Sustainable Power Generation Through Co-Combustion of Agricultural Residues with Coal in Existing Coal Power Plant

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Additional information is available at the end of the chapter

1. Introduction

Waste-to-energy is gaining more and more attention as landfill costs and environmental concerns increase in many developed countries including Malaysia. Biomass from agricultural residues is one of the most important sources of renewable energy in Malaysia. The National Biofuel Policy, launched in 2006 encourages the use of environmentally friendly, sustainable and viable sources of biomass energy. Under the Five Fuel Policy, the government of Malaysia has identified biomass as one of the potential renewable energy. Malaysia produces at least 168 million tonnes of biomass, including timber and oil palm waste, rice husks, coconut trunk fibres, municipal waste and sugar cane waste annually. Being a major agricultural commodity producer in the region Malaysia is well positioned amongst the ASEAN countries to promote the use of biomass as a renewable energy source.

Combustion of agricultural residues is commonly used in industries for energy recovery. However, many researchers found that stand alone biomass firing is difficult to get high efficiency [1-5]. Thus, co-firing biomass with coal in industrial and utility boilers could offer an alternative approach with improved combustion efficiency, lower-cost and reduced risk technology. Significant co-combustion potential for biomass and waste materials exists in all European Union (EU) countries and this is mirrored on a worldwide basis, creating a significant market for equipment and services. Fluidized bed combustion (FBC) technology has already proven highly efficient, economic and environmentally sound combustion of a wide variety of fuels in comparison conventional combustors. Hence, with the current demands in electricity and with the recent developments in biomass energy, co-combustion of bio-

mass with coal must be recognized as one of the most important source of energy for the foreseeable future.

1.1. Biomass as potential renewable resources

A recent study shows that Malaysia has been one of the world's largest producers and exporters of palm oil for the last forty years. The Palm Oil industry, besides producing Crude Palm Oil (CPO) and Palm Kernel Oil, produces Palm Shell, Press Fibre, Empty Fruit Bunches (EFB), Palm Oil Mill Effluent (POME), Palm Trunk (during replanting) and Palm Fronds (during pruning). Almost 70% of the volume from the processing of fresh fruit bunches (FFB) is removed as waste.Malaysia has approximately 4 million hectares of land under oil palm plantation. Over 75% of total area planted is located in just four states, Sabah, Johor, Pahang and Sarawak, each of which has over half a million hectares under cultivation. The total amount of processed FFB was estimated to be 75 million tons while the total amount of EFB produced was estimated to be 16.6 million tons. Around 58 million tons of POME is produced in Malaysia annually, which has the potential to produce an estimated 15 billion m^3 of biogas can be produced each year [6].

Rice husk is another important agricultural biomass resource in Malaysia with good potential for power cogeneration. An example of its attractive energy potential is biomass power plant in the state of Perlis which uses rice husk as the main source of fuel and generates 10 MW power to meet the requirements of 30,000 households. The US$15 million project has been undertaken by Bio-Renewable Power Sdn. Bhd in collaboration with the Perlis state government, while technology provider is Finland's Foster Wheeler EnergiaOy. Under the EC-ASEAN Cogeneration Program, there are three ongoing Full Scale Demonstration Projects (FSDPs) – TitiSerong, Sungai Dingin Palm Oil Mill and TSH Bioenergy – to promote biomass energy systems in Malaysia. The 1.5MW TitiSerong power plant, located at Parit Buntar (Perak), is based on rice husk while the 2MW Sungai Dingin Palm Oil Mill project make use of palm kernel shell and fibre to generate steam and electricity. The 14MW TSH Bioenergy SdnBhd, located at Tawau (Sabah), is the biggest biomass power plant in Malaysia and utilizes empty fruit bunches, palm oil fibre and palm kernel shell as fuel resources [7].

1.2. Fluidised Bed Combustion (FBC) technology

Fluidised bed combustion technology is one of the most significant recent developments in both coal and biomass incineration over conventional mass burning incinerator designs. This technology has been accepted by many industries because of its economic and favourable environmental consequences.

The major advantages of fluidized bed combustors are [8,9]:

• Uniform temperature distribution due to intense solid mixing (no hot spots even with

• strongly exothermic reactions

• High combustion efficiencies

• FBC systems have a very short residence time for their fuels (making these systems

- highly responsive to rapid changes in heat demand).

