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Combustion Characteristics of Refuse Derived Fuel (RDF) in a Fluidized Bed Combustor

(Ciri Pembakaran Bahan Api Janaan Sampah (RDF) di dalam Pembakar Lapisan Terbendalir)

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ABSTRACT

The combustion characteristics of refuse derived fuel (RDF) in a fluidized bed have been studied. The gross heating value (GHV) of the RDF was 14.43 MJ/kg with moisture content of 25% by weight. Parameters of interest for sustainable bed combustion were the fluidization number and primary air factor. The study was performed in a rectangular fluidized bed combustor with dimensions of 0.3 m in width, 0.7 m in length and 2 m in height. Sand with mean particle size of 0.34 mm was used as a fluidization medium. The sand bed height was at 0.3 m above the standpipes air distributor. The range of fluidization number under investigation was 5–7 U_{mf} *in which 5* U_{mf} *was found to be the optimum. The study was continued for the determination of the optimum primary air factor with the selected range of primary air factors being 0.6, 0.8, 1.0 and 1.2 in experiments conducted at 5* U_{mf}*. The final results showed that the optimum primary air factor was at 0.8. An energy balance was also performed to determine the thermal efficiency of the combustion. It was concluded that the thermal efficiency depended on the bed temperature and the primary air factor being used.*

Keywords: Air factor; fluidized bed combustor; fluidization number; operating parameter; refuse derived fuel (RDF); thermal efficiency

ABSTRAK

Ciri pembakaran bahan api janaan sampah (RDF) di dalam pembakar lapisan terbendalir telah dikaji. Nilai pemanasan kasar (GHV) bahan api tersebut adalah 14.43 MJ/kg dan mempunyai 25% berat kandungan air. Parameter yang dikaji untuk pembakaran lestari di dalam pembakar lapisan terbendalir adalah nombor pembendaliran dan faktor pengudaraan utama. Kajian dilakukan di dalam pembakar lapisan terbendalir bersegi empat bersaiz 0.3 m lebar, 0.7 m panjang dan 2 m tinggi. Pasir dengan saiz purata 0.34 mm telah digunakan sebagai medium perbendaliran. Ketinggian lapisan pasir adalah 0.3 m dari pengagih udara. Julat nombor pembendaliran yang dikaji adalah dari 5–7 U_{mf} *dan keputusan menunjukkan 5* U_{mf} *adalah nilai optimum. Kajian diteruskan bagi mendapatkan faktor pengudaraan utama optimum dengan nilai 0.6, 0.8, 1.0 dan 1.2 dan uji kaji dilakukan pada 5* U_{mf}*. Keputusan menunjukkan faktor pengudaraan utama yang optimum adalah 0.8. Kecekapan terma pembakaran tersebut diperoleh dengan pengiraan imbangan tenaga dan didapati bahawa kecekapan terma adalah bergantung kepada suhu lapisan pembakaran dan faktor pengudaraan utama yang digunakan.*

Kata kunci: Bahan api janaan sampah (RDF); faktor udara; kecekapan terma; nombor pembendaliran; parameter operasi; pembakar lapisan terbendalir

INTRODUCTION

There are two commonly used methods for the combustion of the municipal solid waste. Firstly using mass burn incinerator and secondly through the use of fluidized bed combustion system. An alternative to the mass burn approach is to separate the combustibles and incombustibles from the bulk of the raw municipal solid waste. The term refuse derived fuel (RDF) is used for the segregated high calorific value fractions of processed municipal solid waste. The processed municipal solid waste or RDF, is commonly used in fluidized bed combustors as the RDF has the advantages of low moisture content, higher calorific value, high storage capacity due to its compact size, easy to be transported and uniform combustion characteristics.

Studies of the combustion characteristics of high moisture content wastes have been carried out using samples derived from wet sludge, simulated municipal solid waste and mixed solid waste. The combustion characteristic of wet sludge in a fluidized bed has been reported by Ogada and Werther (1996). It was reported that the water content and volatile matter content influences the combustion behavior of the wet sludge. The effect of moisture content on the combustion of simulated municipal solid waste in a fluidized bed was investigated (Suksankraisorn et al. 2003). The fuel component was formulated from Thailand's major waste compositions. It was shown that the combustion of simulated municipal solid waste with 20% water content was not successful because the bed temperature dropped below than 600°C. The combustion efficiency was reduced with the increase in water content in the simulated municipal solid waste. Efforts have been made to simulate the municipal solid waste compositions in Malaysia according to their major compositions and combustion studies have been carried out to determine the optimum operating parameters, such as fluidization number and air factor (Johari et al. 2011). The moisture content of the mixed waste was 52.34% and the results showed that the fluidized bed combustion could not be sustained in the long run.

