Combustion of lignocellulosic materials in an experimental fluidized bed system

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Abstract

Incineration via fluidized bed combustion is a worldwide technology used for the thermal treatment of solid wastes with various calorific values. The objective of the present investigation was to evaluate the combustion efficiency and gas products from a three-phase combustor in order to thermally treat lignocellulosic materials obtained from urban solid wastes generated in Villahermosa-Tabasco, Mexico. The experiments were carried out in three sections: (EXP-1) the bed temperature (*Tb*) was varied from 800 to 900°C, having a static bed height (*Hs*) of 0.15 m; (EXP-2); same *Tb* range but *Hs* = 0.20 m; (EXP-3) same *Tb* range but *Hs* = 0.25 m. Throughout the experiments, the combustor was operated with an average excess air (*XSA*) of 168% and a mean bed particle size (*Dp*) of 0.8 mm. The results revealed that the combustion efficiency varied from 73.6–82.6% for *Hs* = 0.15 m, 78.4–87.9% for *Hs* = 0.20 m, and 80.1–90.6% for *Hs* = 0.25 m. At *Tb* < 815°C and *Hs* = 0.15 m, low combustion efficiencies were obtained (73–80%), with relatively high CO emissions (280–310 ppm). At *Tb* > 850°C and *Hs* = 0.20–0.25 m, higher combustion efficiencies were attained (82–91%), with maximum emission concentrations of CO (102 ppm), SO_2 (13 ppm) and NO_x (17 ppm) that never exceeded the maximum permissible levels established in the current Mexican environmental legislation. The prototype probed to be technically and environmentally feasible for the treatment of lignocellulosic materials via fluidized bed combustion.

Keywords: combustion, lignocellulosic residues, fluidized bed.

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1 Introduction

The handling, treatment and final disposal of urban solid waste (USW) represents a great challenge for environmental authorities. Consequently, a series of control regulations have been created in order to improve the efficiency for handling and disposal of such wastes [1]. In the near future, traditional direct methods (e.g., landfill and underground injection) will be replaced by incineration, combined biological and physical-chemical treatment, chemical stabilization-solidification and others [2, 3]. To date, state of the art incineration systems have been demonstrated to achieve the highest levels of control and destruction of USW. In this context, incineration employs thermal decomposition via oxidation at high temperatures (800–1100 °C) destroying the organic fraction of the residue and, therefore, reducing its volume. Nevertheless, the incinerators must comply with a given regulation for performance and operation, such as: high combustion efficiency, removal and destruction of toxic gases, permissible limits for particulate emission, semi-continuous monitoring in the process, a specific minimum temperature, and acceptable levels of residence time in the exhaust gases [4–6]. Likewise, various incineration technologies have been developed to deal with different types and physical forms of residues.

In the United States of America, a critical review identified 221 incinerators of hazardous and conventional wastes [7, 8] where the design of liquid injection, rotary kilns, fixed hearth and fluidized bed incinerators were highlighted. The fluidized bed combustors represent one of the most promising technologies for incinerating organic and plastic residues, contaminated sludge and biomass [3, 9–11]. Also, control of the combustion process has been selected as the main strategy for reducing emissions into the atmosphere. Furthermore, a strong correlation has been found between temperature, residence time and emission rate [12, 13].

During the operation of a fluidized bed incinerator at pilot plant scale, Saxena and Jotshi [14] reported SO_x and NOx emissions ranging from 20 to 35 ppm and 100 to 139 ppm respectively, having oxygen concentrations in the flue gases between 13.4 and 16.1%. Swithenbank *et al.* [15] found an oxygen concentration of 16.9% in the flue gas of clinical wastes. Likewise, certain operating conditions minimized the CO formation and reduced the dioxin and furan emissions [16, 12]. The CO forms due to incomplete combustion and, therefore, an excess air is required to attain the optimum oxidation of the fuel. Wiley [17] suggested a minimum oxygen concentration of 1–2% in the combustion products. The objective was to evaluate the combustion efficiency and gases products from a three-phase combustor in order to thermally treat lignocellulosic materials obtained from urban solid wastes generated in Villahermosa-Tabasco, Mexico. The experimental combustor was specifically designed and constructed to cope with the operating and fluidizing requirements in the current study. Also, the flue gas composition (CO, NO, NO_x and SO_2) was determined during the combustion process under various operating conditions.

