

Performance Evaluation of a Horizontal Air Staged Inclined Biomass-to-Heat Energy Converter for Drying Paper Egg Trays

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Abstract- This study presents the performance evaluation of a horizontal air staged inclined biomass-to-heat energy (B2H) converter used for drying purposes in the production of paper egg-trays. The thermal properties and moisture content of the selected biomass such as oil palm kernel shell and wood chips were assessed. The influence of air mixture ratio (AMR) on temperature profile, flue gases composition and combustion efficiency of the selected biomass were determined with a Testo 350XL flue gas analyser. It was observed that an increase in AMR led to an increase in the average temperature of the pyrolytic chamber but decreased the average temperature of the exhaust, with insignificant change in the surrounding temperature. CO, H₂, NO_x and SO₂ concentrations were inversely proportional to an increase in AMR and an increase in oxygen content in the B2H converter exhaust. Combustion efficiency of the B2H converter was inversely proportional to an increase in AMR. Combustion efficiency of 67.00 ± 0.34 % was achieved with Experiment vii. CO and NO_x emissions at the B2H exhaust (Experiment-vii) met the EPA regulations, that is, 193.35 ± 9.17 ppmv and 9.20 ± 0.87 ppmv, respectively. SO₂ emission at the B2H exhaust, however, was lower than the NIOSH regulations, that is, 4.57 ± 1.08 ppmv. Thus the B2H converter demonstrated that CO, NO_x and SO₂ emissions can be significantly reduced with oil palm kernel shell and wood chips.

Keywords- Biomass, Gas emission, Combustion, Performance evaluation.

1. Introduction

Malaysia is the world's largest producer and exporter of palm oil and its products. Palm oil production increased from 2.5 million tonnes in 1980 to 17.8 million tonnes in 2009 [1]. Co-products such as fronds, trunks, empty fruit bunch (EFB), palm fibre and shell are not utilized, however. Wood waste in Malaysia found in the logging industries in 2009 alone gave a total production of logs based on the total land area of 18.27 million m³ [2]. From January to February 2009,

Malaysia generated a free on board (FOB) value of more than RM 202 million through logging activities [3]. This generated a huge amount of wood waste, which can potentially give rise to environmentally sensitive disposal issues.

It is known that biomass is most cost-effective for heat production for low carbon taxes (below 50 to 100 USD/Toricredits) [4]. Various types of biomass combustor are currently available such as updraft, downdraft, cross-draft, fluidized-bed design features and others [5].

Generally, biomass combustors have three main applications: (1) heat production, (2) power generation and (3) fuel production [6]. Treatment technologies for drying paper egg-trays and for use in the pulp and paper industries that are cost-effective, available locally and offer serviceable materials and equipment that require low technical skills for operation and maintenance are not available, however [7]. A highly efficient and cost-effective biomass-to-heat energy (B2H) converter is deemed an appropriate solution in those industries, especially in developing countries.

2. Pulp and Paper Industry in Malaysia

In Malaysia 67 paper mills produce more than 50 tonnes of paper per day [8]. In 2012, 30 million tonnes of EFB were produced by 351 oil palm mills. With the organosolv process, five tonnes of EFB can produce one tonne of pulp. Therefore, assuming that 50 % of the EFB is available for pulp production, Malaysia could produce 3 million tonnes of pulp per year from EFB alone. In addition, pulp and paper production from wood discharges a considerable volume of effluent (50 to 200 m³ per tonne of pulp), gaseous and solid waste into the environment [9]. PTM's 2004 study [10] shows that the pulp and paper industries in Malaysia consume 5,080,208 GJ of energy per year, with carbon dioxide (CO₂) emission reduction potential of 194,403 tonnes per year, which is the second highest among industries. Currently, Malaysian pulp and paper industries depend heavily on natural gas, fuel oil and coal as principal fossil fuel [11]. In 2009, only the Nibong Tebal Paper Mill Sdn. Bhd. utilized wood dust as co-generation [12]. Andersson [13] conducted an experiment on three different technologies for pulp mill integrated biofuel drying (steam drying, flue gas drying, and vacuum drying) and concluded the flue gas dryer was the best option.

2.1. Previous Researches on Biomass Combustion

There is much research on the area of biomass combustion: particle size [18, 19]; moisture content of biomass [18, 20]; effect of cellulose and lignin content of biomass [21, 22]; inorganic constituents in the fuel [23, 24]; air staging and its location [25, 26]; excess air ratio [27, 28]; oxygen-enriched combustion [29, 30]; geometrical and heat recovery design [31, 32]; feed rate [29]; method of ignition for biomass [30]; co-combustion [26, 35]; temperature [36, 37].