- Large solid–gas exchange area by virtue of the small solids grain size

- High heat-transfer coefficients between bed and the heat exchanging surfaces; the

- intense motion of the fluidized bed makes it possible to combust a wide range of fuels

- having different sizes, shapes, moisture contents and heating values.

- The fuel supplied can be either wet or dry

- The high heat capacity of the fluidized bed permits stable combustion at low tempera-tures (i.e. 850°C), so that the formation of thermal and prompt nitrogen oxides is sup-pressed

Sets against these advantages are the following disadvantages:

- Solid separation equipment required because of solids entrained by fluidizing gas result-ing in a high dust load in the flue gas;

- Possibility of de-fluidization due to agglomeration of solids;

1.3. Combustion studies

Fluidized bed combustion of alternative solid fuels (including biomass) are attractive as a result of the constantly increasing price of fossil fuels, the presence of high quantities of wastes to be disposed of and global warming issues. Extensive experimental investigation has been carried out to date on the feasibility and performance of different biomass fuels FB combustion such as rice husk [10-13], animal waste [14-15], municipal solid waste (MSW) [16-19] and Refuse Derived Fuel (RDF) [5]. In whatever form biomass residues are fired (loose, baled, briquettes, pellets), a deeper understanding of the combustion mechanisms is required in order to achieve high combustion efficiency and to effectively design and oper-ate the combustion systems. The combustion properties and their effect on combustion mechanisms are all important information required to understand the combustion charac-teristics of biomass residues and their co-combustion with coal in FBC.

In general when a single coal or biomass particle enters a fluidised bed furnace, then three phenomena occur namely [20-22]:

- Heating up and drying – the fuel particle temperature will rise to its ignition temperature and beyond

- Devolatilization (pyrolysis) – for a short period of time (<10 second), volatile matter will be evolved and can be burnt at or beyond the particle.

- Char oxidation – the remaining solid combustible matter (mostly carbon), will be oxidised relatively slowly with the evolution of heat until only incombustible ash remains.

Fuel properties and combustion operating parameters significantly influenced the combus-tion efficiency and emissions. Armesto et al (2002) has stated that the bed temperature has

an effect on combustion efficiency, which improves from 97% to 98% as bed temperature increased from 840 to 880°C. Also, they found that the efficiency increased with decreasing fluidising velocity. They claimed that when fluidisation velocity increased above 1.0 m/s, the combustion efficiency decreased. This behaviour was attributed to an increase in the elutriation of unburned carbon. On the contrary, Suthum (2000) found that the combustion efficiency increased from 88% to 92% with increasing excess air up to 30% during combustion of oil palm waste in a 10 kW FBC with over-bed feeding. Saxena et al., 1993 reported similar results. It was suggested that there is an optimum balance between the carbon to CO conversion rate and increased elutriation with high excess air [22]. Furthermore, Fahlstedt et al (1997) performed a series of tests on co-firing wood chips, olive pit and palm nut shell with coal in 1MW FBC facility. It was noted that the co-combustion had a slightly higher carbon combustion efficiency based on flue gas emissions (97.2 -98.1%) than coal-only combustion (97.1%) [22]. The reason is likely due to the higher volatile matter content of the biomass fuels. Increased volatile matter will also increase the fuel reactivity and hence reduce the unburned carbon. In contrast, a decrease in combustion efficiency was obtained by Armesto et al (2003) and Suksankraison et al (2004) during co-combustion of Lignite-olive waste and Lignite-MSW mixture, respectively, even though the volatility of the fuel used quite similar (60-70% VM). The decrease was mainly attributed to a drop in the bed temperature. Since most fixed carbon generally burns in the bed while the volatile gas burns in the freeboard, there is insufficient chance for CO conversion to CO_2. As the freeboard temperature is maintained at a higher value, devolatilisation occurred rapidly and produced more volatile gases. As the biomass fraction increased, the reduced fixed carbon gives more chance for the volatiles to escape combustion.