2 Materials and methods

2.1 Characterization of USW

The USW samples were taken according to the Mexican technical norm specifications [18]. The field work was performed at the open municipal waste site located outskirts Villahermosa city in Tabasco, Mexico. Indirect methods were employed to quantify the USW, the loading count and the truck number [19]. To determine the USW generation, the samples were applied for a period of eight days and analyzed in seven days. Nevertheless, the first day of USW sampling was excluded for not being representative. In this study six sectors were considered throughout the sampling: central downtown (S1), northeast (S2), southwest (S3), north-northeast (S4), east (S5) and peripherical area (S6). Samplings were carried out three times a week within each sector, allowing for a specific classification and quantification of the products and by-products.

2.2 Design and operating characteristics of the experimental combustor

The design specifications of the combustor can be seen in Figure 1.

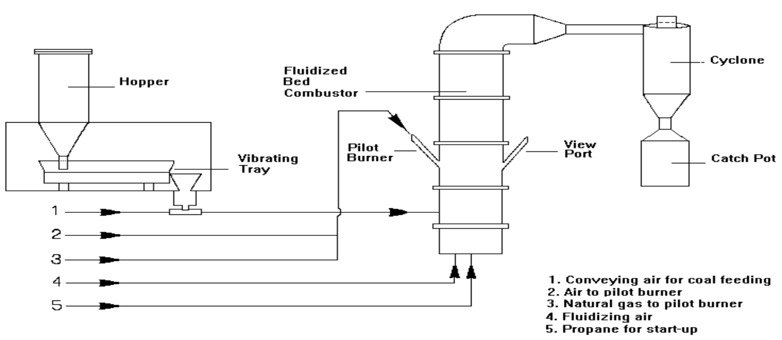

Figure 1: Scheme of the experimental fluidized-bed combustor used in the present study.

The combustor was made up of mild steel and constructed in three cylindrical sections with an internal diameter of 0.1 m. The bed and plenum sections are 0.45 m and 0.25 m high, respectively; while the height (freeboard) of the two remaining sections is 0.50 m each. Two tubes in "V" shape were coupled to the combustor walls in a 45 ° angle. Such adjacent tubes were employed, on the one hand, for the pilot burner and, on the other hand, as an observation port. To feed the USW, an open area was made in the bed section. The bed material was made up of silica sand with a mean particle size of 0.8 mm. The plenum comprised the air and gas distributor and was constructed in stainless steel with a 0.1 m internal diameter and 0.01 thick. To distribute the air and gas inside the combustor, five standpipes were made of stainless steel with 9 mm diameter and 54 mm length. At the top of each standpipe, four orifices were perforated with 2 mm diameter.

The feeding of USW into the experimental prototype was performed manually and discontinuously, working as a batch reactor. The lignocellulosic material was triturated to get an average size of 5 mm diameter [20, 21]. Thermocouples type "K" was used to monitor the temperatures in the bed, the freeboard and the exit flue gas. The thermocouple material was stainless steel with a temperature interval between -129 to 1371 °C, and ± 0.1% error. The temperature was recorded in a Pro TM 45 panel control (43/4 *Digit Microprocessor Based Temperature/Process Indicator*). The air for both the pilot burner and combustion system was supplied by a compressor with a capacity of 0.56 m^3/min and 14 kg/cm^2 pressure. The temperature and concentration of the combustion products were measured with a portable analyzer *TESTO 300 M&XL*.

The experiments were conducted in the fluidized bed combustor, under the following operating conditions: 1–3 h operating time; 66–90 g/min mass flowrate; 800–900° C bed temperature; 0.35–1.06 kg/cm^2 air pressure; 12.4–13.9% excess oxygen; 0.8 mm mean particle bed size and 5 mm average residue size. Three experimental runs were carried out five times each, as follows: (EXP-1) the *Tb* was varied from 800 to 900° C, having a *Hs* = 0.15 m; (EXP-2) same *Tb* range but *Hs* = 0.20 m; (EXP-3) same *Tb* range but *Hs* = 0.25 m.