There is, however, little or no research on (1) the effect of heat recovery from the outer physical boundary of the main combustion chamber and (2) the effect of the angle of the inclination chamber on horizontal fixed-bed biomass combustion. This is an important aspect which warrants investigation if knowledge in this field is to be advanced.

This study investigated the potential of biomass combustion in a B2H converter with oil palm kernel shell and wood chips by evaluating their emissions and performance.

3. Material and Methods

The B2H converter comprised three chambers, a pyrolytic chamber, a tar converter chamber, and a combustible fuel gas-to-heat energy conversion chamber. The overall size of the B2H converter was 1.5 m x 2.1 m x 1.0 m. The pyrolytic chamber consisted of a cylinder 1.5 m in height with a diameter of 0.775 m. It consisted of a thick layer of refractory anchors with a length of 100 mm. The pyrolytic chamber was surrounded by a copper coil (outer diameter of 1.27 cm and 1.00 m height in a consecutive arrangement). A 6° incline was built in the tar removal chamber for optimal effectiveness. About 200 kg of fresh oil palm kernel shell (OPKS) were collected from the Bau Palm Oil Mill Sdn. Bhd. The average size of OPKS is 10.4 mm x 4.8 mm x 12.8 mm. The wood chips were collected from a furniture factory at Kota Samarahan. Each sample was mixed, divided and covered to avoid contamination. The specimen sample was weighed and dried under the hot sun for seven days. Figure 1 shows a schematic diagram of the experimental set-up.

A Shimadzu DTG-60H thermal analyser was used to determine the thermal properties of the selected biomass samples. The selected biomass samples were conducted with alumina as cell, air flow rate at 60 ml/min, sample weight at 20 mg, and temperature rate of 10°C/min. The moisture content of the selected biomass sample was determined with a Binder drying oven according to the British Standard EN 1477-2:2009 [34]. The size of the investigated sample was ground to (1.0 ± 0.1) mm, and the weight at all times was about 200 mg. The average superficial air velocity from HAILEA VB-800G (V_{B1}) and VB-2200G (V_{B2}) impeller blower pumps was determined with a Dwyer VT120 integral vane thermo-anemometer.

3.1. Emission Measurement

The B2H converter temperature profile, flue gas composition, and combustion efficiency were studied in three experimental trial groups: Group A (Experiments i, ii and iii), which studied the influence of the AMR on OPKS with AMR = 9.65:0.00, 9.65:3.83 and 9.65:4.00; Group B (Experiments iv, v and vi), which studied the influence of the AMR on OPKS with AMR = 4.00:0.00, 4.00:5.79 and 4.00:9.65; Group C, which compared the performance evaluation of OPKS (Experiment vii) and wood chips (Experiment viii) with AMR = 3.83:9.65. Once the 3.0 kg of selected biomass and 3.0 litres of methanol were ignited, gas emissions were measured with a TESTO 350 XL flue gas analyser according to British Standard EN 14181:2004 [35].

A sampling duration of 2 min and rinse time of 5 min were used throughout the 20-110 min to obtain correct readings according to the flue gas manual. The measurement principle of this flue gas analyser was electrochemical for CO, H₂, NO₂, SO₂, and NO. NO_x in the flue gas was the sum of the measured NO and NO₂. Emission data for each experimental trial group were taken three times and results displayed graphically with ± standard error of average value.

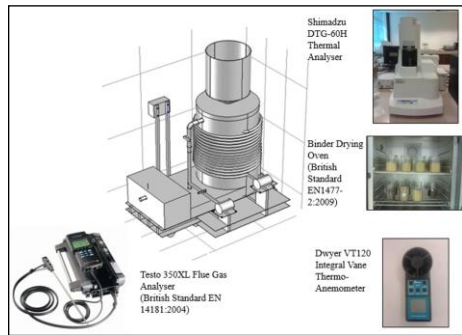


Fig. 1. Schematic diagram of the experimental set-up

4. Results and Discussion

4.1. Emission Measurement

Tables 1 and Figure 2 illustrate the thermal analysis outcome of the investigated OPKS and wood chips. It was observed that all three samples of OPKS and wood chips underwent four stages of transition. This correlated well with the theory of biomass combustion for drying, pyrolysis, gasification and combustion [36].