Significant fluctuations of CO emissions were reported during co-combustion of biomass in a FBC. The value of the CO concentration in the flue gas has been found to depend on the type of fuel, fuel properties (volatility, particle size and density) and the operating conditions (bed and freeboard temperature, excess air, secondary air). In addition to the expected immediate ignition and the high volatile matter contents, the volatiles consist mainly of the combustibles (CO, H_2, CxHy). These factors together indicate that the combustion of the volatiles would be the dominant step during the biomass combustion. At higher temperatures, the combustibles (CO, H_2, CH_4) accounted for more than 70–80 % of the gas components [23]. Saxena et al (1994) found that the hydrodynamic activity in the bed is related to the solid mixing and gas-solids contacting and these in turn are directly related to CO emissions. Higher bed temperature seems to provide optimum conditions for rapid de-volatilisation and hence increased conversion CO to CO_2 [19]. They found that in the turbulent regime, the carbon utilisation efficiency reached a maximum and a further increase in the fluidisation velocity had an insignificant influence on the bed hydrodynamics and hence CO emissions. Similarly, as most of the biomass combustion was observed to take place in the freeboard, the supply of oxygen to this zone in amounts sufficient to achieve satisfactory combustion had to be ensured. Furthermore, Sami et al (2001) found that if the level of CO was within acceptable limits, then approximately 10% excess air and a temperature of 650°C provided optimum conditions for the combustion of manure in a fluidised bed unit [17].

However, there was a significant improvement in CO emissions, particularly when the air to the freeboard was introduced at different heights (air staging). The CO levels were brought down to about 60 mg/N m^3 at 11%O_2 in the flue gases, which is very close to what is permitted by EU directives; 50 mg/N m^3 at 11% O_2.The trends observed during single fuel combustion are reflected also in co-combustion: in the practically important cases with moderate amounts of biomass (an energy fraction of less than 25%) the properties of the base fuels dominate the emission obtained. Suksankraisorn et al (2004) reported that for 100% lignite combustion, CO drops significantly as excess air increases due to the increased CO to CO_2 conversion [16]. The emission of CO is relatively insensitive to changes in excess air and waste fraction, which further strengthen the argument that co-combustion is dominated by the combustion of the volatiles in the freeboard zone.

The feasibility of FBC technologies has been widely demonstrated for the combustion of a variety of fuels. As a drawback, severe problems of agglomeration in the bed as well as fouling and slagging may sometimes occur, especially during combustion of biomass fuels as some agricultural residues have high contents of alkali oxides and salts, the low melting points of which may lead to various problems during combustion. Werther et al (2000) encountered the problems of sintering and agglomeration during the combustion of coffee husks in a 150 mm diameter fluidized bed combustor [24].

1.4. Problem statement

Although there are many potential benefits associated with co-combustion, there are several combustion related concerns associated with the co-combustion of coal and biomass. Utilization of solid biomass fuels and wastes sets new demands for boiler process control and boiler design, as well as for combustion technologies, fuel blend control and fuel handling systems. For example, the different mineral matter composition (high alkali levels) and mode of occurrence (mostly mobile forms) in biomass results in concerns over enhanced fouling and slagging of pulverized coal boilers, particularly when firing agricultural residues or herbaceous materials. The economics of co-combustion in pulverized coal boilers are closely tied to the biomass preparation costs (i.e. drying and milling), so an improved understanding of the effect of biomass particle size and moisture content on combustor performance is needed (e.g. in the areas of flame stability, flame shape, and carbon burnout).Thus, this research was carried out with the objective to characterise biomass properties that affect the co-combustion of biomass with coal, in particular biomass that is available in large quantities in Malaysia.

1.5. Research scope and application

This research was performed with the objective to determine the combustion efficiency of the existing coal-fired combustor during co-firing agricultural residue with coal. The efficiency is calculated mainly based on the carbon monoxide and carbon dioxide emissions. Furthermore, this works also to demonstrate the technical feasibility of a fluidized bed as a clean technology for burning agricultural residues. In addition, the effect of biomass properties such as such as particle size, particle density and volatility as well as influences of oper-

ating parameters such as excess air, fluidizing velocity on axial temperature profile, the combustion efficiencies and CO emissions are also being investigated.

2. Materials and experimental

2.1. Raw materials and characterizations

In this study British coal, rice husk and palm kernel shell originated from Perlis were employed as fuel. These fuels were open air dried for 2 to 3 days to remove moisture. The proximate and ultimate analyses were performed on coal and rice husk are summarized in Table 1.

