

## CO-COMBUSTION OF REFUSE DERIVED FUEL WITH COAL IN A FLUIDISED BED COMBUSTOR

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### Abstract

Power generation from biomass is an attractive technology which utilizes municipal solid waste-based refused derived fuel. In order to explain the behavior of biomass-fired fluidized bed incinerator, biomass sources from refuse derived fuel was co-fired with coal in a 0.15 m diameter and 2.3 m high fluidized bed combustor. The combustion efficiency and carbon monoxide emissions were studied and compared with those from pure coal combustion. This study proved that the blending effect had increased the carbon combustion efficiency up to 12% as compared to single MSW-based RDF. Carbon monoxide levels fluctuated between 200-1600 ppm were observed when coal is added. It is evident from this research that efficient co-firing of biomass with coal can be achieved with minimum modification of existing coal-fired boilers.

Keyword: Co-combustion, Biomass, Coal, Fluidized bed combustor,  
Refuse derived fuel

### 1. Introduction

Waste-to-energy is gaining more and more attention as landfill costs and environmental concerns increase in many developed countries including Malaysia. Malaysia, with a population of 25 million in 2006 has tremendously developed economically with regards to accelerated urbanization and industrialization. Relatively, the generated rates of waste have a strong correlation with the level of economic development in a country. For middle income countries, 0.80 kg/capita/day

**Nomenclatures**

$A$	Mass fraction of unburned carbon in the fuel, kg
$B$	Mass fraction of burnt carbon in the fuel, kg
$C$	Mass fraction of total carbon in the fuel, kg
$E$	Carbon combustion efficiency
$F$	Mass of dry flue gas, kg
$P$	Mass fraction of carbon converted to carbon monoxide per carbon converted to carbon monoxide and carbon dioxide
$X_1$	Total oxygen consumed during combustion, kg
$X_2$	Total oxygen required for stoichiometric combustion of fuel, kg
$Y$	Mass of dry flue gas per unit mass of C burnt in the fuel, kg
$Z$	Fractional excess air supplied

*Abbreviations*

FBC	Fluidised bed combustion
MSW	Municipal solid waste
RDF	Refused-derived fuel

generation of Municipal Solid Waste (MSW) which accounts about 46% is gaining great attention to government to collect, process and dispose this waste safely.

Refused-derived fuel (RDF) is a fuel produced by shredding or steam pressure treatment in an autoclave of MSW creating a heterogeneous mixture of varying composition. RDF consists largely of organic components of municipal waste such as plastics and biodegradable waste and by processing MSW fuel, value can be added to this waste. The processing removes incombustible materials such as dirt, glass, metals and very wet organic materials, thus making RDF more consistent in size than raw MSW and enabling it to be used as a fuel source independently or as a blend. RDF is currently being considered as a solution to municipal solid waste disposal and resource recovery [1]. RDF can replace coal in the industrial sector and has been successfully tried in industrial boilers with clean emissions and high efficiency. An ever increasing population results in ever increasing amounts of MSW, which is generally placed in landfill. Using MSW sourced fuel decreases landfill volume, thus freeing sites for other more useful purposes; it also contributes to a decrease in firewood demand, thereby protecting forests.

Fluidised bed combustion (FBC) has been shown to be a versatile technology capable of burning practically any waste combination with low emissions [2]. The significant advantages of fluidised bed combustors over conventional combustors include their compact furnace, simple design, effective burning of a wide variety of fuels, relatively uniform temperature, and the ability to reduce emissions of nitrogen oxide and sulphur dioxide gases [3].

This research was performed with the objective to characterise the biomass properties that affect co-combustion of RDF with coal in a FBC, particularly RDF from MSW that available in large quantities in Malaysia.

## 2. Experimental

### 2.1. Fuel characterization

In this study British coal and RDF were employed as fuel. These fuels were open air dried for 2 to 3 days to remove moisture. The proximate and ultimate analyses, which were performed on coal and RDF, are summarized in Table 1. In comparison with coal, Table 1 shows that the main characteristics of the dry biomass are of low calorific value (12.3 MJ/kg), high volatile matter content (68%), ash content (23%), low carbon content (59%) and most importantly high oxygen content (31%). This is of particular importance since it influences the stoichiometric air requirement for combustion. It is also important to note that the RDF has a lower particle density and varies in size with a great variation in shape than coal.

