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Temperature Distribution and Combustion Characteristics of Rice Husks in a Fluidized Bed Combustor

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This article presents an experimental study on the combustion characteristics of rice husks in a fluidized bed combustor (FBC). In the experiments, the FBC was tested with rice husk feeding rates ranging from 10-15.5 kg/hr to yield percent excess air (EA) between 25% and 35%. The axial and radial temperature distribution within the FBC was measured at a selected location while gas emissions were also monitored. From the experimental results, it can be seen that the maximum exhaust gas temperature is between 852 and 950 °C. In the exhaust gas emission analysis, CO is in the range of 951-1452 ppm, NO between 271 ppm and 303 ppm, CO_2 between 6.5% and 9.5%, and O_2 between 5.1% and 12.8%.

1. Introduction

Biomass consists of organic materials that exist in nature or are produced agriculturally, either as a crop or as a by-product of crop processing. They can be used to produce energy. Moreover, biomass is not only available from nature and agriculture, but can be obtained from various industries, such as sawdust, shavings and wood chips from the logging and wood processing industries. In Thailand, there is a large amount of biomass. However, in choosing the right type of biomass for energy production, one must take into account other important variables, such as moisture content, particle size and the amount of ash produced from the combustion of such fuels. Generally, most biomass, such as sugar cane bagasse and rubber wood, have a high moisture content, resulting in low combustion efficiency. Therefore, the moisture content of these materials must first be reduced. Rice husks have a low moisture content (about 10-15%), while biofuels with larger sizes have low combustion efficiency. If a fuel is to be burned, there must be a process of size reduction to produce smaller such materials such as rubber wood chips. However, rice husks are the ideal size to be burned in a combustor. Additionally, biomass has very low ash content, about 1-2%, except rice husks, which are about 20% ash. This can cause serious air pollution problems. However, we can solve this issue by burning rice husks in a closed system and removing particles using various types of dust separators. Additionally, the caloric value of rice husks is high, 2900-4560 kcal/kg. The husks also contain a small amount of sulphur, 0.05%. Therefore, the combustion of rice husks will result in an effluent with a low sulphur dioxide content. However, due to its high ash content, rice husk have proven to be a problematic fuel for gasification and fluidized bed combustion, resulting in inefficient carbon conversion. In Thailand, various biomass resources, such as rice husks, have been used for a long time. However, they have been burned in open combustors, resulting in heat loss and air pollution. There have been numerous reports of various furnaces using biomass or coal as fuel. Of those, fluidized bed technology seems most suitable for converting solid fuels or agricultural residues into energy. Fluidized bed technology can create amorphous rice husk ash with extremely low carbon content in a very quick reaction due to its high combustion intensity and great mixing behaviour (Rozainee *et al*., 2008). Jeon *et al*. (2008) performed a study of the effects of bed temperature and gas velocity in a square orifice draft tube on the heat transfer coefficient and the overall combustion efficiency in an internally circulating fluidized bed combustor. Chirone *et al*. (2008) studied the combustion of three pelletized biofuels (sewage sludge, wood, and straw) in a fluidized bed