2.3 Combustion efficiency

The combustion efficiency (η) was determined by monitoring carbon monoxide (CO) and carbon dioxide (CO_2) in the exit flue gases. The CO and CO_2 concentrations were measured with a portable combustion gas analyzer and used to calculate the combustion efficiency, as follows:

$$\eta = 100 - \left[K_{net} \frac{\left(T_g - T_a\right)}{C_{CO_2}} + \left(X \frac{\left(210 + 2.1T_g - 4.2T_a\right)}{1000Q_{gr}} \right) + \frac{k_1 Q_{gr} C_{CO}}{Q_{net} C_{CO_2} + C_{CO}} \right]$$

where T_g is the flue gas temperature, T_a is the room temperature, C_{CO2} is the CO_2 concentration measured, C_{CO} is the CO concentration measured, K_{net} = 0.390, K_1 = 40, Q_r = 53.42 y Q_{net} = 48.16. In addition, nitric oxide (NO), nitrogen oxides (NO_x) and sulfur dioxide (SO_2) were measured in the exhaust gases. The combustion products were analyzed every 10–15 min period after reaching stable operating conditions, that is, 5 min of constant bed temperature. The desired bed temperature was obtained by adjusting the USW feeding flow.

3 Results and discussion

From the USW estimated in six sectors of Villahermosa city, sector S1 was shown to be the highest generation with 210 tons/day and average density of 230.3 kg/m^3. The other five sectors produced various quantities of volumetric weight and USW generation, as illustrated in Table 1. In average, the six sectors generated 740 tons/day throughout the sampling period. In some sectors, certain materials are recovered before its final disposal. In Mexico, this pre-selection of recycled material is known as "pepena". Because of this activity, the information shown in Table 1 does not represent the USW generation but the USW composition at site. Sector S5 was chosen to be the fuel supply for feeding the lignocellulosic material in the experimental fluidized-bed combustor. Such a sector represents approximately 12% of the total USW volume generated in the city and the "pepena" reduces the recyclable material (e.g., textiles, aluminum, cardboard, paper and cans). The following by-products were found in S5: rigid plastic (12.7%), paper (29%), polyethylene (9.9%), organic matter (30.3%), glass (4.6%), fine residues (1.7%), textiles (1.0%) and aluminum (9.9%). Likewise, Table 2 shows the elemental analysis for both the USW composition and the lignocellulosic material from S5.

Table 1: USW generation for each zone in Villahermosa, Mexico.

	Sector 1	**Sector 2**	**Sector 3**	**Sector 4**	**Sector 5**	**Sector 6**
Volumetric weight (kg/m^3)	230.3	203.7	216.3	215.9	180.3	200.2
Generation (Tons/day)	210.0	160.0	100.0	70.0	92.0	115.0
Subproducts			**Percentage (%)**			
Rigid plastic	10.0	2.7	26.7	26.3	12.7	13.0
Paper	17.3	5.9	15.8	7.0	29.0	11.2
Polyethylene	15.5	9.7	12.7	11.9	9.9	8.9
Plastified cardboard	7.7					6.3
Organic matter	43.6	47.9	29.0	29.0	30.3	47.7
Glass	3.2	10.3			4.6	0.9
Fine residues	2.7	11.9			1.7	3.9
Textiles		2.9			1.0	2.3
Aluminum		2.2			9.9	
UNICEF		6.8			0.9	
Cardboard			8.3	11.3		
Cans			7.5	14.4		5.8

For the EXP-1 (Figure 2), the combustion efficiency varied from 74 to 82% at bed temperatures ranging from 810 to 900° C, respectively. In this experiment, the CO concentration diminished from 310 to 146 ppm as the bed temperature increased from 810 to 900° C. This behavior may be explained by the oxidation of CO to form CO_2 at high temperatures, since the reaction velocity at 900° C is six times higher than that at 800° C [22]. On the contrary, the CO_2, NO and NOx values increased as the temperature was raised above 855° C.

The increase in NO concentration was presumably due to the kinetic reaction of NO according to the extended Zeldovich mechanism, where the atomic oxygen reacts with the molecular nitrogen to form NO and atomic nitrogen [22]. Basically at 900° C, the NO reaction velocity is 20 times higher than that at 800°

C, which favors its formation. Meanwhile, the SO_2 concentration did not present a clear tendency. Also, it was observed that SO_2 values from 2 to 5 ppm were attained for the highest bed temperature.

Table 2: Elemental composition of USW and lignocellulosic material.

Sector	Elemental composition (% in weight) USW					Ash	Moisture
	C	H	O	N	S		
1	32.7	4.6	20.6	1.4	2.0	20.1	18.6
2	41.5	5.9	30.0	3.4	0.3	5.2	13.7
3	26.3	5.5	28.0	0.3	0.2	7.0	32.7
4	34.4	4.3	32.2	1.8	0.5	4.0	22.8
5	42.2	5.5	29.3	1.6	0.3	2.2	18.9
6	34.2	5.0	30.6	0.4	2.3	3.6	23.9

Sector	Elemental composition (% in weight) Lignocellulosic Material					Ash	Moisture
	C	H	O	N	S		
5	41.04	5.87	40.02	0.23	0.02	9.41	3.41

Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Sulfur (S). N.B. Oxygen was obtained by difference [100% - Σ (C + H + N + S)].

