Experimental investigation into the incineration of sewage sludge in a fluidised bed

Suthum Patumsawad
The Waste Incineration Research Center (WIRC),
Department of Mechanical Engineering,
King Mongkut's Institute of Technology North Bangkok,
Bangkok, Thailand 10800.
Tel: 66-(0)-29132500-24 Ext. 8303, Fax: 66-(0)-25870026, E-mail: stt@kmitnb.ac.th

Abstract

The main purpose of this research was to investigate the combustion of sewage sludge within the bed of a fluidised bed. Since the sewage sludge is characterised by high moisture, high volatile matter, and high ash content with low level of fixed carbon, it makes incineration difficult. For high volatile matter fuels, the volatiles released from the fuels during the devolatilisation process tend to burn above the bed surface or in the freeboard area. This causes insufficient heat for sustained combustion, particularly for the high moisture and high ash content fuel.

The effect of varying the moisture content on the incineration was studied and the concentrations of O_2, CO_2 and CO above the bed surface were measured. The fraction of fuel burn within the bed was determined from a mass balance. The optimal operating condition was at an equivalence ratio of 1.0 and the fluidisation number of 3 in which the carbon combustion efficiency within the bed is at the maximum of 60%. The information generated could lead to a redistribution of the heat absorption in the boiler when burning sewage sludge.

Combustion of sewage sludge at 60% moisture content with methane was also investigated and the results show that a combustion efficiency of 90% could be achieve at the bed temperature of 820°C.

Keywords: Fluidised bed, Sewage sludge, Waste incineration.

1. Introduction

In recent years the treatment of municipal sewage water has become an important facet of the conservation of our environment. One consequence of the rapid rise in the number of waste-water treatment plants is the greater production of sewage sludge and nowadays its disposal is one of the most pressing environmental problems. In European countries, for example, 54% of the sludge is dumped in filling sites, 27% used as fertilisers in agriculture or composted and 14% incinerated [1]. Because of the limited capacities of filling sites, sludge disposal in them is becoming more difficult. And there is growing resistance to sludge as a fertiliser because it contains heavy metal. Therefore, sludge incineration is expected to rise.

Fluidised bed combustion 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 emission of nitrogen oxide and sulphur dioxide gases [3].

The high moisture content in sewage sludge gives rise to some operational problems. The water in the sewage sludge is evaporated as it enters the bed and this requires heat. Waters [4] demonstrated that fuels with up to 85% inerts (i.e. mineral-matter plus water and with heating values as low as 5 MJ/kg can be burnt in a fluidised bed combustor. The fuels with 85% inerts would have a theoretical furnace temperature of 1000°C and could be burnt in a fluidised bed combustor at 900°C, however these adiabatic furnace temperatures are calculated for a coal feed with different percentages of inerts. For high volatile matter fuels, the volatiles released from the fuels during the devolatilisation process tend to burn above the bed or along the freeboard height [5] and [6]. This causes insufficient heat for maintaining the bed temperature.

The main purpose of this research was to investigate the combustion of sewage sludge within the bed in a fluidised bed, in order to generate information for the design and operation of a fluidised bed incinerator suitable for burning sewage sludge.

2. Experiment

2.1 Experimental apparatus

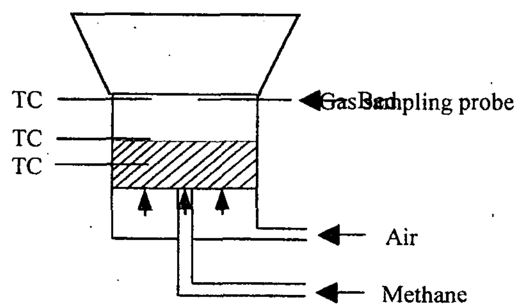

Fig. 1 Experimental apparatus

Fig. 1 shows the schematic diagram of the bench scale fluidised bed combustor. The combustor was fabricated from stainless steel and consisted of a plenum section, a distributor and a combustion section. The combustion section consisted of a stainless steel cylinder with an internal diameter of 140-mm expanding to 220 mm in the freeboard. The top end of the combustor was open to atmosphere. The distributor was made of a sintered ceramic plate.