**Table 1. Coal and RDF Characterization.**

<i>Proximate analysis (% wt, dry basis)</i>	<b>Coal</b>	<b>RDF</b>
<b>Fixed carbon</b>	58.90	9.70
<b>Volatile matter</b>	38.20	67.61
<b>Ash</b>	2.90	22.69
<i>Ultimate analysis (% wt, dry basis.)</i>		
<b>Carbon</b>	80.10	58.95
<b>Hydrogen</b>	5.30	9.55
<b>Nitrogen</b>	0.90	0.61
<b>Sulphur</b>	0.70	0.01
<b>Oxygen</b>	13.00	30.88
<b>Calorific value (MJ/kg)</b>	31.1	12.3
<b>Particle size (outer diameter × length) (mm)</b>	1.4 - 4.8	21.5 × 10
<b>Particle density (kg/m<sup>3</sup>)</b>	1200	435

### 2.2. Experimental apparatus and operating procedures

Figure 1 is a schematic diagram of the Atmospheric Fluidized Bed combustor used in this investigation. The system comprises of a 0.15 m diameter and 2.3 m high combustion chamber, allows for bed depths of up to 0.3 m using 850 µm sand, cyclone, screw feeder and gas analyzer. The combustor body is constructed from 1-cm thick 306 stainless steel and covered in Kaowool insulation to prevent excessive heat loss during operation. Fluidising air was introduced at the base of the bed through a nozzle distributor and provided fluidisation and combustion air. Start up of the bed was achieved using an in-bed technique; Propane was introduced directly into the distributor plate by injectors and mixed with air in the nozzles, providing a combustible mixture at the nozzle exit. Bed and freeboard temperatures were measured at 8 different heights above the distributor plate by means of sheathed Ni/Cr-Ni thermocouples (TC) type K. Fuel was fed pneumatically into the bed surface

from a sealed hopper through an inclined feeding pipe the flowrate for which flow rate was controlled by a screw-feeder. A cyclone was fitted to the combustor exit and the carryover from the bed was collected for analysis. CO and O<sub>2</sub> were measured using a Xentra 4904 B1 continuous emissions analyzer, whereas CO<sub>2</sub> was measured using a non-dispersive infrared absorption spectrometry analyser.

In the absence of complete combustion, a certain amount of thermal energy is lost which corresponds to the values associated with the conversion of carbon to CO and CO<sub>2</sub> and the unburned carbon in ash. Thermal efficiency is defined as the ratio of rate of energy release to rate of energy supply. Thus, the percentage of carbon combustion efficiency have developed a procedure to calculate the combustion efficiency based on the carbon balance and so accounts for material elutriated from the bed as recommended by Saxena et al [3]. The percentage of carbon combustion efficiency was computed using Eq. 1 below:

$$E (\%) = (B + \text{unburned carbon in ash})/C \times 100\% \quad (1)$$

$B$  can be calculated by knowing flue gas composition, fractional excess air, and the ultimate analyses of fuel, while  $C$  of the raw feedstock is determined by elemental analysis only. Detail calculations for the above equation are given in the Appendix A.

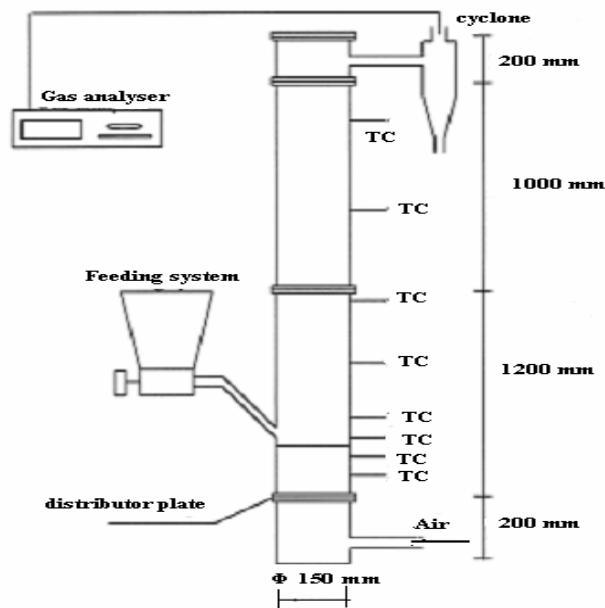


Fig. 1. A Schematic Diagram of the Laboratory Scale Fluidized Bed Combustor.