An endothermic process was observed in the early stage, which represents the drying process. The average drying temperatures of OPKS and wood chips are 28.00-183.33 °C and 28.00-116.67 °C, respectively (Table 1). In Figure 2, the

Table 1. Thermal analysis of OPKS and wood chips

Sample	Average drying temperature (°C)	Average pyrolysis temperature (°C)	Average gasification temperature (°C)	Average combustion temperature (°C)
OPKS	28.00 – 183.33	183.33 – 300.00	300.00 – 373.33	373.33 – 900.00
Wood chips	28.00 – 116.67	116.67 – 260.00	260.00 – 365.00	365.00 – 900.00

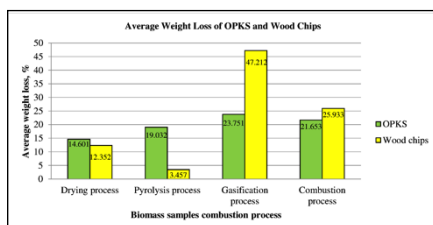


Fig. 2. Average weight loss of OPKS and wood chips for biomass combustion process

4.2. Moisture Content

Figure 3 illustrates that the moisture content of the selected wood chips (16.2 ± 1.1 wt. %) was higher than selected oil palm kernel shell (11.7 ± 0.1 wt. %). Nevertheless, it is suitable (< 20 wt. %) for effective drying, as suggested by the EU [40]. The results for oil palm kernel shell correlate well with Zafar [41] and Dagwa [42]. Moisture content of the selected wood chip is higher than the oil palm kernel shell possibly because of its morphology; it has a high moisture content [43]. Therefore, the exhaust temperature from oil palm kernel shell is expected to be higher than wood chip thanks to its moisture content.

weight loss of OPKS in the drying process is a higher percentage (14.601 %) compared with wood chips (12.352 %). Although the moisture content of the wood chips (16.2 ± 1.1 wt. %) in this experiment is higher than OPKS (11.7 ± 0.1 wt. %) (Figure 3), the average drying temperature of wood chips is lower than OPKS (Table 1). This might be because of the higher permeability of OPKS than wood chips, as pointed out by Simão [37].

After the drying process, the investigated biomass samples were subjected to pyrolysis, gasification and combustion processes which can contribute to the decomposition of cellulose, hemicellulose and lignin components in the biomass [38]. According to the literature, hemicellulose starts to degrade at 220 °C, cellulose decomposes at temperatures greater than 300 °C, and lignin degrades slowly in a wider temperature range [39]. Thus, the decomposition of cellulose is responsible for the pyrolytic process. Subsequently, the decomposition of hemicellulose contributed to the gasification process, and decomposition of lignin accomplished the combustion process. Generally, the average pyrolytic temperature of OPKS and wood chip samples is 183.33-300.00 °C and 116.67-260.00 °C, respectively (Table 1). The average gasification temperature of OPKS and wood chip samples is 300.00 – 373.33 °C and 260.00 – 365.00 °C, respectively. Finally, the average combustion temperature of OPKS and wood chip samples is 373.33- 900.00 °C and 365.00-900.00 °C, respectively.

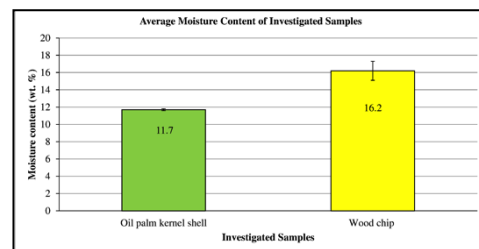


Fig. 3. Average moisture content of investigated biomass samples

4.3. Air Flow Rate of Blowers

The relationship between the air flow rate (Nm³/s) and the AMR is directly proportional; as the velocity of the blower increased, the volume of the air supplied also increased (Figure 4). Experiment iv gave the lowest air flow rate (0.01824 Nm³/s) and Experiment iii gave the highest air flow rate (0.07661 Nm³/s) among other experimental trials. Air flow rate is one of the main determining factors in the performance evaluation of B2H converters. According to Reed and Das [44] and Yamazaki and colleagues [45], air flow rate has an important effect on the gas production rate, gas energy content, fuel consumption rate, power output,

char, and tar production rates, and is independent of the reactor dimensions.