Air was supplied by a compressor and metered by a rotameter before being fed into the bed through the plenum section. Methane was also fed into the bed through the plenum section to raise the bed temperature to a designed temperature, normally above the ignition temperature of the fuel.

Type K thermocouples were used to measure the temperatures at different positions. The bed temperature (T_b) was measured at the middle of the bed, the bed surface temperature (T_s) and the temperature of the flue gas (T_f) were measured at approximately 50 mm above the distributor plate and approximately 50 mm above the bubbling bed surface, respectively.

A stainless steel probe was used to extract a sample of the flue gas and positioned approximately 50 mm above the bubbling bed as shown in Fig. 1. The gas sample was passed through a glass wool filter, a water cooled heat exchanger and a drier consisting of magnesium chloride granules before entering on-line gas analysers. O_2 was measured using a Servomex 570A paramagnetic analyser. CO and CO_2 were measured using non-dispersive infrared absorption spectrometry analysers manufactured by Analytical Development Company Limited (ADC). These gas analysers were calibrated with standard gas samples before using.

The percentage of carbon fed into the fluidised bed that has been consumed to produce CO_2 and CO was computed using Eq. 1 [3].

$$\eta = (B/C) \times 100\% \quad (1)$$

where B and C are, respectively, the mass fraction of burnt and total carbon in the fuel. Knowing flue gas composition, fractional excess air, and the ultimate analyses of fuel, B can be calculated. This methodology is convenient since determining experimentally the unburnt carbon is difficult.

2.2 Sewage sludge

Table 1 shows the composition of sewage sludge and, for comparison purpose, coal. The heating value of sewage and coal on the dry basis are 14 MJ/kg and 33 MJ/kg, respectively. The sewage sludge as received from the plant is a thick sludge that has moisture content of around 60%. From the ultimate analysis, it shows that carbon composition of sewage sludge is lower than that in coal, 36% compared to 80% on a dry basis. In contrast, oxygen content in sewage sludge is higher than that in coal, 31% compared to 10% on a dry basis. While other components are slightly different. These chemical components influence the stoichiometric air requirement. The volatile matter of sewage sludge is higher than that of coal, 65% and 38%, respectively, so the relative air requirement for consuming the volatile matter and fixed carbon is different.

The moisture content affects not only the combustion process and the efficiency, but also greatly effects the heating value. Table 2 shows the higher heating value and combustible content of sewage sludge as a function of the moisture content.

Table 1 Proximate and ultimate analyses of sewage sludge and coal

	Sewage sludge	Coal
Ultimate analyses, wt% (dry basis)		
C	36	80
H	5	5
O	31	10
N	2	1
S	-	1
Ash	26	3
Proximate analyses, Wt% (dry basis)		
Volatile	65	38
Fixed carbon	9	59
Ash	26	3
HHV, MJ/kg (dry basis)	14	33

Table 2 Composition of sewage sludge as a function of moisture content

Moisture (%)	Combustibles (%)	Ash (%)	HHV (MJ/kg)
0	74	26	14.0
5	70	25	13.6
10	66	24	12.8
15	63	22	12.2
20	59	21	11.4
25	55	20	10.7
30	52	18	10.1
35	48	17	9.3
40	44	16	8.5
45	41	14	8.0
50	37	13	7.2
55	33	12	6.4
60	29	11	5.6

3. Results and discussion

The operating conditions and the experimental results are shown in Table 3.