The high water content in municipal solid waste affects the combustion characteristics and several researchers have shifted their intention to the combustion studies of the segregated municipal solid waste or known as RDF. The combustion of RDF was carried out in a bubbling fluidized bed of a square column (Piao et al. 2000). Silica sand was used as a fluidization medium with a mean diameter of 0.3 mm and the minimum fluidization velocity, U_{mf} of 0.075 m/s. The bed temperature was controlled to be in the range of 800–1000°C. The total air ratio (air supplied to combustor/stoichiometric air) was conducted in the range of 1.1 to 2.4. The results showed that the freeboard temperature was higher than the bed temperature due to high volatile matter contents in the RDF. The temperature distribution in the combustor was slightly affected by changing the air ratio. It was also observed that the air ratio strongly affected the carbon monoxide (CO) concentration when air ratio was increased from 1.4 to 2.4, with the CO concentration decreasing at the higher air ratio. It was also found that secondary air injection resulted in a decrease in CO concentration. The combustion behavior and compositions of the flue gas from seven different types of RDF were investigated (Kobyashi et al. 2005). The chemical compositions and compounds ratio of the RDF were adjusted and manufactured from industrial wastes such as plastic waste, paint waste and domestic waste. It was found that the compositions of a RDF as well as the air ratio strongly affected the flue gas compositions. An investigation of the combustion efficiency of RDF has been carried out (Hernandez-Atonal et al. 2007). The mean sand size employed was 1.3 mm and the bed temperature was in the range of 700 – 1000°C. The air ratio used in the tests varied between 1.08 and 3.1. The results showed that the combustion efficiency was significantly increased at higher air ratio. It was also pointed out that gas temperature increased as the gas traveled up the freeboard region and the combustion efficiency was observed to increase at higher freeboard temperature. The introduction of secondary air also improved the combustion efficiency with a drop in the CO concentration.

In line with the issues mentioned above, the objective of this study were to investigate the combustion characteristics of RDF in a fluidized bed, with fluidization number ranges from 5 to 7 U_{mf} and primary air factor ranges from 0.6 to 1.2 for sustainable RDF combustion in a bubbling fluidized bed. In addition, the thermal efficiency of the combustion process was determined to quantify the heat released into the bed.

Materials and Methods

The study was aimed at obtaining the optimum fluidization number and primary air factor for sustainable combustion of the RDF in a bubbling fluidized bed. The range of fluidizing numbers for the bubbling bed was between the U_{mf} (minimum fluidizing velocity) and the U_t (terminal velocity). Beyond that, the particles were carried over past their transport disengaging height (TDH) and thus the operation falls into the circulating fluidized bed operation. The minimum fluidization velocity, U_{mf}, of sand sieve No. 30/60 was calculated at 0.09 m/s. The calculated range of fluidization numbers for a bubbling fluidized bed using sand sieve No. 30/60 (mean sand size of 0.34 mm) was from 1 U_{mf} to its terminal velocity at 15 U_{mf}. However, due to constraints in compressor power and current fluidized bed design, the range of fluidization numbers was chosen to be between 5 and 7 U_{mf}, which is in the middle range of the bubbling regime. Initially, each set of experiments was conducted at stoichiometric condition or air factor (AF) = 1. The result of the optimum fluidization number in experiments conducted at the AF = 1 was used as an input for the determination of the optimum primary air factor (air supplied to the combustor/stoichiometric air) for the sustainable combustion of the RDF. The tested air factors were AF = 0.6, AF = 0.8, AF = 1 and AF = 1.2. The RDF samples were obtained from a local manufacturing company. The properties of the RDF are shown in Table 1.

