Available online at www.sciencedirect.com
ScienceDirect
Journal of Hazardous Materials 154 (2008) 38–43
Journal of Hazardous Materials
www.elsevier.com/locate/jhazmat

Risk assessment on processing facility of raw organic garbage

Xin-Rui Li *, Hiroshi Koseki, Yusaku Iwata

National Research Institute of Fire and Disaster, 4-35-3, Jindaijihigashi-machi, Chofu, Tokyo 182-8508, Japan

Received 18 December 2006; received in revised form 24 September 2007; accepted 25 September 2007
Available online 2 October 2007

Abstract

To investigate the cause of an explosion during disposal processing of raw garbage, the property of the raw garbage was primarily examined by a thermo gravimetry-differential thermal analyzer. With mutable oil concentration, the results showed variable onset temperatures of the exothermal reaction for the samples, for example, decreasing from 150 °C in the samples typically containing 10.9–14.1% oil to 114 °C when the oil content was raised to 40%.

The disposal process was then simulated in a laboratory-scale facility being heated by hot air of 150 °C, which was blown into the bottom through nozzles. In the case of the dried garbage containing 14.1% oil, white smoke emitted after several hours, accompanying with an abrupt rise of the temperatures in particular at the bottom of the facility. The maximum temperature reached to 1070 °C. Meanwhile, gases, including flammable ones, whose amounts were $CO_2 \approx CO > H_2 >$ methane > ethane in order, were yielded. It indicated that smoldering developed from the zones near the hot air supply nozzle and propagated along the pathway of the imposed air. The continuously released gases possibly induced the transition of smoldering to flame or explosion after accumulating for hours.

Keywords: Raw garbage; Disposal processing; Heat accumulation; Fermentation; Smoldering combustion; Propagation; Flammable gases; Explosion

1. Introduction

To implement the Food Recycling Law, industrial scale raw garbage is usually disposed at large shopping malls for volume reduction and recycling. However, an explosion in succession to smoke emission in a facility (8 m long, 2.7 m wide and 2.1 m high, volume 19.8 m^3) in the Kanagawa prefecture of Japan in November 2003 revealed potential risk involved in such a process. In this accident, 11 people, including fire fighters, were injured. The facility, located in a room (15.8 m long, 8.6 m wide and 5.6 m high) at the ground floor of a five-layer shopping mall, served as a fermentation tank with a disposal capacity of 1000 kg/day. In the process, sawdust and slake lime were matted at the bottom of the facility to adjust the pH value for promoting microbial activities. Through an automatic feeding tank, the raw garbage was loaded into the facility and then simultaneously dried, mixed, fermented and degraded over several hours. To warm up the tank for facilitating fermentation, hot air, which was sent from an air ration blower to a heater, where it was heated up to 150 °C, was ventilated to the back of the bottom of the tank through several air nozzles from five pairs of inspirators at equal intervals. Stirring by six screw augers, the temperature was supposed to be maintained at 60–70 °C throughout the tank. The processed garbage was then moved to a drying tank and finally treated as the source of fertilizer or derived fuel. In general, about 2100 L processed waste was taken away once a week from the system. Regarding to abnormalities in the accidental case, occasional stop working of the stirrers before the accident occurred and a slight higher greasy level of 14.1% in the garbage, were reported [1].

The components of raw garbage vary from day to day. A typical composition by food sorts is given in Table 1 [2]. These organic combustible wastes have usually been separated from plastics and metals. Table 2 is an analytical result by sampling the garbage from a variety of locations in the facility after the accident. It shows that the main ingredients of the garbage are carbonaceous organic substances (about 50%) and oil (the content at the bottom of the facility was not detected since most of oil might have been exhausted in the accident). Though the average content of oil in the raw garbage is actually about 10% of the dried matters, it seems that it may reach to a higher value in some locations because of its non-uniform distribution in the waste,

* Corresponding author. Tel.: +81 422 44 8392; fax: +81 422 44 8392.
E-mail address: li@fri.go.jp (X.-R. Li).

0304-3894/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2007.09.109

Table 1
Typical components in a raw garbage

Material	Vegetable	Fish paste	Meat	Fruit	Bread/rice	Bean	Fish	Deep fried
Mass (%)	32	24	18	16	7	2	1	0.2

The percentages refer to wet matters. Moisture concentration is 30–35%.

e.g., the non-combusted oil at some of the upper part reached to 20%. The moisture content in Table 2 was not available to be analyzed after water extinguishment. The actual moisture content is reported as about 30%.