### 3. Results and Discussion

#### 3.1. Carbon combustion efficiencies

The combustion tests were performed using different coal mass fraction; 0, 50 and 100%, corresponding to heat input of 10 kW under optimum excess air conditions. Figure 2 shows the effect of different mixtures of RDF with coal on carbon combustion efficiency with the same heat input. Generally, Carbon combustion efficiency for single RDF is low but increases with increasing coal addition. The following carbon combustion efficiencies, from Eq. (1), range between 80-85% for burning 100% RDF and 82 - 86%, 82 - 88% and 87 - 92% for 30%, 50% and 70% of coal addition to RDF, respectively.

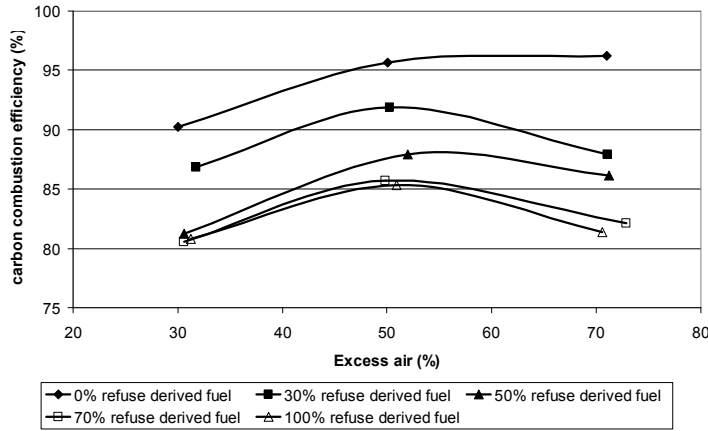


Fig. 2. Carbon Combustion Efficiency during Co-combustion of Coal with RDF as a Function of Excess Air.

The improved carbon combustion efficiency by co-combustion of RDF with coal can be attributed to an increase in bed temperature, Fig. 3, which is caused by the addition of fixed carbon content in the mixture. This fixed carbon, from coal, burns in the bed while the volatile gas burns in the freeboard region. Thus,

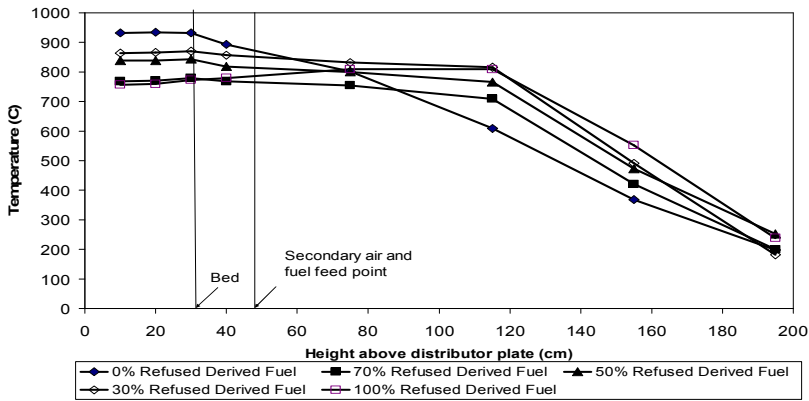
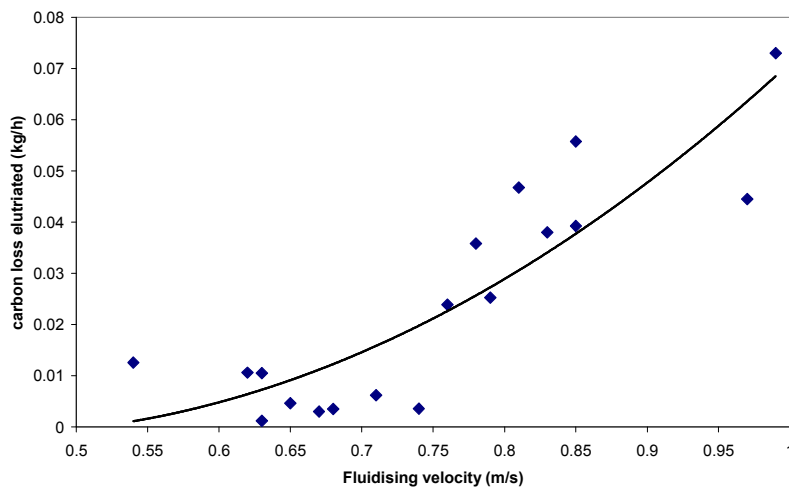