The calculation of stoichiometric air requirement is important for the determination of the nature of the burning process. H_2O, C, H, O, N and S represent the weight percent of moisture, carbon, hydrogen, nitrogen and sulphur in the RDF, respectively. The volume of the theoretical air requirement for complete combustion is calculated as follows (Rozainee 1998):

$$A_0 = 4.76 \times 22.4\, {}^{L}\!/\!{}_{mol} \left(\frac{gC}{12\, {}^{g}\!/\!{}_{mol}} + \frac{gH}{4\, {}^{g}\!/\!{}_{mol}} - \frac{gO}{32\, {}^{g}\!/\!{}_{mol}} + \frac{gS}{32\, {}^{g}\!/\!{}_{mol}} \right) \text{L(Normal)/100 g of RDF}$$
$$= 8.88C + 26.66H - 3.33O + 3.33S \text{ L(Normal)/100 g of RDF}. \tag{1}$$

Assuming that the nitrogen content in the RDF exerts no significant effect on the oxygen requirement for the combustion stoichiometry and the amount of sulphur in the RDF is negligible, the volume of the theoretical air required was thus calculated from the ultimate analysis. The ash content was 10%. Therefore 100 g of dry ash free (DAF) sample has the following composition; C = 56.56 g, H = 7.44 g and O = 29.67 g. Hence, substitution into (1) yielded the volume of theoretical air of 601.80 L (Normal)/100 g

TABLE 1. Properties of the RDF (dry basis)

Parameter	Content
Heating value, (GCV)	14.43 MJ/kg
Moisture content	25%
Ash content	10 wt. %
Volatile matter	90 wt. %
Carbon, C	50.9 wt. %
Hydrogen, H	6.7 wt. %
Oxygen, O	26.7 wt. %
Nitrogen, N	1.6 wt. %
Chlorine, Cl	0.25 wt. %
Sulphur, S	0.06 wt. %

of RDF. The air was supplied at room temperature (25°C), thus, amount of theoretical air required was 601.80 L × (298K/273K) or 656.91 L. Therefore, for the RDF feeding rate of 100 g/min, the theoretical air flow rate required was 656.91 l/min. The bed temperature was maintained at about 800°C throughout the experiment and due to the gas expansion in a hot combustion, the volume of air into the fluidized bed combustor was reduced by a factor of 0.28 (from 298K/1073K). Table 2 summarizes operating parameters for the combustion of RDF at 5, 6 and 7 U_{mf} conducted at stoichiometric condition, AF = 1.

The sand bed behaves like a heat source to maintain sufficient energy transfer for the combustion of the RDF. Hence, the ability of the sand bed to sustain the combustion at high temperature is very important. The outcome of the first stage of the study shows that operation at 5 U_{mf} resulted in the most stable bed temperature distribution in the fluidized bed. The findings are discussed in detail in later sections. Therefore, the second stage of the study was conducted at 5 U_{mf} and various air factors in the range of 0.6 to 1.2. Table 3 summarizes the feed and air inputs needed for different air factors in the combustion of the RDF.

The experimental rig was of a rectangular column and its operation was carried out at atmospheric pressure. The combustor was made of stainless steel 306 with dimensions as follows; 700 mm length, 300 mm width and 2000 mm in height. The fluidized bed combustor was insulated with thermal ceramic blanket to reduce heat loss to the surrounding. Fluidization air was introduced at the bottom of the bed through three air distributor pipes. The air distributors were equally positioned inside the bed. The orifice diameters were 3 mm and the distance between the orifices was 10 mm each. Air was supplied by air compressor and Ni/Cr type K thermocouples were positioned at various locations inside the combustor and monitored continuously throughout the experiments using a data logging system. Prior to the combustion tests, the fluidization medium (sand bed) was preheated to about 800°C. A schematic diagram of the fluidized bed combustor is shown in Figure 1.

An energy balance was conducted to determine the thermal efficiency of the combustion process carried out at 5 U_{mf} and different air factors. The thermal efficiency of the fluidized bed combustion is calculated by assuming a steady state conditions in which the rate of heat generated is equal to the heat removal. It is also assumed that the combustor operates adiabatically and the energy released in

TABLE 2. Operating parameters for the combustion of RDF at 5, 6 and 7 U_{mf} at AF = 1

Combustor dimension	0.7 m × 0.3 m		
Combustor cross sectional area, m^2	0.21		
Mean sand size, mm	0.34		
Sand bed height, mm	300 mm above air distributor		
Minimum fluidization velocity, U_{mf}, (m/s)	0.09		
Fluidization No.	5	6	7
Air velocity, m/s (at room temperature, 25°C)	0.45	0.54	0.63
Air flow rates (at room temperature), LPM	5670	6804	7938
Air flow rates (combustion study), LPM	1596	1921	2242
Feed rate, g/min	243	292	341
Feed rate, kg/h	14.58	17.52	20.46