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combustor. Janvijitsakul and Kuprianov (2008) developed a mathematical model based on analysis of the trends of CO and NO production in a conical fluidized-bed combustor (FBC) fired using rice husks and pre-dried sugarcane bagasse. They co-fired “as-received” rice husks with “as-received” sugarcane bagasse and observed wide ranges of fuel properties and operating conditions. Varol and Atimtay (2007) investigated the combustion performance and emission characteristics of olive cake and coal in a bubbling fluidized bed. Flue gas concentrations of O_2, CO, SO_2, NO_x, and total hydrocarbons (CmHn) were also studied. Ridluan *et al*. (2007) presented the vortex combustor concept, which was developed from fundamental knowledge of highly swirling gas–solid flows and burning in vortex chambers at low temperatures. Rozainee *et al*. (2010) carried out a study of the influence of the secondary air flow rate and feeding on the combustion efficiency of rice husks in a fluidized bed combustor. They found that a secondary air flow rate equal to 80% of the primary air flow rate provided the highest combustion temperature, up to 680 °C, while producing the lowest residual carbon content in the ash, around 2.7 wt.%. Duan *et al*. (2013) reported on rice husk combustion in a vortexing fluidized-bed combustor (VFBC) with flue gas recirculation. The influence of flue gas recirculation, the in-bed stoichiometric oxygen ratio and the excess oxygen ratio on the temperature distribution, pollutant emissions and combustion efficiency were studied. They showed that the combustion efficiency was up to 99% while CO emissions increased with the in-bed stoichiometric oxygen ratio. Bharath *et al*. (2018) investigated co-gasification of rice husks and coal in a bubbling bed gasification reactor. They observed that when rice husks were added, the cold gas efficiency and calorific value of the synthetic gas were increased with a total carbon conversion of 89% and a cold gas efficiency of 78%. Chokphoemphun *et al*. (2019) studied the combustion characteristics of rice husks in rectangular fluidized bed combustors. The effect of excess air percentage (EA = 40-70%) on the temperature distribution and gas emissions in rectangular fluidized bed combustors on combustion behaviour was reported. Sirisomboon and Laowthong (2019) studied heat transfer coefficients in a conical bed swirl fluidized bed combustor to determine the effects of combustor design. Combustion was done at a ratio of secondary and tertiary air to primary air ranging from 0 to 0.5 at primary (upward flow) air speeds near the minimum swirling fluidization conditions (ums). Recently, Arromdee and Sirisomboon (2021) conducted rice husk combustion experiments in a VFBC with flue gas recirculation (FGR). The effects of FGR on combustion characteristics were examined. The impacts of operating variables such as the excess oxygen ratio were also studied. Kurkela *et al*. (2021) studied a 200-kW fluidized bed gasification (PDU) development plant that operates with recoverable solid fuels (SRFs) and demolished wood. They also studied the effects of operating conditions on successful carbon conversion and tar formation as well as other gas contaminants. Therefore, in the current paper, experiments were conducted in a fluidized bed combustor that was designed using various percent excess air (EA) between 25% and 35% and adjusting the combustion chamber characteristics to allow the fuel to burn longer in the combustion chamber. Additionally, at the bottom of the bed, a dual distributor plate was fitted to supply primary air (a: the main distributor plate) and rice husk feeding (b: the secondary distributor plate) to promote the distribution and mixing of the air and rice husks. A dual distributor type feeding mechanism was developed for feeding low density fuels such as rice husks in this fluidized bed combustor prototype.

Table 1: Properties of rice husks

Carbon	37.2 %
Hydrogen	5.9 %
Oxygen	36.9 %
Nitrogen	0.15 %
Sulphur	0.1 %
Moisture	7.9 %
Ash	19.1 %
Density	102 kg/m^3
Gross heat of combustion	3319 kcal/kg
Stoichiometric air	5.2 kg/kg fuel