3.1 Effect of moisture content on auto-thermal combustion

Exploratory experimental runs with vary moisture contents showed that self-sustaining combustion of the sewage sludge could only be achieved for moisture content of up to 20%. At 30% moisture content, the combustion process could not be sustained. The bed temperature was 620°C and the flue gas temperature was 560°C. The low temperature above the bed region shows that flaming combustion could not be sustained to burn volatiles escaping from the bed. Thick black smoke was observed and there was no visible flame above the bed surface. Sewage sludge devolatilisation could be achieved at a temperature as low as 350°C, however, a much

Table 3 Combustion of sewage sludge in a fluidised bed

No.	Fluidisation number	Equivalence ratio	Moisture (%)	T_b (°C)	T_s (°C)	T_f (°C)	η (%)
1	3	1.0	5	750	760	810	61
2	3	1.0	15	700	710	750	59
3	3	1.0	20	680	690	750	63
4	3	0.5	20	720	710	680	44
5	3	1.5	20	560	560	440	-

higher temperature was necessary to ignite the released volatiles, probably above 600°C [7]. Hence, in order to burn the released volatiles and to maintain stable combustion process, the bed temperature must never fall below 600°C. If the bed temperatures dropped below the ignition temperatures, the volatiles could not be burnt and energy could not be generated to maintain the combustion process. The results also indicate that the bed temperature should be above 680°C to maintain stable combustion. If the bed temperature dropped below 680°C, the combustion process might not be able to be sustained and could cause a smoke problem.

The moisture content of the sewage sludge has a significant effect on the bed temperature (Test No. 1 to 3, Table 3). The bed temperature for the combustion of sludge with a moisture content of 5% was 750°C while for a moisture content of 30% was 620°C. However, the difference in moisture content between 5% and 20% did not have a significant effect on the carbon combustion efficiency in the bed. This suggests that sewage sludge with a higher moisture content has a longer residence time inside the bed than that of relatively drier sewage sludge. Wet sewage sludge had a higher density thus it could penetrate the bed more easily. The rate of drying and devolatilisation of the wet fuel was lower than that of the dry fuel [8]. Hence, the volatiles from the wet sewage sludge should have a better chance to be burnt in the bed.

Waters [4] estimated that the lower limit of heating value to achieve auto-thermal combustion was 5 MJ/kg. While the heating value of the sewage sludge with 60% moisture was 5.6 MJ/kg (see Table 2). This theoretical calculation assumed that the combustion process went to completion inside the bed and all of the heat content of the fuel was liberated inside the bed. However, the results of this study show that part of heat content (~60%) of the sewage sludge was released in the bed.

Werther *et al.* [9] studied the devolatilisation and combustion characteristics of sewage sludge and found that the combustion of volatiles occurred far away from the particle surface releasing their heat of combustion away from the surface of the particle. Therefore most of the volatiles were burnt in the freeboard which explained the higher temperature of the freeboard compared to the bed temperature. Thus, the volatiles not only release most of the potential energy from the sewage sludge outside the bed, the unburnt volatiles also absorb available heat energy from the bed. In addition, elutriation of fuel particles and unburnt CO from the bed also caused energy loss. It was concluded that the bed temperature was contributed mainly by the char content of the sewage sludge.

3.2 Effect of fluidising air velocity

This study shows that the fludisation number (U/Umf) has a significant influence on combustion efficiency through related changes in the quality of bed fluidisation. At a fluidisation number of 1 (at Umf), combustion could not be sustained. The bed mixing was very poor. In fact, the sand and ash particles were fused together resulting in a big lump, which caused malfluidisation. The bed temperature was not the cause of the ash fusion problem because the bed temperature was below 700°C that is well below the temperature likely to cause ash melting. What happened was probably due to a poor mixing. Without good bed mixing, the heat generated from the burning residual char of the sewage sludge produced a heat spot surrounding it. As a result, the surface of the ash and sand particles in these heat spot regions would melt.

At a fluidisation number of 2, combustion also could not be sustained and black smoke was observed. Ash fusion, however, did not occur. The average bed temperature was 600°C. The bed mixing was poor.

At a fluidisation number of 3, combustion of sewage sludge was stable. The bed temperature was 680°C. The bed was in the turbulent region and mixing was good.