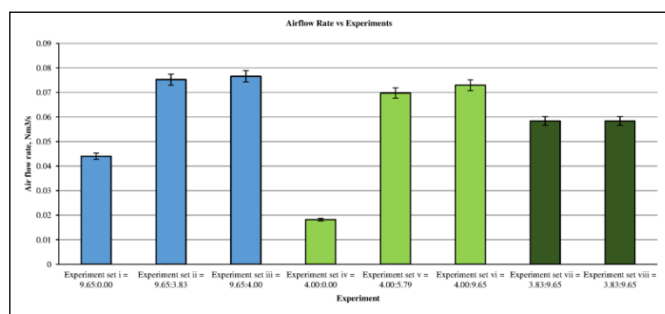


Fig. 4. Air flow rate of the experiments

4.4. B2H Temperature Profile

(i) Temperature of Pyrolytic chamber

Generally, the average temperature of the pyrolytic chamber increased with an increase of AMR. This was in agreement with Surjosatyo [23], and was owed to the good mix of fuel and air that promoted the heat and mass transfer in the biomass combustion [46]. Group A (Experiments i, ii and iii) gave the lowest average temperature range, that is, 205.41 ± 10.19 °C to 224.73 ± 39.20 °C. In Group B (Experiments iv, v and vi), the average temperature ranged from 196.03 ± 30.78 °C to 303.41 ± 49.75 °C. Group C (Experiments vii and viii) contributed the overall highest average temperature range among the groups, i.e. 263.53 ± 21.46 °C to 336.80 ± 21.81 °C, even though the AMR was lower than in Experiments ii, iii, v, and vi (Figure 5). In Group C, wood chips in Experiment viii recorded higher average temperature of pyrolysis, perhaps because it possesses a wider effective surface area for reaction than OPKS [14]. The abnormally high average temperature of the pyrolytic chamber in Experiment v could be due to owed to the burning fuel that spread over the measured thermocouple and was removed after about 18 minutes.

(ii) Temperature of Exhaust

It can be observed that the average temperature of the exhaust consistently decreased with an increase in AMR and/or excess air (Figure 5). This was attributed to the convective cooling effect of the secondary air, which became higher than the energy released by the exothermic reaction and also higher than the radiative heat transfer from the solid phase [47]. As the air flow rate increases above the theoretical value, the B2H input energy per kg of fuel gases is reduced and the exhaust gas temperature decreases [48]. Therefore, it can be concluded that AMR is an important factor in achieving the desire temperature. As shown in Figure 5, Group A generally recorded the highest average temperature of the exhaust, followed by Group B and then Group C.

Fagnäs [49] suggested that exhaust temperature (<100 °C) should be maintained when possible. It would be possible to dry wood fuels to about the 10 wt. % moisture content without emitting a harmful amount of organic compounds [50]. Prerequisites are that drying occurs in a

bed, the inlet drying gas temperature is not higher than 180 °C and the steam is not condensed. The average exhaust temperature of Experiments vi, vii and viii meet these prerequisites.

(iii) Surrounding Temperature

Generally, small changes of B2H surrounding temperature were observed (Figure 5). The lowest surrounding temperature was 30.14 ± 2.22 °C, and the highest recorded was 33.32 ± 1.44 °C. This was because of the use of refractory with high heat capacity and low thermal conductivity which absorbed the radiated energy for energy saving [51].

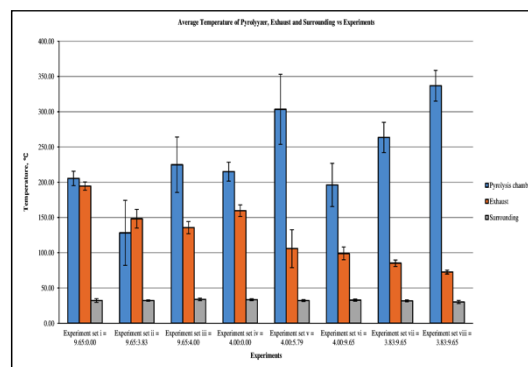


Fig. 5. Average temperature of pyrolysis chamber, exhaust and surrounding vs experiments

4.5. Gas Compositions

(iv) Combustible Gases (CO, H₂)

CO and H₂ concentrations were inversely proportional to an increase in excess air (Figure 6). This was attributed to the air staging method applied in this experiment, and the fuel-rich zone and the fuel-lean zone in the pyrolytic chamber and tar removal chamber, respectively. The results of Ishak [52] is in agreement with this finding.