	British Coal	Palm Kernel shell	Rice Husk
Proximate Analysis (wt % dry basis) Volatile matter	58.90	18.60	15.00
Fixed carbon	38.20	72.50	60.70
Ash	2.90	8.90	24.30
Ultimate Analysis (wt % dry basis)			
Carbon	80.10	49.5	36.20
Hydrogen	5.30	6.74	5.71
Nitrogen	0.90	1.85	0.10
Sulfur	0.70	0.00	0.00
Oxygen	13.00	41.91	57.99
Calorific value (MJ/kg)	31.1	18.0	13.5
Particle size (mm)	1.4-4.8mm	3x6 mm	0.8x1.00 mm
Particle density (kg/m^3)	1200	435	98

Table 1. Coal and biomass characterization

2.2. Experimental set up and procedures

Figure 1, is a schematic diagram of the Atmospheric Fluidised Bed combustor used in this investigation. The system comprises of a 0.15m diameter and 2.3m high combustion chamber, allows for bed depths of up to 0.3m using 850μm 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_2 were measured using a Xentra 4904 B1 continuous emissions analyzer, whereas CO_2 was measured using a non-dispersive infrared absorption spectrometry analyser. A fly ash sample was collected from the catch pot after finishing the combustion run. The fly ash sample was then weighed and analysed to determine the total amount of unburned carbon of the fuels in the test. The percentage of combustion efficiency was computed using Equation 1. Based on the values of combustion efficiency from experiments where duplicate runs were conducted under almost identical conditions, the combustion efficiency values should be within ±2%.

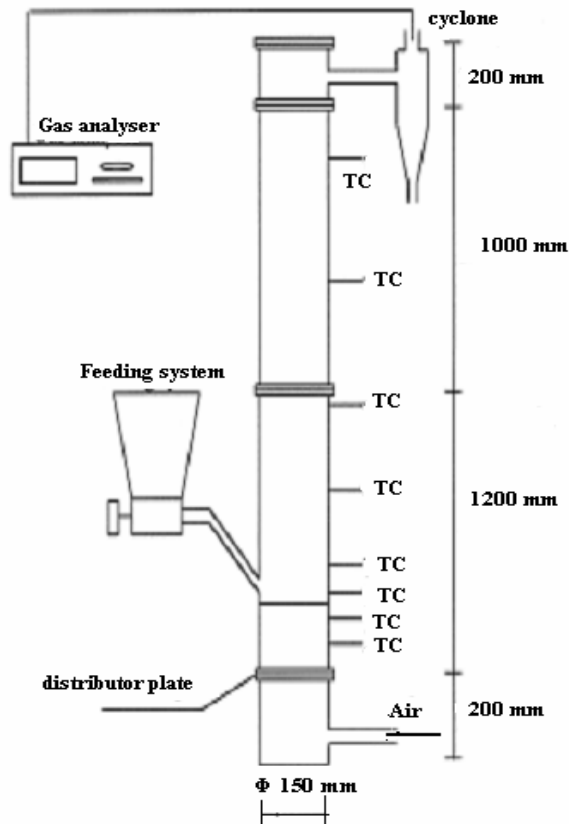**Figure 1.** Schematics diagram of the laboratory scale fluidized bed combustor (Tc =Thermocouple).

2.3. Operating conditions

In this experiment, baseline data was first obtained for single combustion of 100% British bituminous coal. Also, single combustion of other biomass fuels was carried out to investigate their combustion characteristics in comparison to coal during the co-combustion study. Co-combustion tests at biomass fractions of 30%, 50%, and 70% were performed. For each biomass fraction, excess air was varied from 30% to 70% at 20% intervals. For each excess air condition, air staging combustion was applied where the total secondary air is maintained at 65 l/min (about 10-20% to total air ratio). In order to study the impact of fuel property changes (volatiles, ash, and combustibles), heat input was fixed at the design value of the experimental rig i.e. 10 kW. The combustion tests were operated in the bed temperature range of 700-950 °C and superficial velocity range of 0.63 – 1.12 m/s.

2.4. Carbon combustion efficiency calculation

The carbon combustion efficiency of a system has been expressed as:

$$\eta CE = \frac{B}{C} x 100\% \tag{1}$$

where B and C are *the mass fractions of burnt and total carbon in the fuel*, respectively. Knowing the flue gas composition, the flue gas composition, fractional excess air and the fuel ultimate analyses of the fuel, B can be determined [20].