Fig. 3. Axial Temperature Profiles for Co-combustion of Coal with RDF Combustion in the Case of Excess air = 50%.

there is more chance for fuel conversion carbon to carbon dioxide as the coal fraction increases and less volatile and tend to escape combustion, because of the reduced biomass concentration [4]. In addition, increasing the fluidizing velocity increases the turbulence in the bed leading to better solid mixing and gas-solid contacting and so as the amount of carbon in the bed is burnt at higher rate. Consequently, higher carbon burn out obtained leads to higher carbon combustion efficiency. However, when the combustion is stabilized, increasing fluidizing velocity contributed to a greater particle elutriation rate than the carbon to CO conversion rate and hence increased the unburned carbon [4]. In addition, increasing the fluidizing velocity increases the turbulence in the bed burn in a faster rate. Consequently, higher carbon burn out leads to higher carbon combustion efficiency.

However, when the combustion is stabilized, increasing the fluidizing velocity contributes to a greater particle elutriation rate than carbon to carbon monoxide conversion rate and increases the amount of unburned carbon. This phenomenon can be seen in Fig. 2 where the carbon combustion efficiency is lower than expected for 50% RDF mixtures when the fluidizing velocity increases beyond the optimum value. Apart from solid mixing, increasing the fluidizing velocity also influences the fuel particle settling time during the combustion process in the FBC. Increasing fluidizing velocity drives the lighter fuel particles upwards and into the freeboard region, which is indicated by higher freeboard temperatures. Thus, the settling time for the biomass to reach the bed will be greater and a significant portion of the combustion will be completed before the particles return to the bed is reached, although this is dependent upon fuel particle size and density. This settling time depends on the fuel particle size and particle density. This phenomenon is verified in Fig. 4 where the carbon loss elutriated in their ash increases significantly with increases fluidizing velocities. Also, the greater settling time the higher the freeboard temperature due to greater volatile combustion contributing to higher combustion efficiency providing the bed temperature is maintained within the range of 800 - 900°C.



**Fig. 4. The Influence of Fluidising Velocity on Carbon Loss Elutriated during Co-combustion.**

### 3.2. Temperature profiles

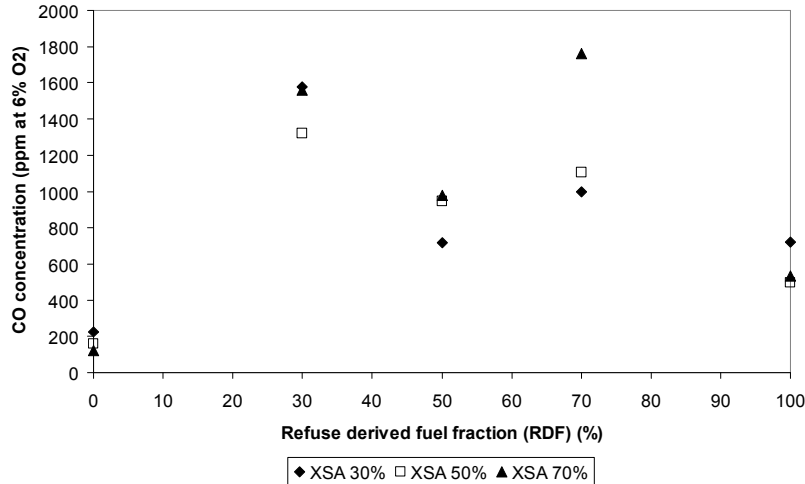
Figure 3 illustrates the axial temperature distributions along the FBC height for fuel studied at 50% excess air. As can be seen from the figure, coal combustion gives higher bed temperature ( $y = 0 - 40$  cm) but lower freeboard temperature ( $y = 450 - 120$  cm) in comparison to biomass. Then, all the temperatures shows start to fall from 120 cm above distributor plate indicating that most of the combustion was completed. This significant combustion behavior can be explained by the devolatilization process of the fuel [5]. With high volatility (more than 50%) and low ignition temperature (250 - 350°C), RDF will start to devolatilize upon feeding at 45 cm of the FBC height (freeboard region) and was mostly burned before it reached the bed region. While coal with low volatility (30%) and higher ignition temperature (400 - 600°C) will travel down to the bed and completed combustion in the bed region. This was also greatly influenced by settling velocity of the fuel particles which correspond to the fuel particle size and fluidizing velocity [4].