There were CO emission reductions of 46.78 % and 81.28 % for Groups A (Experiments i, ii and iii) and B (Experiments iv, v and vi), respectively. Experiment iv (non-air staging) in Group B recorded the highest CO emission, which was attributed to the deficiency of air combustion of 53.94 %. This was followed by Experiment i (non-air staging) in Group A as it only had 2.84 % excess air combustion. In Group B, the CO emission reduction of more than 80 % was achieved by using an air staging test (Experiment vi) compared with non-air staging test (Experiment iv). The CO emission from the combustion process was attributed to the lack of sufficient oxygen to complete the reaction from CO to CO₂. When secondary air is added to the tar removal chamber to complete the combustion, the exhaust temperature will drop. In this particular experiment, the optimum condition of the air staging method in B2H was about 78.18 % excess air combustion with the lowest CO emission measured. In Group A (Experiments i, ii and iii), the CO concentration in Experiment iii is abnormally higher than in Experiment ii, because of the smoke measured at the B2H exhaust during the initial combustion, and subsequently caused the Testo

350XL analyser to malfunction [53]. This phenomenon usually happens during the first two minutes. This could be related to relatively low temperature and insufficient residence time of the gases in the pyrolytic chamber [54].

The H₂ concentration was inversely proportional to excess air (Figure 6). This is because of the dilution effect caused by the increase of nitrogen content (introduced along with air). An introduction of higher oxygen content diminished the reduction conditions because of the rate of oxidation reaction (exothermic burning) which is opposite to the cracking and reforming reaction, so the H₂ content decreased [4].

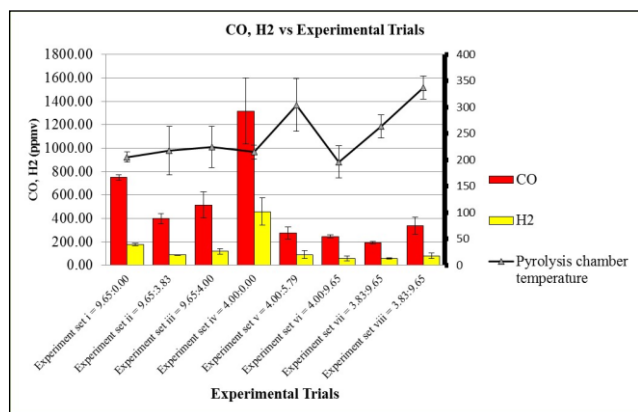


Fig. 6. CO and H₂ vs experimental trials

(v) Nitrogen Oxides (NO_x: NO, NO₂)

The measured nitrogen oxides (NO_x) are the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO₂). Figure 7 shows that an increase in excess air leads to a decrease in NO_x level. This is in agreement with the findings of Habib [55] and Baxter [56]. The trend might be owed to the dilution of NO_x by an increase of excess combustion air. At some point, the formation of NO_x becomes independent of a large excess of combustion air, and therefore the only changes in NO_x concentration are noted with excess combustion air [56].

Temperature and staged combustion play the most important role in NO emissions. It was observed that NO concentration decreased with an increase in the pyrolytic chamber temperature. This could be because higher temperature favours both higher volatile-nitrogen release and oxidation of volatile-nitrogen species in the gas phase [57]. Higher temperature also reduces carbon loading in the bed, thereby lessening NO reduction by char [58]. At higher temperature, NO decreased because of the increasing importance of the NO destruction reactions with NH₃ and HCN [59]. Subsequently, NO concentration in the B2H decreases as the bed temperature increases.

Figure 7 illustrates the degree of reduction in NO_x at greater secondary air ratio. This suggests that staged combustion is more effective in reducing NO_x emission at higher pyrolytic chamber temperature, even in a horizontal air staged inclined B2H converter. In Group A (Experiments i, ii and iii) the NO_x concentrations could be reduced by about 39.37 % (from Experiment i to Experiment ii) and 8.62 % (from Experiment ii to Experiment iii) as the average

pyrolytic chamber temperatures increased about 5.73 % and 3.48 %, respectively. For Group C (Experiment vii and viii), the NO_x emissions concentration could be reduced by about 64.13 % (from Experiment vii to Experiment viii) as the average pyrolytic chamber temperatures increased by about 86.0 %.