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,

$$A + B = C \tag{2}$$

Further define

$$P = \frac{C \ converted \ to \ CO}{C \ converted \ to \ CO \ + CO_2} = \frac{C \ converted \ to \ CO}{B} \tag{3}$$

$$C \ converted \ to \ CO \ = \ PB \tag{4}$$

$$C \ converted \ to \ CO_2 = (1 - P)B \tag{5}$$

$$Mass \ of \ CO_2 \ in \ the \ flue \ gas \ = \left(\frac{44}{12}\right)(1 - P)B \tag{6}$$

$$Mass\ of\ CO\ in\ the\ flue\ gas = (28/12)PB \tag{7}$$

$$O_2\ consumed\ to\ produced\ CO_2\ +\ CO = (32 - 16P)B/12 \tag{8}$$

Assuming that H, N, and S present in the fuel are completely converted to H_2O, NO and SO_2 respectively,

$$O_2\ consumed = (16/2)H\ +\ (16/14)N\ +\ (32/32)S = X1 \tag{9}$$

$$SO_2\ produced = (64/32)S \tag{10}$$

$$NO\ produced = (30/14)N \tag{11}$$

Therefore, total O_2 required for stoichiometric combustion of fuel

$$(32/12)C\ +\ (16/2)H\ +\ (16/14)N\ +\ (32/32)S\ -\ O = X2 \tag{12}$$

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

$$O2\ supplied = X2(1+Z) \tag{13}$$

$$Mass\ of\ N2\ in\ the\ flue\ gas = (79/12)(28/32)\ X2(1+Z) \tag{14}$$

$$O2\ consumed\ during\ combustion = (32 - 16P)B/12\ +\ X1 \tag{15}$$

$$Mass\ of\ O2\ in\ the\ flue\ gas = \left(X2(1+Z) - \frac{(32 - 16P)B}{12}\ +\ X1 \right. \tag{16}$$

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 SO_2 and NO in the flue gas. Hence the flue gas may be taken as consisting of CO, $CO2$, N_2 and O_2.

Let Y be the mass of dry flue gas per unit mass of C burnt in the fuel. Then,

$$Y = \{44[CO_2]\ +\ 32[O_2]\ +\ 28[N_2]\}/12\{[CO]\ +\ [CO_2]\} \tag{17}$$

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

$$Y = \{4[CO_2]\ +\ [O_2]\ +\ 7\}/3\{[CO]\ +\ [CO_2]\} \tag{18}$$

By substituting

$$[CO] + [N_2] + [CO_2] + [O_2] = 1 \qquad (19)$$

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

$$F = YB \qquad (20)$$

Substituting F in (A-6.18) into (A-6.17), then the fraction of C burnt, B, can be written as follows:

$$B = \frac{\left[4.29(1+Z)\left[\left(\frac{32}{12}\right)C + \left(\frac{16}{2}\right)H + \left(\frac{16}{4}\right)N + \left(\frac{32}{32}\right)S - O\right] - 8H + N + S\right]}{Y - 1} \qquad (21)$$

$$\eta CE = (B(21) + Unburned\ carbon\ in\ ash) / C \times 100\% \qquad (22)$$

3. Results and discussion

This section describes the combustion of agricultural residue in a fluidized bed combustor. The influences of fuel properties such as particle size, particle density and volatility as well as influences of operating parameters such as excess air, fluidizing velocity on axial temperature profile, the combustion efficiencies and CO emissions are discussed.

3.1. Carbon combustion efficiencies

The combustion tests were performed using different coal mass fraction; 0, 50 and 100%, corresponding to heat input of 10kW under optimum excess air conditions. Figure 2 shows the effect of different mixtures of rice husk and palm kernel shell with coal on carbon combustion efficiency with the same heat input. Generally, Carbon combustion efficiency for single biomass (rice husk and palm kernel shell) but increases with increasing coal addition and experimental runs. The following carbon combustion efficiencies, from Eqn. (1), range between 67-75% for burning 100% rice husk and 80-83% for burning 100% palm kernel shell, 83-88%, and 86-92% for 50% of coal addition to rice husk and palm kernel shell, respectively. The improved carbon combustion efficiency by co-combustion of rice husk with coal can be attributed to an increase in bed temperature, Figure 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 [16].