TABLE 3. Feed and air inputs needed at 5 U_{mf} at different air factors (at room temperature, 25°C)

Fluidization No.	Air factor (AF)	Air low rate (l/min)	Stoichiometric air (l/min)	Fuel required (g/min)
5	0.6	2667	4445	406
	0.8	1997	2496	304
	1.0	1596	1596	243
	1.2	1334	1112	203

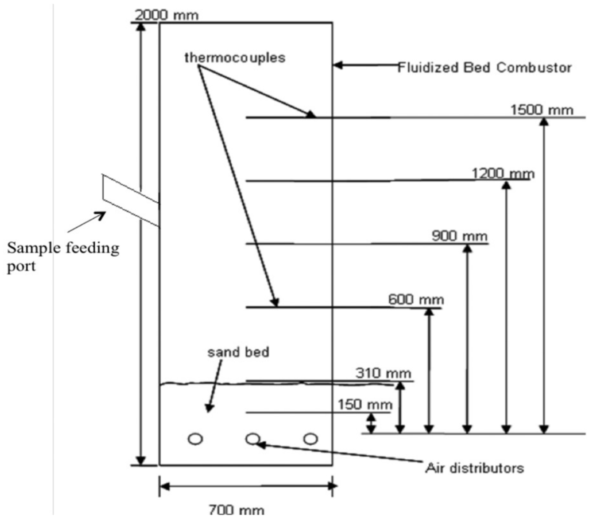

FIGURE 1. Schematic diagram of the fluidized bed combustor

the bed is used to heat up the RDF waste contents (moisture, volatile organic matters, char and ash) and the combustion air to reach the bed temperature. The schematic diagram for the steady state fluidized bed combustion is shown in Figure 2.

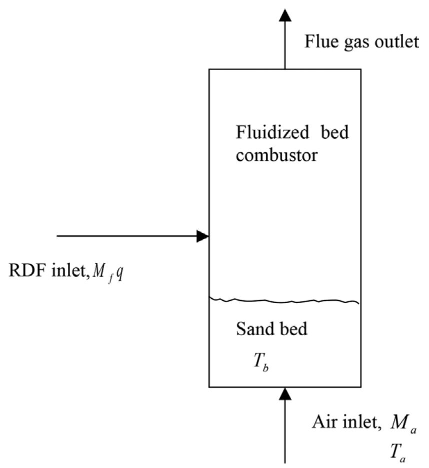

FIGURE 2. Schematic diagram of heat balance of a fluidized bed

The heat balance equation for the RDF combustion is as follows (Rozainee 1998);

$$M_f q = M_a C_{Pa}(T_b - T_a) + M_w \lambda + M_w C_{Pwv}(T_b - 100°C) + M_{ds} C_{Pds}(310°C - 100°C) + M_v C_{Pv}(T_b - 310°C) + M_{ca} C_{Pca}(T_b - 310°C), \tag{2}$$

where; q is the heat liberated per unit mass of RDF fed into the bed (J/g), M_a is the mass flow rate of air (g/min), M_f is the mass flow rate of RDF (g/min), M_w is the mass flow rate of water (g/min), M_v is the mass flow rate of volatiles (g/min), M_{ds} is the mass flow rate of dry RDF (g/min), M_{ca} is the mass flow rate of residual char and ash (g/min), λ is the amount of heat required to raise the moisture from ambient conditions to the boiling point and to evaporate the moisture, (J/g), C_{Pa} is the average heat capacity of air (J/g°C), C_{Pwv} is the average heat capacity of water vapor (J/g°C), C_{Pds} is the average heat capacity of dry RDF (J/g°C), C_{Pv} is the average heat capacity of volatiles (J/g°C), C_{Pca} is the average heat capacity of char and ash (J/g°C), T_b is the bed temperature (°C) and T_a is the inlet air temperature (°C).

The percentage of heat released into the bed (thermal efficiency), η_{TE},

$$\eta_{TE} = \frac{q}{HHV} X100, \tag{3}$$

where; q is the heat liberated/unit mass of RDF into the bed (J/g) and HHV is the gross calorific value of the RDF (J/g) in which water and solid coexist before the combustion.