Figure 7 also shows that the NO_x emission in Group A is higher than that in Group B. This was because of the higher percentage of air (mostly composed of nitrogen) consumed for combustion. Comparatively, NO_x emissions from the wood chips were about 64.13 % lower than OPKS. This is attributed to the higher fuel nitrogen in OPKS than the wood chips. Much research also shows that the fuels with higher nitrogen content generally have lower conversion rates and vice versa [60]. Published articles show that the fuel nitrogen range of OPKS and wood chips ranges from 0.89 % to 1.73 % [61] and from 0.18 % to 0.3 % [62], respectively. Other studies also show that bulk density and volatile matters in fuels also contribute to chemical reactions [48].

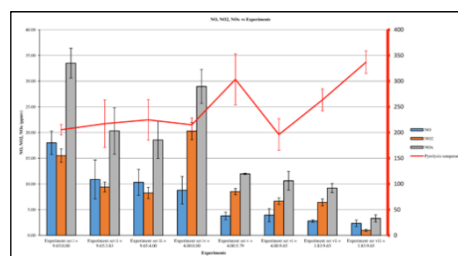


Fig. 7. Nitrogen oxides vs experimental trials

(vi) Sulphur Dioxide, SO₂

Figure 8 shows that SO₂ is inversely proportional to AMR. In Group B (Experiments iv, v and vi), SO₂ concentration is significantly reduced to approximately 72.88 % with air staged combustion. A theoretical study by Gungor and Eskin [63] on a circulating fluidized bed combustor confirms this trend. This phenomenon was also observed in the study by Lyngfelt [64]. It could be the result of the dilution caused by the increase of excess air [63]. The SO₂ emissions from the investigated wood chip were higher than OPKS, perhaps because of the fuel bound sulphur. Fuel bound sulphur can range from 0.01 % to 2 % in biomass fuel [44]. It was confirmed by Werther [65] that SO₂ emissions vary as a function of fuel bound sulphur. Thus, SO₂ emissions are proportional to fuel bound sulphur. SO₂ emission can create environmental pollution if not treated properly. During flue gas cooling, a proportion of SO₂ is converted to sulphur trioxide (SO₃) which may subsequently be converted into sulphuric acid (H₂SO₄), and this can cause significant corrosion if allowed to condense [66]. It is technically difficult and expensive to remove the fuel bound sulphur before burning the fuel [67]; however, regulating the SO₂ can help to reduce the chlorine content of deposits and hence corrosion-related operating problems. The environmental benefit of reduced SO₂ makes the B2H converter a favoured approach for drying paper egg trays.

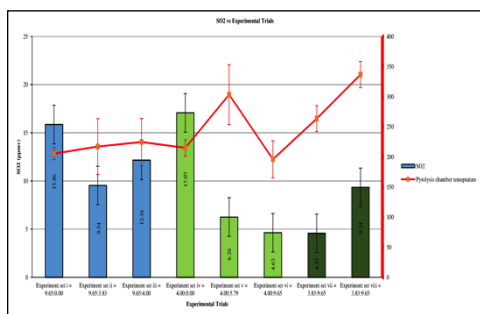


Fig. 8. SO₂ versus experiments trials

(vii) Oxygen Levels at the B2H Exhaust

Figure 9 shows the trends of the increase in oxygen levels at the B2H exhaust as the AMR increased from Group A to Group B followed by Group C. This was owed to an increase of the air volume from the blowers which increased the oxygen levels [68]. Generally, it can be seen that experiments with a higher pyrolyser temperature have higher oxygen levels (Figure 9). Luo and colleagues [25] showed that with an increase in oxygen concentration, the volatile release temperature, ignition temperature and burnout temperature decrease as shown in Figure 9.

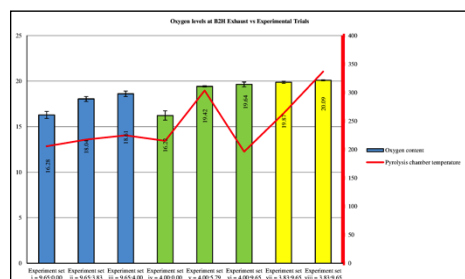


Fig. 9. Oxygen levels at B2H exhaust vs experimental trials

(viii) Combustion Efficiency

Figure 10 shows that the combustion efficiency decreases with an increase in AMR and/or excess air. This is in agreement with IEA [69], and Gungor and Eskin [63] in that high excess air (more than about 50 % excess air) can lead to a reduction in combustion efficiency. This might be owed to an increase of the bed operating velocity, thus reducing the mean residence time of char particles in the chambers and reducing the combustion efficiency. Combustion efficiency found in this experiment ranged from 61.89 % ± 2.24 to 74.44 ± 3.54 %. Permatasari [70] found that the combustion efficiency of a fluidized bed with OPKS is 63 % with 40 % excess air and 20 % secondary air ratio. In a modified fluidized combustor, a maximum of 99.2 % of combustion efficiency was achieved at 65 % excess air combustion with sawdust [71].