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 [5]. 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 Figure 2 where the carbon combustion efficiency is lower than expected for 50% rice husk 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. 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.
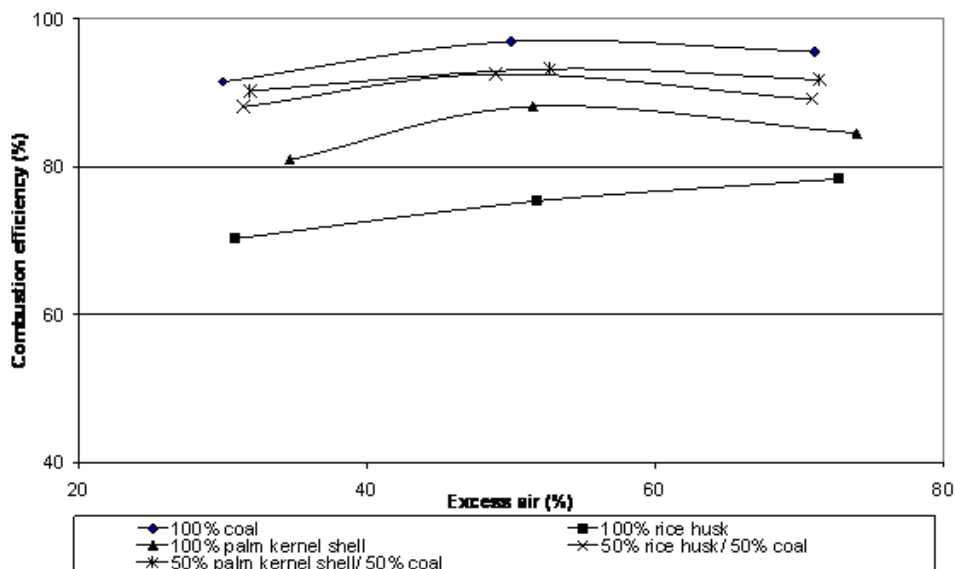

Figure 2. Combustion efficiency during co-combustion of coal with rice husk and palm kernel shell

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 = 0-40cm) but lower freeboard temperature (y = 450-120cm) 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 behaviour can be explained by the devolatilization process of the fuel [17]. With high volatility (more than 50%) and low ignition temperature (250-350°C), biomass (rice husk and palm kernel shell) 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 [5]. Those explain why palm kernel shell has higher bed temperature than rice even though the volatility is almost similar (see Table 1).This was due to the fact that greater particle size contributed to a greater devolatilization time and settling time. 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.
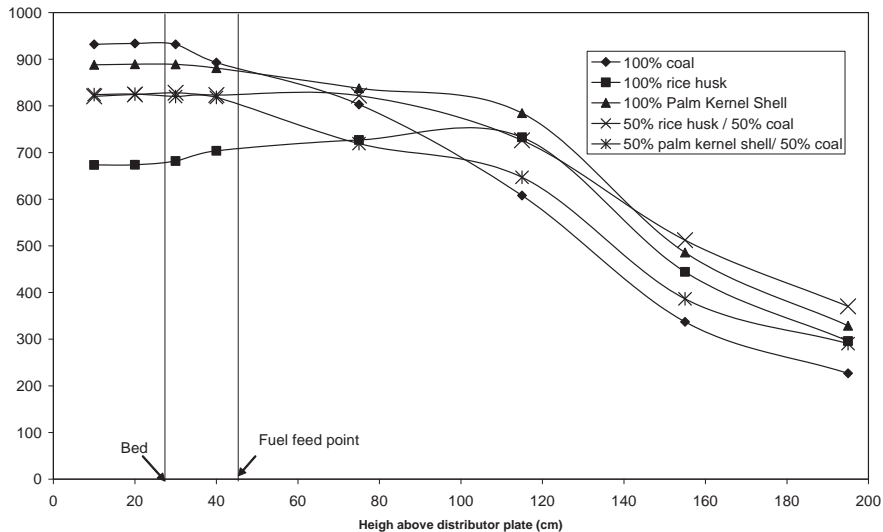

Figure 3. Axial temperature profile for co-combustion of coal with rice husk and palm kernel shell combustion in the case of excess air = 50%

Significant increment of carbon combustion efficiencies was noted with coal addition to bio-mass fraction (see Figure 2).The improvement can be attributed to an increase in bed tem-perature, Figure 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 biomass increases the amount of fixed carbon reaching the bed resulting in higher bed temperatures. This observation agrees with the results of Abelha et al. (2003) and Suksankraisorn et al. (2003) who investigated the co-firing of coal and chicken litter and co-firing of lignite with municipal solid waste in a flui-dised bed combustor, respectively.