Significant increment of carbon combustion efficiencies was noted with coal addition to biomass fraction (see Fig. 2). The improvement can be attributed to an increase in bed temperature, Fig. 3, which is caused by the addition of fixed carbon content in the mixture. This fixed carbon, from coal, burns in the bed while the volatile gas burns in the freeboard region. Thus, there is more chance for fuel conversion carbon to carbon dioxide as the coal fraction increases and less volatile and tend to escape combustion, because of the reduced biomass concentration. Furthermore, this can be explain by the fact that biomass fuels with lower density (about half) compared to coal tend to burn in freeboard and coal tends to burn in the bed region. Therefore, the addition of coal in RDF increases the amount of fixed carbon reaching the bed resulting in higher bed temperatures. This observation agrees with the results of Abelha et al [6] who investigated the co-firing of coal and chicken litter and co-firing of lignite with municipal solid waste in a fluidised bed combustor.

### 3.3. Carbon monoxide (CO) reading

In order to enable comparison of CO from all tests were converted to CO emitted 6% flue gas oxygen. It is evident from Fig. 5 that there are significant fluctuations in CO emissions, which between 200 and 900 ppm under the same conditions. The orders of fluctuation were similar to those observed by Sami et al [5] and Abelha et al [6]. The fluctuations are caused by slight variations in feed composition and this effect is reflected in the temperature profiles. It is noted that the addition of coal has no significant influence on CO emissions during all co-combustion cases, except at coal (50%):RDF (50%) where emissions tend to be lower than expected in reference to the other RDF fractions. This phenomenon is due to the synergistic nature of the coal and RDF mixture, which enhances the fuel reactivity and lowers the CO emissions [7]. In most cases the emission of CO seems relatively insensitive to changes in excess and fluidising air. This insensitivity to increase excess air due to increased segregation of fuels in the combustor between the feed point and the bed. If the combustor receives a batch with a relatively high amount of fuel pellets, then as burning CO<sub>2</sub> is produced since the pellets need

to be heated and dried first. While this occurs, oxygen is not consumed and results in high CO emissions. The decrease in CO levels at low percentages of excess air, not below than 50%, can be attributed to low excess air, relatively high bed temperatures (about 900°C) causing rapid enhances and ignition of volatiles from RDF. Thus, higher CO to CO<sub>2</sub> conversion rates and enhancing the reactivity of the mixture [4].



**Fig. 5. CO Emissions as a Function of Excess Air and Rice Husk Fraction Combustion at Heat Input 10 kW.**

#### 4. Conclusions

The fluidized bed combustor was found to be capable of co-firing a mixture of refused derived fuel with coal (up to 70%) with comparable carbon combustion efficiency (up to 90%) and within acceptable carbon monoxide emissions limit (<2500 ppm). The combustion behavior of those mixtures was found to be different from burning single coal. Generally, most co-firing cases have both higher bed and freeboard temperature which resulted higher combustion efficiency. In this case, each fuel will compensate each other and burnt more efficient. Furthermore, other parameters such as fluidizing velocity and excess air have pronounced effect on the combustion efficiencies but not the emissions level. The mixture of refuse derive fuel burnt successfully at 50 % excess air where fluidizing air ranging from 1.2-1.4 m/s.