Assumptions of the steady state heat balance are as follows; Particle drying – drying is an endothermic process and occurs when the temperature is about 100°C (moisture evaporation). The amount of heat required to raise the moisture from ambient conditions to the boiling point and to evaporate the moisture, λ, is 2572.83 J/g (Felder & Rousseau 2000). Particle pyrolysis – A typical temperature for pyrolysis initiation is about 310°C for RDF (Gullet & Vesilind 1985). Hence, the pyrolysis initiation temperature of the RDF is assumed at 310°C. The energy required to raise the dry RDF temperature to the reaction temperature depends on the heat capacity of the RDF, Cp_{ds} (Tillman 1991). It is assumed that the volatiles released from the particles are heated up to the bed temperature and depends on the average heat capacity of volatiles, Cp_v (Chern & Hayhurst 2006). Char heating – heating of the residual char and ash from the pyrolysis temperature (310°C) to the bed temperature and depends on the average heat capacity of residual char and ash, Cp_{ca} (Perry et al. 1997).

RESULTS AND DISCUSSION

The effect of the fluidization number and primary air factor on the combustion of the RDF in a rectangular fluidized bed combustor was investigated. The first part of the study aimed to determine the optimum fluidizing number from a range of 5 to 7 U_{mf}. Table 4 summarizes the average temperature profile of bed, surface and freeboard temperatures operating at AF = 1 at selected fluidization numbers of 5, 6 and 7 U_{mf}.

Fluidization at 5 U_{mf} showed very good results regarding its average temperatures for the fluidized bed, bed surface and freeboard regions. The average bed temperature (T1) was at 788°C, whilst the average bed surface (T2) was at 714°C. This shows that the combustion was almost uniform and took place inside the bed. The high average bed temperature found at 5 U_{mf} indicated that the air quantity, circulation and mixing of sand with air and

TABLE 4. Average temperature operated at 5, 6 and 7 U_{mf} and AF = 1

Fluidization No	M_f (g/min)	Air flow rate (l/min)	AF	T1 °C	T2 °C	T3 °C	T4 °C	T5 °C
5	243	1596	1.0	788	714	690	691	516
6	292	1921	1.0	706	679	639	646	590
7	341	2242	1.0	686	795	827	856	527

Notes:
T1 is the average bed temperature at thermocouple location 150 mm above the air distributors
T2 is the average surface temperature at thermocouple location 300 mm above the air distributors
T3 is the average freeboard temperature at thermocouple location 600 mm above the air distributors
T4 is the average freeboard temperature at thermocouple location 900 mm above the air distributors
T5 is the average freeboard temperature at thermocouple location 1200 mm above the air distributors

fuel were at their optimum for the range of conditions investigated. However, operating at 6 and 7 U_{mf}, resulted in a drop in average bed temperatures to 706°C and 686°C at 6 and 7 U_{mf}, respectively.

At higher fluidization velocities, the combustion rates increased because of the enhanced mixing. However, at too high fluidization velocities, despite improving mixing, the thermal and combustion efficiency eventually decrease due to the heat removal by excess air (heat being carried out by air) and due to the carbon loss resulting from particle entrainment and elutriation. Operating at 6 to 7 U_{mf} also resulted in a shift of combustion location from in-bed combustion to surface and freeboard combustion due to the RDF's low density and physical characteristics. The RDF used in the combustion study consists of mainly plastic film which tends to float and burn above the bed surface and in the freeboard region. The combustion of the RDF is mainly derived from the combustion of the volatiles. The results from proximate analysis (on a dry basis) showed that the RDF contained only 10% ash but 90% volatile matter. The high level of volatile matter in the RDF indicated that most of the heat was released in the combustion of the volatiles. During the combustion studies, as the fuel was heated, most of the volatiles were driven off and so their combustion happened at the top of the bed and at the freeboard region. Since the amount of fixed carbon was negligibly small, it was unable to sustain the in-bed combustion and therefore, the bed temperature fell rapidly. Operating with high fluidization number significantly pushed the volatile combustion into the freeboard. In the case of the RDF combustion, the highest average freeboard temperature was obtained at 7 U_{mf} in which the burning of the volatiles released most heat into the freeboard and less heat into the fluidized bed. The secondary air injection directly into the freeboard was effective in reducing the CO levels produced and so helped complete combustion of the RDF in the freeboard space (Kobyashi et al. 2005). With respect to the fluidized bed temperature profiles, the most suitable fluidization number was 5 U_{mf} for the combustion to be self-sustaining. Figure 3 shows the temperature profiles in the bed, measured by a thermocouple located 150 mm above the standpipe air distributors for all fluidization numbers operating at stoichiometric condition, AF = 1.