To evaluate the risk from such a process, Miyake et al. performed the thermal analysis on the garbage, which was sampled from the accidental site, in a high pressure thermo gravimetry/differential thermal analysis (TG-DTA) and a Setaram heat flux calorimeter. They found that the onset temperature of the heat generation of the garbage varied considerably within the facility. Moreover, self heating behavior at 125 °C and ignition at 135 °C were observed by using an adiabatic spontaneous ignition tester (SIT) [2]. Flammable gases, which were generated by burning the garbage, possibly led to explosion besides fire. To better understand the hazard involved in the process, the present study firstly examined the thermal properties of raw garbage and the influence of the oil content in a TG-DTA test. Then a simulated processing facility was set up in the laboratory to observe the phenomenon and the mechanism relating how explosion was possibly developed from the raw garbage processing. Temperature distribution, flow along the air supply, gas generation, weight loss, and thermal image were monitored during the whole processing.

2. Experimental

2.1. Examination of thermal characteristics of raw garbage and effect of oil content

The thermal characteristics of raw garbage was measured in a thermo gravimetry/differential thermal analysis system. It monitors the weight loss as well as the heat change of a material as a function of temperature or time during thermal processing. In the measurement, the sample of about 17 mg was held in an open aluminum pan. The program temperature rose at a heating rate of 2 K/min from the room temperature to 500 °C. The measurements were carried out under an air flowing of 150 mL/min.

Fresh garbage was used for measurements. The basic sample contained 10.9% oil (it refers to the concentration in dry matter, the below is the same). Based on the fact that the greasy level was 14.1% in the accidental case and that oil might further reach to higher values at some locations in the facility when the stirrer failed to work, the samples with a series of oil contents, such as 14.1%, 20.0%, 30.5% and 40.0%, were measured for comparison by extra addition of edible vegetable oil. Pure oil was measured as reference.

2.2. Disposal processing

To examine the plausible hazard involved in the garbage disposal process, a simulated fermentation tank of 0.51 m long and wide, 1 m high, was assembled, which was at a cross section area ratio by 1:50 of the real one. As shown in Fig. 1, the equipment was consisted of three stainless steel walls and one pyrex wall for observing. In the experiments, 187 L (about 80 cm high) waste was loaded above the bedded 21 L sawdust (about 8 cm high). Hot air, which was heated up to 150 °C, was blown into the corners at the bottom of the equipment at a velocity of 320 L/min through four air nozzles. When the process was started, the following measurements were performed:

(1) Twenty-six thermocouples (TC) were set to obtain the temperature profile within the tank and at its surrounding during the test. Fig. 2 illustrates the scheming construction of the temperature measuring system. Four (N1–N4) of them were placed at the outlets of each nozzle and twenty at four different heights (B, the bottom; M, the middle; U, the upper of the garbage and S, the space above the garbage, respectively) within the tank. At each level, one TC stayed at the

Table 2
The components of the raw garbage in its facility after the accident

Location	Moisture (%)	pH	EC (ms /cm)	Oil (dry matter %)	Carbon (dry matter %)	Nitrogen (dry matter %)	Na (dry matter %)	K (dry matter %)	Ca (dry matter %)	Mg (dry matter %)
Upper	12.1	5.36	12.6	21.8	55.0	2.21	0.54	0.92	3.21	0.18
	13.7	5.14	13.8	24.0	53.6	2.66	0.47	0.81	3.37	0.17
	26.0	5.96	17.2	1.4	47.2	2.13	1.18	2.09	4.56	0.32
	29.9	4.85	11.6	ND	50.1	2.73	0.83	1.40	4.65	0.26
Bottom	29.5	5.80	14.8	ND	51.2	3.15	0.92	1.50	7.10	0.36
	45.5	6.37	12.2	14.9	57.9	2.80	1.34	1.91	17.65	1.22
	21.3	5.84	14.5	ND	51.1	2.78	0.88	1.23	3.31	1.21
	45.7	5.42	15.7	ND	52.3	2.94	1.13	1.58	7.76	0.34
Surface	58.4	4.24	10.0	12.0	51.3	3.86	0.38	0.72	2.86	0.13

EC: thermal conductivity, ND: not detected.