2. Methodology

The experimental setup system consisted of a fluidized bed combustor as shown in Figure 1. The combustor had an inner diameter (D) of 200 mm and total height of 2400 mm. The bed and mixing chamber had heights of 2100 mm and 303 mm, respectively. All outer surfaces of the combustor were insulated to reduce combustion heat losses. The axial and radial temperature distribution within the combustor was measured at 13 selected positions (x = 0.075, 0.225, 0.375, 0.525, 0.675, 0.825, 9.75, 1.125, 1.275, 1.425, 1.575, 1.725 and 1.875 m) using 13 K-type thermocouples. Air from a high-pressure blower was split into two parts. One part flowed through a centre tube and was mixed with rice husks before entering the bed, while the other flowed through the bottom chamber and passed through the distribution plate. A set consisting of an orifice meter (ANSI/API 2530) and control valve was installed for measuring and adjusting the volumetric air flow rates. The rice husks were extracted from a feed hopper using a screw feeder driven by a 0.5 HP motor and an inverter. Rice husk quantity was controlled by modulating the rotation speed of the feeder. A dual distributor plate was installed at the bottom of the bed to provide primary air (a: the main distributor plate) and rice husk feeding (b: the secondary distributor plate). In the fluidized bed combustor, a dual distributor type feeding mechanism was designed for feeding low density fuels such as rice husks. The annular region of the main distributor plate, which had inner and outer diameters of 75 and 150 mm, respectively, was drilled in circular patterns with 200 circular holes that were 2 mm each. For the secondary distributor plate, 100 holes with a diameter of 2 mm were drilled. Stainless steel was used for both plates. The flue gas composition (O_2, CO_2, CO, and No) was determined using a Flue Gas Analyzer (testo 350XL). The bed and combustion chamber walls were made of steel with 50 mm ceramic fibre material as insulation and sheathed with a 1 mm thick galvanized steel sheet, while the exhaust center pipe was made of stainless steel. Rice husk particles were milled, ground and filtered to 2-8 mm^2 and stored in a laboratory under dry conditions (9.2% relative humidity). The properties of the husks are given in Table 1. The fluidized bed combustor was heated with an LPG torch in the lower nozzle slot to start the operation. Combustion air was fed into the bed by a 7.5 kW blower. Rice husks were conveyed in the second air section after being fed to the bottom of the combustor bed using a screw feeder. The chamber temperature increased to approximately 400 °C after around 30 minutes of preheating. Feeding was then started through the hopper, slowly at first with fine rice husks until 15.5 kg/hr was reached, and thereafter at a continuous rate. Then, the feed rate was kept constant. When the temperature in the chamber reached 400-500 °C, preheating was stopped. Experiments were done with rice husk feeding rates ranging from 10-15.5 kg/hr to yield percent excess air (EA) between 25% and 35%. Simultaneously, the air mass flow rate was maintained at 95 kg/h. Gasification tests were carried out in this work using an air-blown fluidized bed gasification system. This system's minimum fluidization velocity (U_{mf}) is 0.06 m/s. As rice husk particles burn, their mass and size decrease until they are totally consumed. The bulk of ash particles become light or tiny enough to be entrained by flue gas and leave as fly ash. Large ash particles are caught in a cyclone chamber, which has a greater temperature storage capacity and operates as a thermal flywheel. Data was collected every 10 minutes for a specified period along the radial direction of the bed for each test run, which took around two hours to complete. Radial temperature profiles were measured using 13 K-type thermocouple probes installed along the fluidized-bed combustor. Temperature at various places, air flow rate, and fly ash sampling for each run were all measured under steady-state conditions. The combustion temperatures were measured at 13 stations (x = 0.075, 0.225, 0.375, 0.525, 0.675, 0.825, 9.75, 1.125, 1.275, 1.425, 1.575, 1.725, 1.875 m) with six radial stations (r/R = 0.0, 0.2, 0.4, 0.6, 0.8, 1.0) in the tests. Three tests were run on each condition set to confirm that the data was accurate.

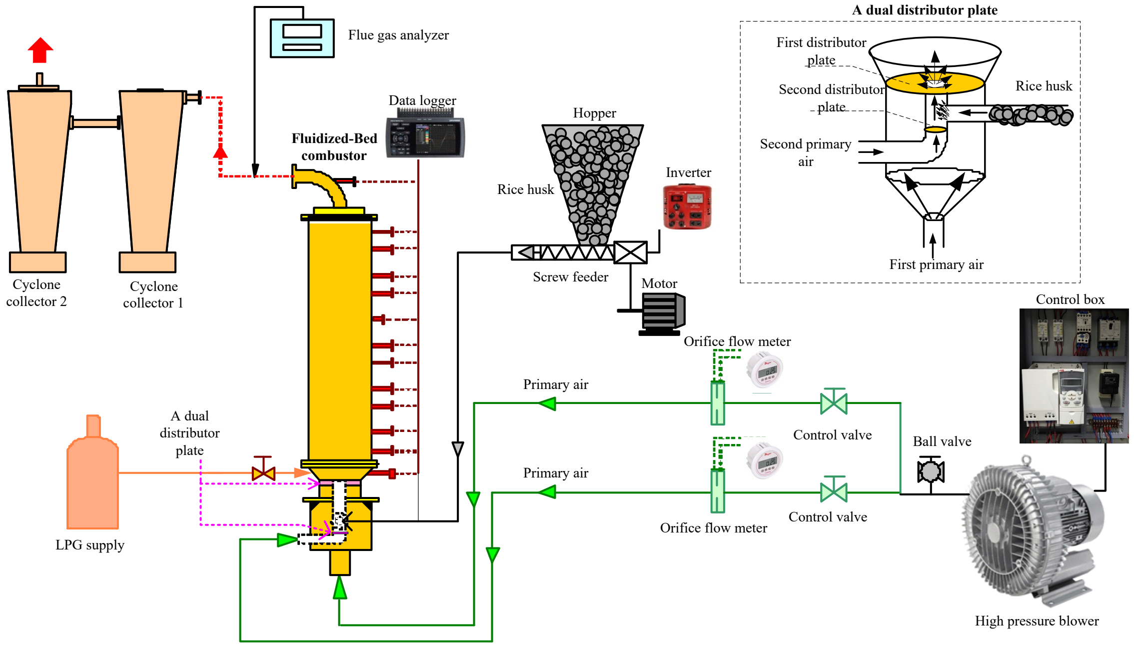

Figure 1: Experimental set-up of a fluidized bed combustor system using rice husks as fuel.