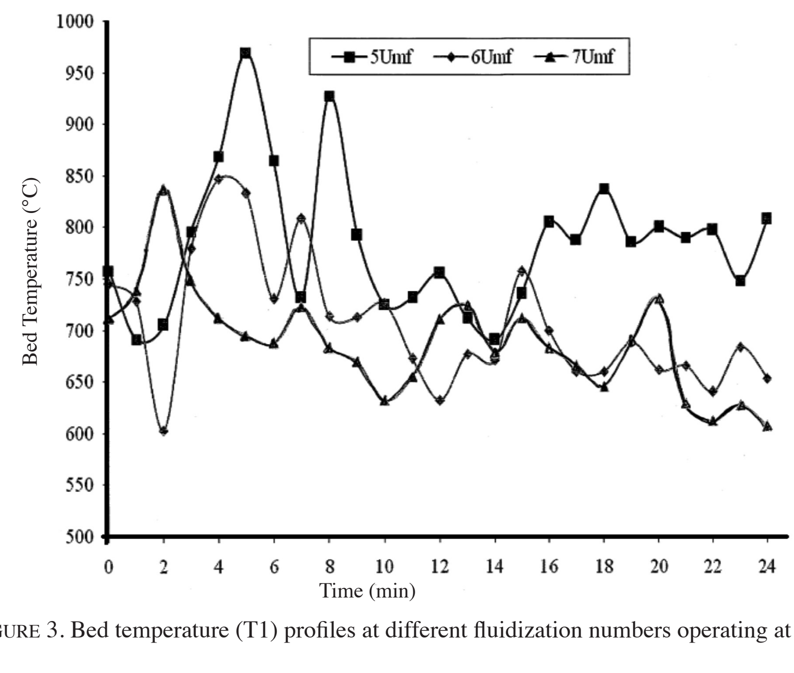

FIGURE 3. Bed temperature (T1) profiles at different fluidization numbers operating at AF = 1

The selection of the optimum primary air factor for the combustion of the RDF was based on the most sustainable bed combustion obtained earlier. The lower limit of air factor used represents a higher amount of fuel into the combustor as compared with higher air factor since the operating fluidization number was fixed at 5 U_{mf}. Thus, at the lower air factor, the condition was 'fuel rich' and the supplied air was inadequate to fully combust the RDF. As the air factor was increased, the combustor temperature also increased as a higher proportion of fuel was being burnt. The average temperatures in-bed (T1), bed surface (T2) and freeboard (T3, T4 and T5) measured when operating at various primary air factors at 5 U_{mf} are tabulated in Table 5.

The optimum primary air factor (AF), where the in-bed combustion temperature was maintained at a relatively high level was in the range of 0.8 to 1.0. Operating at AF = 0.8 for instance resulted in the average in-bed temperature of 808°C (T1) whilst operating at AF = 1 showed a slight reduction in-bed temperature to 788°C (T1). In both cases, the in-bed temperature was higher than the bed surface temperature (T2) indicating that the combustion was being successfully carried out inside the bed. The results for AF = 0.6 and 1.2 however showed that the average surface temperature (T2) was higher than that of the average in-bed temperature (T1). It is thus suggested that more of the combustion at these primary air factors happened at the bed surface. Operating at sub-stoichiometric air (AF<1) especially at lower limit of primary air factor of AF = 0.6, produces un-burnt carbon which accumulates on the bed surface, resulting in poor mixing of the RDF sample inside the bed and eventually drops the bed temperature (T1). On the other hand, operating at higher primary AF of 0.8 and 1.0 showed a higher and stable in-bed temperature (T1). This was a result of less RDF being added into the fluidized bed, which would improve the mixing behaviour of sand, air and the RDF. The most stable and highest bed temperature was observed at AF = 0.8. Operating the fluidized bed at above stoichiometric (AF>1), resulted in a lowered in-bed temperature profile as shown in the operation at AF = 1.2. The addition of air of more than stoichiometric air causes the combustion to experience a 'thermal sink' or cooling effect. Figure 4 shows the effect of different air factors conducted at 5 U_{mf}. The location of the thermocouple (T1) was at 150 mm above the air distributors.