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## Appendix A

### Carbon Combustion Efficiency Calculation

This method is particularly appropriate for solid fuels and is described as follows: Let C, H, O, N, and S be the mass fractions of carbon, hydrogen, oxygen, nitrogen and sulphur, respectively, in the feed. Further, let *A* and *B* be the mass fractions of unburned and burnt carbon, respectively, in the fuel. Then,

$$A + B = C \quad (\text{A-1})$$

Further define

$$P = \frac{\text{C converted to CO}}{\text{C converted to CO} + \text{CO}_2} = \frac{\text{C converted to CO}}{B} \quad (\text{A-2})$$

$$\text{C converted to CO} = PB \quad (\text{A-3})$$

$$\text{C converted to CO}_2 = (1-P)B \quad (\text{A-4})$$

$$\text{Mass of CO}_2 \text{ in the flue gas} = (44/12)(1-P)B \quad (\text{A-5})$$

$$\text{Mass of CO in the flue gas} = (28/12)PB \quad (\text{A-6})$$

$$\text{O}_2 \text{ consumed to produced CO}_2 + \text{CO} = (32-16P)B/12 \quad (\text{A-7})$$

Assuming that H, N, and S present in the fuel are completely converted to H<sub>2</sub>O, NO and SO<sub>2</sub> respectively,

$$\text{O}_2 \text{ consumed} = (16/2)H + (16/14)N + (32/32)S = X_1 \quad (\text{A-8})$$

$$\text{SO}_2 \text{ produced} = (64/32)S \quad (\text{A-9})$$

$$\text{NO produced} = (30/14)N \quad (\text{A-10})$$

Therefore, total O<sub>2</sub> required for stoichiometric combustion of fuel

$$(32/12)C + (16/2)H + (16/14)N + (32/32)S - O = X_2 \quad (\text{A-11})$$

Let  $Z$  be the fractional excess air supplied, which is defined as the excess air divided by the stoichiometric air. Therefore,

$$\text{O}_2 \text{ supplied} = X_2(1+Z) \quad (\text{A-12})$$

$$\text{Mass of N}_2 \text{ in the flue gas} = (79/12)(28/32) X_2(1+Z) \quad (\text{A-13})$$

$$\text{O}_2 \text{ consumed during combustion} = (32-16P)B/12 + X_1 \quad (\text{A-14})$$

$$\text{Mass of O}_2 \text{ in the flue gas} = X_2(1+Z) - (32-16P)B/12 + X_1 \quad (\text{A-15})$$

Let  $F$  be the mass of dry flue gas can also be estimated from the flue gas composition. The flue gas flow rate and composition are not appreciably influenced by neglecting the presence of  $\text{SO}_2$  and  $\text{NO}$  in the flue gas. Hence the flue gas may be taken as consisting of  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{N}_2$  and  $\text{O}_2$ . Let  $Y$  be the mass of dry flue gas per unit mass of  $\text{C}$  burnt in the fuel. Then,

$$Y = \{44[\text{CO}_2] + 32[\text{O}_2] + 28[\text{N}_2]\} / 12\{[\text{CO}] + [\text{CO}_2]\} \quad (\text{A-16})$$

The square brackets represent the volume fraction of the particular chemical species in the flue gas and  $Y$  can be simplified to

$$Y = \{4[\text{CO}_2] + [\text{O}_2] + 7\} / 3\{[\text{CO}] + [\text{CO}_2]\} \quad (\text{A-17})$$

By substituting

$$[\text{CO}] + [\text{N}_2] + [\text{CO}_2] + [\text{O}_2] = 1$$

mass of dry flue gas per unit mass of the fuel is

$$F = YB \quad (\text{A-18})$$

Substituting  $F$  in Eq. (A-18) into Eq. (A-17), the fraction of  $\text{C}$  burnt,  $B$ , can be written as follows:

$$B = [4.29(1+Z)[(32/12)C + (16/2)H + (16/4)N + (32/32)S - O] - 8H + N + S / (Y-1) \quad (\text{A-19})$$

$$E = (B + \text{Unburned carbon in ash}) / C \times 100\% \quad (\text{A-20})$$