at 1198.7K when EA=39% and then started to decrease. The decrease in the temperature was due to the entered air being too much and absorbing the heat generated and transporting the heat out the exhaust.

Furthermore, the mass fraction of CO and CO_2 was obtained and observed to decrease with the increase of excess air. The decrease in CO was due to more CO being reacted with air to form CO_2. The decrease of CO_2 was because the maximum of CO_2 was formed and they were diluted by the air. The combustion efficiency for the different excess air percentages was successful determined which also achieved the second objective of the study. The efficiency of combustion was increasing when the excess air was increasing. The trend of the combustion efficiency was increasing and approaching 100%, however, in real life, the efficiency will never meet 100% due to the heat losses during the combustion.

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