Marker [72] indicated that reducing CO emissions has no significant improvement on combustion efficiency. According to Bhattacharya and Weizhang as cited by Srinivasa and Reddy [71], the loss of unburned carbon in the form of CO is in the range of 3 to 10 %. In conclusion, the combustion efficiency of the B2H converter is mainly affected by air staging and incomplete combustion but not CO emission. In this experimental operation condition,

increasing excess air leads to a decrease in combustion efficiency.

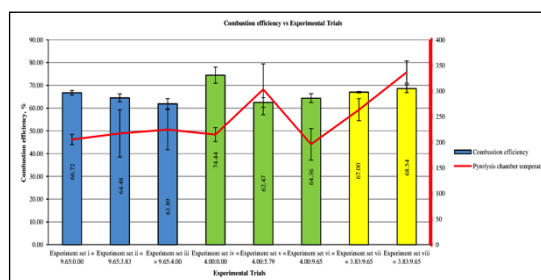


Fig. 10. Combustion efficiency vs experimental trials

4.6. Summary of the Average B2H Combustion Operation

Combustion efficiency of 67.00 ± 0.34 % was achieved with AMR of 3.86:9.65, air flow rate of 0.05837 Nm³/s, and excess air combustion of 78.18 %. Under these conditions, the temperature of the pyrolytic chamber, B2H exhaust and B2H surrounding are 263.53 ± 21.46 °C, 85.71 ± 4.64 °C and 31.67 ± 1.26 °C, respectively. Fagnäs's [49] experiment showed that the optimal flue gas temperature for drying pulp is below 100 °C. Zaidi [73] suggests the paper sheet should be brought up to about 82 °C. The CO and NO_x emission at the B2H exhaust (Experiment vii) met the EPA regulation, that is, 193.35 ± 9.17 ppmv [74] and 9.20 ± 0.87 ppmv [75], respectively; SO₂ emission at the B2H was lower than the NIOSH regulation, that is, 4.57 ± 1.08 ppmv [76].

5. Conclusion

This study presents a performance evaluation of a horizontal air staged inclined B2H converter with OPKS and wood chips. The following conclusions can be drawn from the results:

- (1) The OPKS and wood chip samples undergo four distinct stages, i.e. drying, pyrolysis, gasification and combustion. The average pyrolytic temperature range for OPKS and wood chip samples is 183.33 to 300.00 °C and 116.67 to 260.00 °C, respectively. The average gasification temperature range of OPKS and wood chip samples is 300.00 –to 373.33 °C and 260.00 to 365.00 °C, respectively. The average combustion temperature range of OPKS and wood chip samples is 373.33 to 900.00 °C and 365.00 to 900.00 °C, respectively.
- (2) OPKS recorded moisture content of 11.7 ± 0.1 wt. %, whereas wood chip recorded moisture content of 16.2 ± 1.1 wt. %.
- (3) It was observed that an increase in AMR led to an increase in average temperature of the pyrolytic chamber, but decreased the average temperature in the exhaust, with insignificant change in the surrounding temperature. CO, H₂, NO_x and SO₂ concentrations were inversely proportional to an increase in AMR and an increase in oxygen content in the B2H exhaust. The combustion efficiency of the B2H converter was inversely proportion to an increase in AMR.

(4) Combustion efficiency of 67.00 ± 0.34 % was achieved with Experiment vii. CO and NO_x emissions at the B2H exhaust (Experiment vii) met the EPA regulation, that is, 193.35 ± 9.17 ppmv and 9.20 ± 0.87 ppmv, respectively. SO₂ emission at the B2H was lower than the NIOSH regulation, that is, 4.57 ± 1.08 ppmv.

Current experimental trials confirm that the horizontal air staged inclined B2H converter allows cleaner and more efficient combustion with OPKS and wood chips as feedstocks. Thus, B2H converters have commercial potential for use in drying.

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