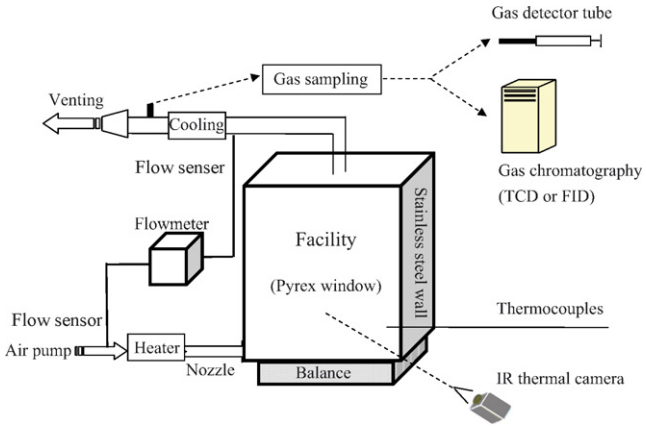


Fig. 1. Schematic illustration of the equipment.

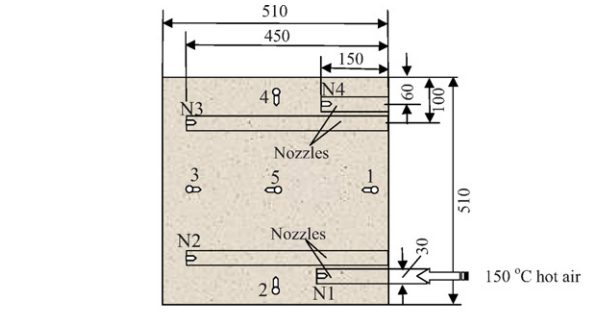
center axis while the other four TCs evenly at four rims. Other two TCs were at the outlet of the venting exit and the outside of the facility wall (W).

(2) Flowmeters were installed at the inlet of the nozzles and the outlet of venting to measure the airflow change into and out of the system.

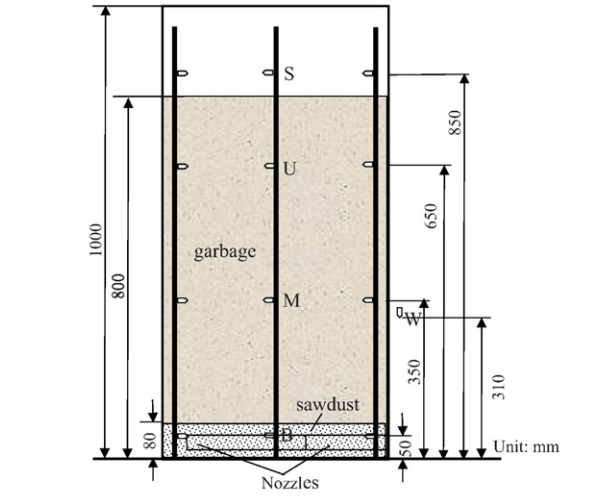
(3) Gases released from the processing facility were collected from the venting duct by a Kitakawa vacuum pump. Gas analysis was carried out in a gas chromatograph (GC) and gas detector tubes based on the target gaseous specimens and their detectable ranges. For instance, CO, methane, ethane and CO_2 were detected by an FID, whereas hydrogen was detected by an TCD in the GC. As for the FID, a reaction tube of methanizer (MTN-1) was installed between the column outlet and the detector to provide reduction of CO and CO_2 to CH_4 for detection by the FID. Other materials, like acetone, acetic acid, hydrogen, and H_2S were inspected by gas detector tubes.

(4) Weight loss was monitored by setting the facility on a large electric balance during the process.

(5) A thermal infrared image camera, AVIO TVS 200, was used to record the whole thermal image in the facility through the front observing window, based on the radiation intensity from the facility.



Cross section (Thermocouples at N1~N4: the outlets of the nozzles; and 1~5: one at the central axis while the other four evenly along the rims)



Longitudinal section (Thermocouples at four heights: B- Bottom; M- Middle; U- Upper; S- Space above the garbage)

Fig. 2. Schematic construction of temperature measuring system.