3.3. Carbon monoxide (CO) emissions

In order to enable comparison of CO from all tests were converted to CO emitted 6% flue gas oxygen. Figure 4, it is evident 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 Abelha et al. (2003) and W.A.W.A.K. Ghani et al. (2009). 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%) / rice husk (50%) where emissions tend to be lower than expected in reference to the other rice husk fractions. This phenomenon is due to the synergistic nature of the coal and rice husk mixture, which en-hances the fuel reactivity and lowers the CO emissions [10]. In most cases the emission of CO seems relatively insensitive to changes in excess and fluidising air. This insensitivity is 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_2 is produced since the pellets need to be heated and dried first. While this occurs, oxy-gen is not consumed and results in high CO emissions. The decrease in CO levels at low per-centages 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 rice husk. Thus, higher CO to CO_2 conversion rates was observed which enhanced the reac-tivity of the mixture [13].

3.4. Analyses of carryover

Tables 2 and 3 present the ash collection and unburned carbon analyses during combustion tests. Generally, the mass balance on the ashes particles accounted for over 90% of the ash input from the fuel. The analyses of the ash collected in all tests for unburned carbon dem-onstrates that with biomass only, there was the least amount of unburned carbon detected in ash collected from the cyclone. However, the unburned carbon content increased when coal was added which suggested that some fine particles were elutriated with the fluidising gas-

es. The amount of unburned carbon was, however, quite low, corresponding to about less than 5% of the total carbon input. Such observations seem to suggest that the large particle size and lower heating value of the biomass fuel did not adversely affect combustor performance, probably due to the higher volatile matter content of the biomass fuel. The volatile matter burns rapidly and the higher volatile matter content of the biomass can also result in a highly porous char, thus accelerating the char combustion as well. In all cases the amount of unburned carbon in the ash increased as the percentage s of coal increased which is due to the low volatility of coal. For the biomass materials the low density of palm fibre and rice husk are also led to increased carbon content in the ash. The initial particle size of the biomass does not appear to be significant.
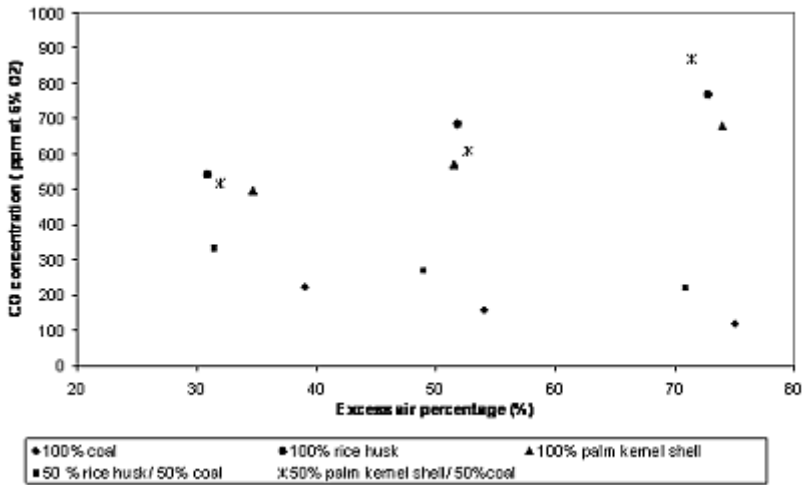

Figure 4. CO emissions as a function of excess air and Rice husk fraction combustion at heat input 10KW

Fuel	Feed (kg/h)	Superficial Velocity (m/s)	Carbon feed (kg/h)	Ash (kg)	**Carbon in Ash(%)**	Efficiency (%)
Coal (100%)	1.20	0.67	0.900	0.039	23.0	90.25
Rice husk (100%)	2.97	0.56	1.038	0.621	14.5	66.62
Coal (30%) : Rice husk (70%)	2.16	0.99	1.149	0.348	20.9	75.33
Coal (50%) : Rice husk (50%)	1.60	0.85	1.159	0.196	28.7	83.24
Coal (70%) : Rice husk (30%)	1.40	0.81	1.094	0.176	26.6	86.07

Table 2. Ash analysis for single and co-combustion of coal and rice husk at varies percentage of excess air

Fuel	Feed (kg/h)	Superficial Velocity (m/s)	Carbon feed (kg/h)	Ash (kg)	**Carbon in Ash(%)**	Efficiency (%)
Coal (100%)	1.20	0.67	0.900	0.039	23.0	90.25
Palm kernel shell (100%)	1.97	0.59	0.898	0.028	5.0	80.67
Coal (30%) : Palm kernel shell (70%)	1.74	0.74	0.949	0.030	11.7	80.73
Coal (50%) : Palm kernel shell (50%)	1.59	0.65	0.962	0.031	14.9	89.86

Table 3. Ash analysis for single and co-combustion of coal and palm kernel shell at varies percentage of excess air.