At a fluidisation number of 4 and 5, it was observed that elutriation of unburnt sewage sludge was excessive resulting in lower temperatures and carbon combustion efficiencies. Saxena *et al.* [10] reported that in the turbulent region the rate of heat transfer from the bed to the surface of the fuel particles was sufficiently high so that it was no longer a limiting factor on the rate of sewage sludge combustion. Internal heat transfer (the rate of heat transfer from the particle surface to the inner layer of the sewage sludge) then became the limiting factor. The rate of the internal heat transfer depended on the particle properties such as moisture content, size and density, and could not be improved by improving the quality of fluidisation such as increasing the fluidising velocity. Then an increase in the air flow-rate would increase the elutriation rate.

3.3 Effect of combustion air supply

Results from this study show that the optimum air supply should be around an equivalence ratio of 1. The less air supply, the higher the bed temperature. For example, at equivalent ratio of 0.5 (Test No. 4, Table 3), the bed temperature was 720°C compared to 680°C at the equivalent ratio of 1.0. However, the combustion efficiency at equivalent of 0.5 was very low and flame combustion in the freeboard region could not be maintained resulting in a smoke problem. The air supply was too low to support volatile combustion above the bed without the addition of secondary air supply.

An excess primary air supply was detrimental to sewage sludge combustion in the fluidised bed. At 50% excess air (equivalent ratio of 1.5), the bed temperature was below 600°C thus combustion could not be sustained. The combustion process of high volatile fuel is largely dependent on the efficiency of the devolatilisation process, which is governed by the heat transfer mechanism [11]. It should be noted that the air level is not important for the devolatilisation process but the temperature is. This is in contrast with char combustion where an excess air level increases the rate of char oxidation [12].

3.4 Co-combustion of sewage sludge with methane

Combustion of sewage sludge at 60% moisture content with methane as a support fuel was also investigated. Since it was necessary to maintain the bed temperature to achieve stable combustion of sewage sludge. Results from this study show that combustion efficiency increased with bed temperature, which corresponds to an increase the rate of methane supplied. At the supplied methane of 10 MJ per kilogram of the sewage sludge, the combustion efficiency was 90% at the bed temperature of 820°C. While at the supplied methane of 6.5 MJ per kilogram of the sewage sludge, the combustion efficiency was 80% at the bed temperature of 700°C. It was speculated that the sewage sludge with higher moisture content had a higher density, thus it could penetrate into the bed more easily and the higher the moisture, the slower the rate of the sludge devolatilisation. Thus, the sewage sludge had more chance to burn inside the bed.

The combustion efficiency of the sewage sludge could be achieved at a relatively low bed temperature, which might be an advantage for the sewage sludge with high content heavy metals. The rate of heavy metals evaporation should be less at the lower bed temperatures thus minimising the rate of heavy metals loading into the flue gas. Litt and Tewksbury [13] studied the capture of heavy metals on the bed material in a fluidised bed combustor. The capture mechanism of these heavy metals is to agglomerate the metal oxide with silica in the fluidised bed. They concluded that it could capture over 90% of the heavy metals on the bed material tested from the combustion of liquid hazardous waste at less than 750°C bed temperature. They also suggested that some waste may require higher operation temperature than those tested in their work in order to achieve complete combustion.

4. Conclusion

From this experimental study, it may be concluded that sewage sludge with up to 20% moisture content can be burnt in a fluidised bed combustor without an additional fuel. Moisture content greater than 20% caused the bed temperature to drop to a level such that combustion could not be sustained. The suitable operating condition was decided from the maximum carbon combustion efficiency of sewage sludge within the bed and it was found that at the equivalent ratio of 1.0 and the fluidisation number of 3, the carbon combustion efficiency is at maximum (60%). It was believed that the rest of combustible matter, mainly volatiles, would be burnt in the freeboard area resulting in higher freeboard temperature. Secondary air may need to be injected above the bed to obtain complete combustion and larger heat transfer surface areas would be required for above bed heat removal than for heat removal by in-bed tubes, for which the heat transfer coefficients are much higher.

Combustion of sewage sludge at 60% moisture content with methane showed that a combustion efficiency of 90% could be achieve at the bed temperature of 820°C.

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