3. Results and discussion

The effects of the percent excess air on the temperature distribution in the FBC are shown in Figure 2. A close temperature distribution reveals that the axial and radial temperature distributions are consistent over the combustion chamber cross-section for all percent excess air (EA) conditions. At x = 0.075-1.425 m, the axial/radial temperature profiles in the combustor are virtually equal for all percent excess air values. However, at x = 1.575-1.875 m or at the top of the bed, they are substantially different. The radial temperature distribution at x = 0.075 m is the location where combustion began. This is the location where air and fuel join near the distributor plate. Therefore, the temperature in this area is not very high as the fuel starts to ignite. Considering the temperature distribution, EA = 35% provides the highest temperature distribution across the chamber. Since, high air volume is used at EA = 35%, higher combustion temperatures result in both cases. EA > 35% cannot be tested since too much air enters the combustor in this case, causing low temperatures inside the combustor that gradually decrease.

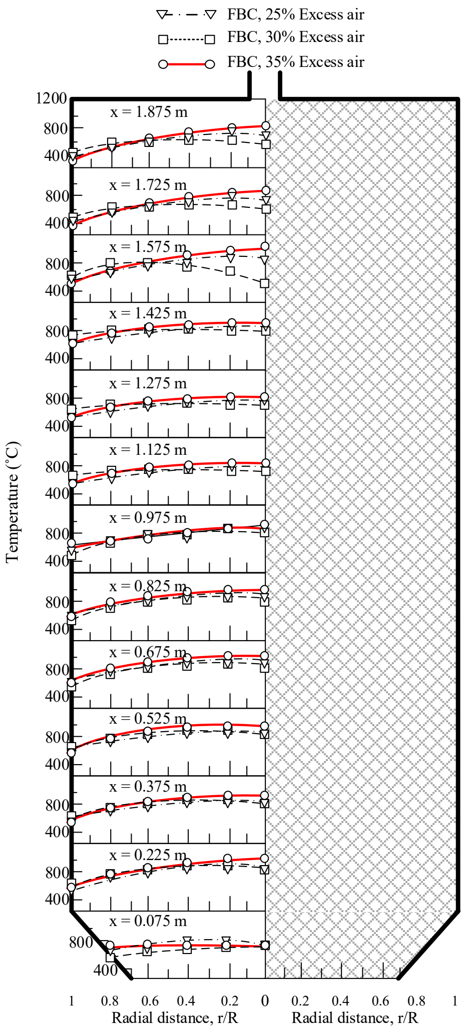

Figure 2: Temperature distribution in a fluidized bed combustor (FBC) as a function of radial distance.

Figure 3 depicts the temperature distribution along the height of the combustor. It can be seen that at EA = 25%, x/D = 2.0 and r/R = 0.4, the temperature is 852 °C and higher at r/R = 0.0 and 0.2. This is because this region is the fluidization phase where solids behave like fluids and it is the area where the fuel and air are mixed. It has the shape of a fountain, enabling fuel in this region to burn more completely with higher temperatures than in the range r / R = 0.0 and 0.2. The centre of the chamber is the merging point of the air and fuel. Therefore, combustion temperatures are high here. At a higher position, x/D = 2.0 (1.5 m), the temperature distribution at all EAs begins to differ greatly since this region is near the exhaust pipe exit. Most of the heat from combustion is transferred to the outside of the combustor. At percent excess air of EA = 30%, at a distance of r/R = 0.0 and height of 0.075 m, the initial phase of combustion and the temperature begin to increase and are almost constant throughout the rest of the combustor. The average temperature throughout the combustor was about 793 °C, while at r/R = 0.2 and r/R = 0.4, the temperature was slightly lower, and significantly lower at the top of the combustion chamber. At EA = 35%, it can be seen that the initial combustion temperature is low, since primary air is used and the air volume is small, allowing the air and fuel to mix well for consistent combustion. Throughout the combustor, a maximum average temperature of about 904 °C was observed at a distance of r/R = 0.4. At the wall of the combustor, where r/R = 1.0, it can be seen that the combustion temperature with all EA values is not very high. The average temperature in this area is about 610-707 ^{o}C.