The thermal efficiencies, η_{TE}, of the RDF combustion were calculated for the different primary air factors operated at 5 U_{mf} and are shown in Table 6.

These results showed that the thermal efficiency of the combustion of the RDF was influenced by the bed temperature and air factor being used. Zhao et al. (2005) also pointed out that both the extra air ratio and the injection of secondary air affected the NO_x formation characteristics.

TABLE 5. Average temperature at different air factors operated at 5 U_{mf}

Fluidization No	M_f (g/min)	Air flow rate (l/min)	Air factor (AF)	T1 °C	T2 °C	T3 °C	T4 °C	T5 °C
5	406	2667	0.6	681	746	699	691	558
	304	1997	0.8	808	714	564	588	542
	243	1596	1.0	788	714	690	691	516
	203	1334	1.2	728	745	656	655	471

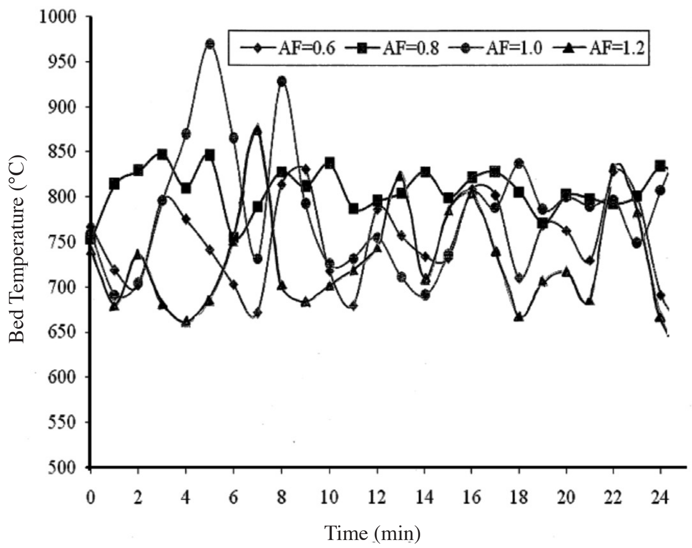

FIGURE 4. Effect of air factor on bed temperature profile at 5 U_{mf}

TABLE 6. Thermal efficiency at different primary air factor operated at 5 U_{mf}

Fluidization No	Air factor (AF)	Bed temperature °C	Feed rate (g/min)	Thermal efficiency (%)
5	0.6	681	406	50.06
	0.8	808	304	59.76
	1.0	788	243	58.21
	1.2	728	203	53.64

Notes:-
Thermal efficiency was calculated from moisture content of 25%, 5 U_{mf} and bed temperature of 681, 808, 788 and 728°C at AF = 0.6, 0.8, 1.0 and 1.2, respectively

In the gasification mode (AF<1), more RDF sample was added into the combustor compared to the required air for complete combustion. Thus, it caused an accumulation of the RDF inside the combustor as the RDF could not be fully combusted due to insufficient air being supplied into the combustor. However, in the stoichiometric combustion (AF = 1), an adequate quantity of the RDF was supplied with respect to its stoichiometric air requirement and so the RDF was able to be fully combusted. As a consequence, no accumulation of the RDF or excess un-burnt RDF was left inside the combustor and the mixing between sand, air and the RDF was improved significantly. In the excess air combustion (AF>1), the RDF was already fully combusted and the excess air was only meant to improve the burning of the volatiles. However, supplying too much air (in excess of stoichiometric air requirement) had an adverse effect on the overall combustion such as reducing the temperature of the bed and freeboard regions. Similar findings were reported by Lin et al. (2004) in their study on the effect of the concentration of bed materials on combustion efficiency during waste incineration.

CONCLUSION

Combustion of the RDF has been investigated using a rectangular fluidized bed operating at atmospheric pressure. The middle range of bubbling bed fluidization, of 5 to 7 U_{mf} was chosen due to technical and financial constraints. It was concluded that within the range, the most optimum fluidization number for sustainable bed combustion was 5 U_{mf}. The most optimum primary air factor was AF = 0.8 where the bed temperature was observed at its highest and most stable among the selected air factor. The thermal efficiency was observed to depend on the average bed temperature and air factor.

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