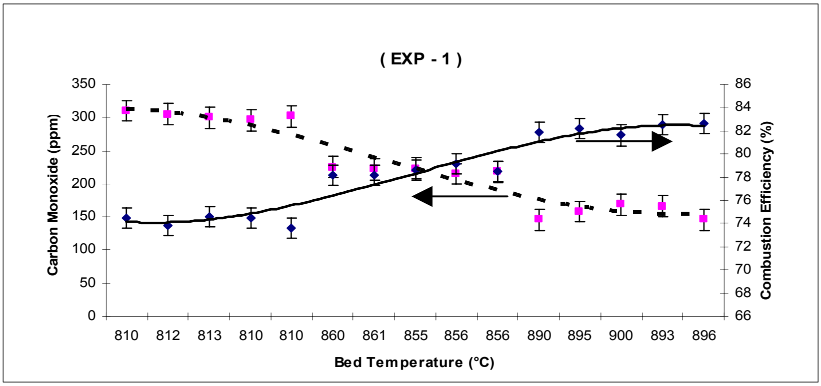

Figure 2: Combustion efficiency and CO concentration tendencies in EXP-1.

For the EXP-2 (Figure 3), the combustion efficiency was also increased when increasing the temperature of the fluidized bed combustor. The lower (78%) and higher values (87%) for combustion efficiency were obtained at 810 and 885° C bed temperature, respectively. The CO concentration decreased from 296 to 122 ppm. Likewise, Table 3 showed that CO_2, NO and NOx values increased as the temperature was raised above 850° C, however, the SO_2 concentration was kept constant in the range of 3 and 6 ppm throughout de experiments.

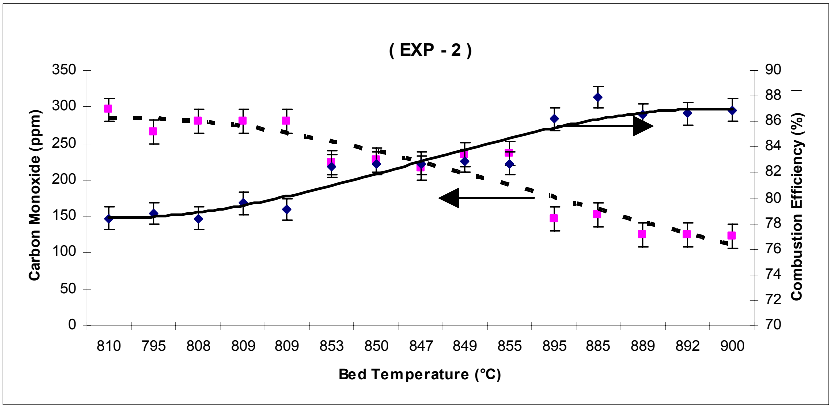

Figure 3: Combustion efficiency and CO concentration tendencies in EXP-2.

The results in EXP-3 showed a significant increase in combustion efficiency when increasing the temperature, having a decrease in CO concentration (Figure 4). Combustion efficiencies of 80 and 90% were determined at bed temperatures of 813 and 902°C, respectively. Under such operating conditions, the values of CO concentration were 268 ppm for the lowest temperature and 102 ppm for the highest. Unlike EXP-1 and EXP-2, the CO_2, NO, NOx and SO_2 concentrations behaved steadily in relation to the increase in bed temperature.

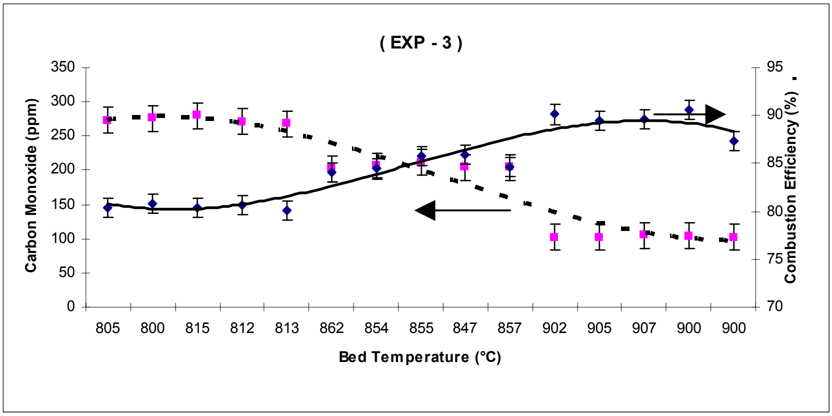

Figure 4: Combustion efficiency and CO concentration tendencies in EXP-3.