4. Conclusion

The conclusions obtained in the present investigation on the temperature profile, carbon combustion efficiency and CO emissions in a 10 kW FBC can be summarised as that biomass combustion behaves differently in comparison to coal due to the significant difference in volatile matter content and variations of particle size and particle density. The carbon combustion efficiency was influenced by the operating and fluidising parameters in the following order: a) settling velocity; b) coal mass fraction; c) fluidising velocity; d) excess air and e) bed temperature (Tb). The maximum carbon combustion efficiency increased in the range of 3% to 20% as the coal fraction increased from 0% to 70%, under various fluidisation and operating conditions. Generally, the carbon combustion efficiency increased with increases of excess air and peaks at 50%. The corresponding increasing carbon combustion efficiency with excess air from 30-50% was found to be in the range of 5 – 12 % at 50% coal mass fraction in the biomass mixture. Further increase of excess air to 70% reduced the carbon combustion efficiency. Increasing the fluidising velocity increases the turbulence in the bed leading to better solid mixing and gas-solid contacting and shows as the amount of carbon in the bed is burnt at higher rate. However, when the combustion is stabilised, increasing fluidising velocity contributed to a greater particle elutriation rate than the carbon to CO conversion rate and hence increased the unburned carbon. Apart from solid mixing, increasing fluidising velocity also influenced settling time of fuel particle during the combustion process in FBC. Increasing fluidising velocity brought the lighter fuel particle upward to the freeboard region and completed before they reached the bed surface.The bed temperature had a small effect on carbon combustion efficiency for the biomass fuels. The turbulence created by increasing excess air related with increases in fluidising velocity had a greater influence than reduced bed temperature. Significant fluctuations of CO emissions observed when coal was added into almost all biomass mixtures depending upon excess air ranges between 200-1500 ppm.The analyses of the ash collected in all tests for unburned carbon demonstrates that with biomass only, there was less unburned carbon detected in the ash collected from the cyclone indicating that the combustion of fixed carbon was almost complete. The percentages of unburned carbon increased in the range 3 to 30% of the ash content with the increases of coal fraction in the coal/biomass mixture. This can be explained by the fact that

as the coal fraction increased the higher char combustion and less volatiles combustion occurred. Moreover, the elutriated carbon loss increased as fluidising velocity increased resulting in the lower carbon combustion efficiency. On the contrary, it was found that the bed temperature had no strong influence on carbon loss during the tests.As a conclusion, the combination factors of operating parameters attributed to the resulting effects of biomass co-combustion.

5. Further research

As for further research work, the followings are suggested:

a. Modify the combustor to compare in-bed with overbed feeding of coal/biomass mixtures.

b. Investigate the effect of air staging on combustion.

c. Study the effect of bed temperature on combustion efficiency by having a cooling coil in the bed instead of using air flowrate.

d. To investigate the release of NO_x from coal/biomass mixtures. Although the nitrogen content of biomass is generally low the compounds have a lower molecular weight and are more volatile.

e. Investigate co-firing of a wide range of densified biomass fuels that are currently available with coal.

Abbreviations and nomenclature

CO= Carbon monoxide

ASEAN = Association of South East Asian Nations

EU= European Union

FBC= Fluidized bed combustor

MSW= Municipal solid waste

RDF= Refuse Derived Fuel

H_2=Hydrogen

CxHy= hydrocarbons

CH_4=methane

O_2= Oxygen

η_{CE}= Carbon combustion efficiencies

B = burnt carbon

C = Carbon

H = Hydrogen

N= nitrogen

S= sulphur

H_2O= water

NO = Nitrogen Oxide

SO_2= Sulfur dioxide

Z = fractional excess air supplied

F = mass of dry flue gas

Y = mass of dry flue gas per unit mass of C burnt in the fuel

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