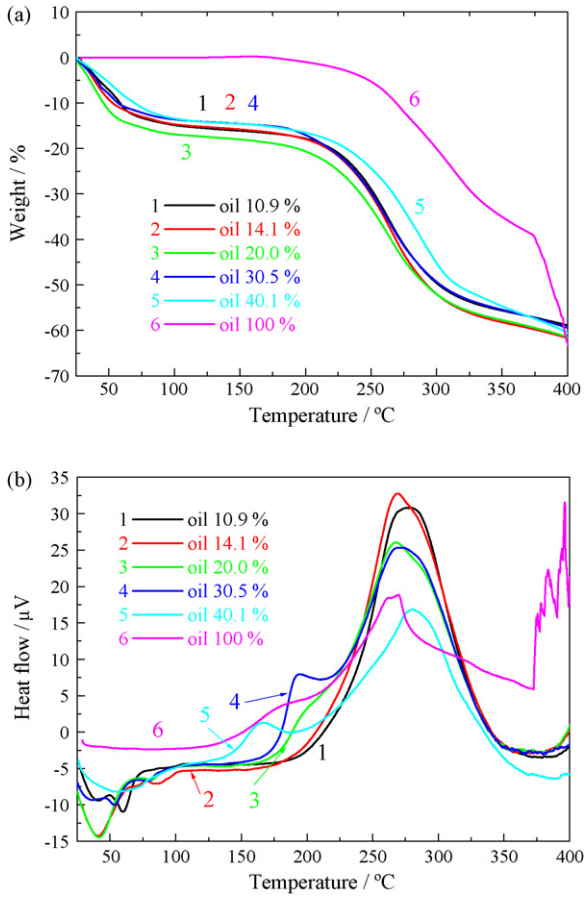


Fig. 3. TG (a)–DTA (b) results of the waste and mixtures with oil.

The tests were conducted for three times: the first for the virgin sample with 10.9% oil and the other two tests for naturally dried samples which contained 14.1% oil.

3. Results and discussion

3.1. Thermal properties in TG-DTA

Curves of weight loss and differential thermal property versus temperature of the raw garbage, and in particular, the proper-

Table 3
Test in the fermentation process tank of the raw garbage in a facility at a horizontal project area ratio by 1:50 of the accidental one

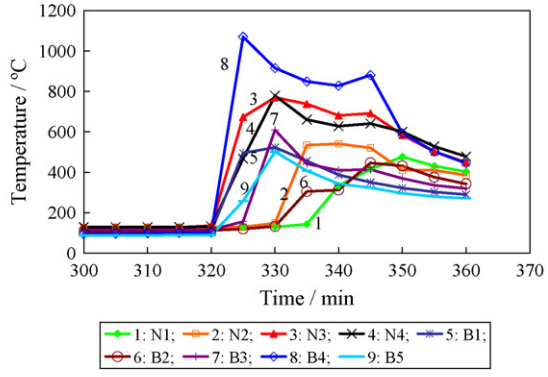
Test no.	Drying treatment	Oil concentration (%)	Time to white smoke emission	Detected gases	
				In the GC	In the tube
1	No	10.90	No smoke	None	Acetaldehyde, acetic acid
2	Natural drying	14.08	4 h and 50 min	H_2, CO, Methane, CO_2, Ethane	Acetaldehyde, acetic acid
3	Natural drying	14.08	11 h	H_2, CO, Methane, CO_2, Ethane	Acetaldehyde, acetic acid, acetone

ties of the garbage with different oil contents in the TG-DTA are plotted in Fig. 3(a) and (b). Weight loss by about 15% was observed from the start of the measurement up to about 100 °C due to moisture evaporation. DTA curves also presented an endothermic peak. After water was driven out, a stagnant stage appeared up to 150 °C for the basic 10.9% oil contained garbage. Thereafter significant weight loss took place and meanwhile an exothermic peak of DTA initiated and gradually went into a major reaction. It results from two types of reactions, oxidation and pyrolysis of the organic components. Both are related to the carbonaceous organic substances (such as protein, cellulose, and hydrocarbons) and oil. The onset temperature of the reactions decreased with increasing the oil content. It was 152.1 °C for the sample containing 14.1% oil, which is 3.4 °C lower than that of the sample with 10.9% oil. It decreased to 114.6 °C at the oil concentration of 40.1% and 96.4 °C for the pure oil, respectively. This implies that the oxidation of non-saturated fats, such as linolic acid and olein in the range of 60–80 °C [3], is mainly responsible for declining the onset reaction temperature of the wastes. This explains that the onset temperature of the garbage within the facility varied noticeably with the position since the concentration of oil was readily mutable in the garbage particularly without stirring, as measured by Miyake et al. [2].