Although the current experimental combustor does not have any connection to other treatment system or gas recirculation by-pass, the combustion efficiencies achieved in the fluidized bed were relatively high (90%) at high temperatures (902° C). The CO, NO, NOx and SO_2 concentrations were found to be below the maximum permissible levels established in the Mexican environmental legislation [18]. The proposed experimental prototype showed that high combustion efficiencies can be proportional to the increase in temperature within the fluidized bed combustor. In this case, the combustor could presumably reach higher efficiencies if heat losses to the surroundings were reduced and the excess air was appropriate [5].

In a fluidized-bed incinerator at pilot scale, Saxena and Jotshi [14] reported that oxygen concentrations in the flue gas should be ranging between 13.4 and 16.1%; Swithenbank *et al.* [15] determined an optimum oxygen concentration of 16.9% during the incineration of clinical waste. Previous works on this field have also found that commercial incinerators were operated under similar excess oxygen conditions. In agreement with these investigations, the proposed fluidized bed combustor presented similar oxygen concentrations varying from 12.0 to 16.9% throughout the experiments. On the other hand, companies like *Energy Incorporated Co* (EIC) and *Energy Products of Idaho* (EPI) reported CO_2 values in the flue gas in the range of 5.2 and 6.6% [17]. For the clinical waste incinerator, the CO_2 discharges were found to be in 3.1% [15]. While in the current experimental combustor, the CO_2 concentrations were measured between 1.2 y 5.6%.

In this context, Saxena and Jotshi [14] reported SOx and NOx values in the range of 20–35 ppm and 100–139 ppm, respectively. The EIC and EPI prototypes showed SOx concentrations of 350 ppm and NOx concentrations of 35 ppm. Likewise, Swithenbank *et al.* [15] found higher emission levels for NOx (51 mg/m^3) than SO_2 (17 mg/m^3) from the incineration of clinical residues. In the current experiments, the SOx and NOx concentrations never exceeded 40 ppm in the exhaust gases under similar operating conditions (900° C). Regarding the combustion efficiency, the experimental works mentioned above reported higher values (93–99%) than those obtained in this investigation (80–90%) since they combined the fluidization process with pyrolysis. These prototypes operated at temperatures between 850 and 950°C and excess air ranging from 35 to 60% (Table 3).

Table 3: Operability and flue gas composition from the current experimental prototype compared to others cited in the literature.

Parameters	Saxena	EIC-EPI	GA Tech.	LIN	DACBIOL
O_2 (%)	13.4–16.1	16.9	0	6	12.4–13.9
CO_2 (%)	5.2–6.6	5.2–6.6			3.2–4.9
NO_x (ppm)	100–139	35		<100	<40
SO_x (ppm)	20–35	350		<100	<40
CO (ppm)	30	0	100		102–310
Combustion efficiency (%)	99	93	99.9	96	73–90
Operating Temperature (°C)	800	750–800	1100	800–940	800–900

GA Tech, prototype designed by *GA Tech. Inc. Company* (Rickman *et al.*, [24]). EIC-EPI, prototype developed by *Energy Incorporated Company* (EIC). Saxena, prototype developed by Saxena and Jotshi [14]. LIN, prototype developed by Lin *et al.* [23]. DACBIOL, prototype was developed by the corresponding author.

4 Conclusions

The experimental prototype demonstrated to be technically and environmentally feasible for the thermal treatment of lignocellulosic materials via fluidized bed combustion. The highest combustion efficiency (90%) was obtained at 902°C bed temperature and 13.9% excess oxygen. The experimental results suggest that higher combustion efficiencies may be achieved if: 1) the USW mixtures are homogenized, 2) a continuous feeding system is used and 3) the combustor is well insulated as to avoid important energy losses to the surroundings. Also, the SO_2 and NO_x emissions did not exceed the maximum permissible levels established by the Mexican environmental legislation. It is recommended to run more experiments in order to better understand the heterogeneous combustion fundamentals of USW as well as its solid and gaseous emissions, under various fluidizing and operating conditions. Likewise, a number of studies will be required to understand the combustion behavior of both USW and lignocellulosic materials at different bed particle sizes.

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