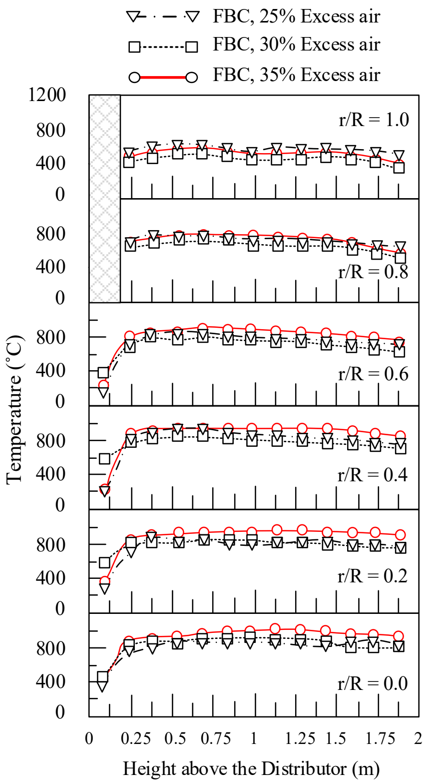

Figure 3: Temperature distribution in a fluidized bed combustor (FBC) as a function of height above the distributor.

The exhaust gas compositions (O_2, CO, CO_2, NO and NO_x) are shown in Figure 4. It can be seen that NO is in the range of 271-303 ppm while CO is in the range of 951-1452 ppm. It can be seen that in the experiment, a large amount of air is used in the combustion process, so the combustion temperature was not very high. As a result, the level of residual O_2 from combustion is quite high, with an O_2 content of up to 12.5%. Conversely, when the amount of O_2 is high, the CO content is reduced by about 5.1%. It can be seen that the amount of excess air produced by EA = 30% is more than that obtained by EA = 25%, resulting in in a lower combustion air volume and more complete combustion while the equivalent percent of 35% is combustion that uses primary air and air supplied through a nozzle. Using 100% primary air, only 4.5% of the O_2 content remains and CO_2 increases to 9%, resulting in an increase of CO of up to 1452 ppm and NO gases at a level of 303 ppm. The combustion smoke is very dark grey and ash from combustion is relatively fine with a blackish-grey colour.

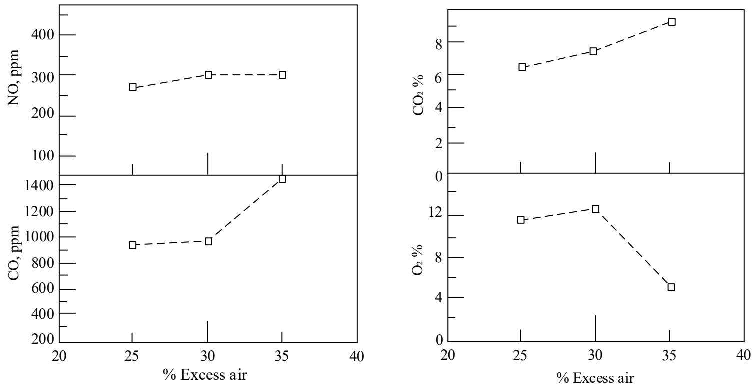

Figure 4: Exhaust gases in a fluidized bed combustor (FBC).

4. Conclusions

The combustion characteristics of rice husks in a fluidized bed combustor are experimentally investigated at an air flow of 95 kg/hr with various percentages of excess air, 25%, 30% and 35%. From the experimental results, it can be concluded that combustion requires an excess air level that keeps the fuel in the combustion chamber longer. In the test results, the temperature distribution inside the combustor was measured at 6 axial and 13 radial points (x = 0.075, 0.225, 0.375, 0.525, 0.675, 0.825, 9.75, 1.125, 1.275, 1.425, 1.575, 1.725 and 1.875 m), while exhaust gases (O_2, CO, CO_2 and NO) were measured at the outlet of the combustor. The results of the study found that the average combustion chamber temperature is 610-707 $^{\circ}$C with a maximum of 950 $^{\circ}$C. It is also found that EA = 35% yields higher temperatures than EA = 25% or 30%.

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