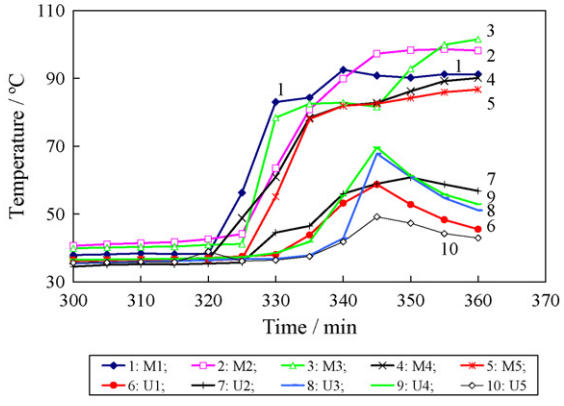
3.2. Tests of disposal process

The experimental conditions and results for the disposal processing of raw garbage are summarized in Table 3. In the first test, smoke release was not observed even after one month from the virgin non-dried sample. However, some species of gases, like acetaldehyde and acetic acid, which were more likely to be liberated from fermentation actions of the organic components, were detected by gas detecting tubes. These reactions were not detected by the TG-DTA tests and hardly lead to hazard. The weight of the virgin sample decreased by 35% after the measurement due to water evaporation. By contrast, in the second and the third tests, oil was raised up to 14.1% for the samples naturally being dried prior to the measurements. The decrease of the weight was only 0.7% in these samples after the measurements. White smoke came out in these two measuremnts after 4 h 50 min and 11 h, respectively. Meanwhile, several species of gases were formed.

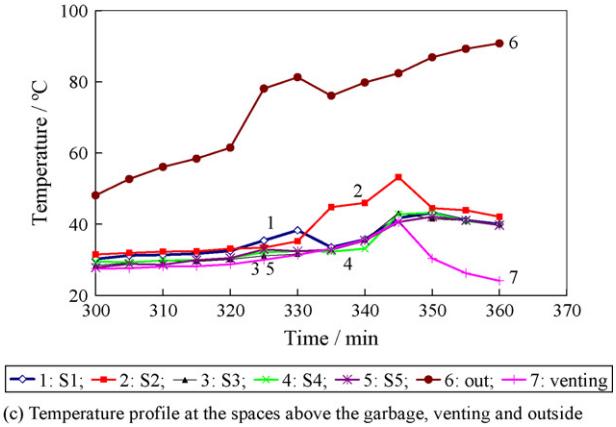
The temperature change during the disposal at various positions in the facility and its surroundings are illustrated in Fig. 4 for the second measurement. Diverse temperature distribution can be observed along the vertical direction. Without stirring, hot air could soly effectively heat the regions of the bottom up to about 130 °C, the middle part to 60–70 °C, while the upper part still remaining at 30–40 °C. Under such condition, temperature elevation at the bottom was ready to attain a value necessarily to start the exothermic reaction for the waste. Accompanied with



(a) Temperature profile at the outlets of the nozzles and the bottom



(b) Temperature profile at the middle and the upper surface



(c) Temperature profile at the spaces above the garbage, venting and outside

Fig. 4. History of the temperature distribution of the waste in the second run.

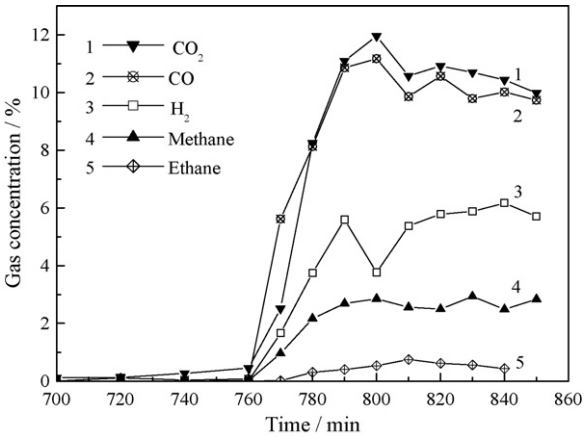


Fig. 5. Gas generation from the waste in the third run.

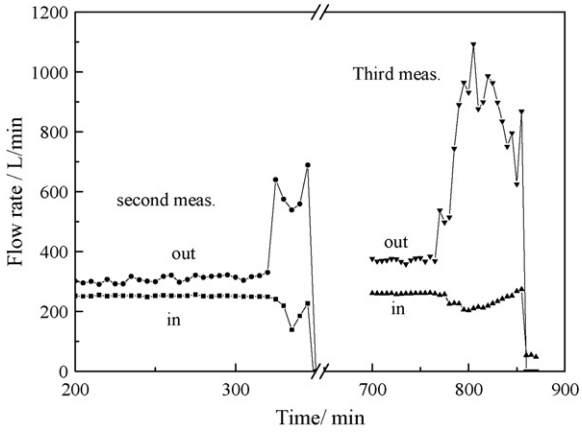


Fig. 7. Flow rate in the nozzle and at the venting exit.

smoke emission at 320 min (5 h and 20 min), the temperatures near the air supply nozzle area soared over and reached to an maximum of 1070 °C. Temperatures rose to 100 °C at the middle level and minor inceases at upper levels. After the tests, the garbage charred and cremated more severely at the bottom than other locations. This had also been observed around the stirring and the bottom of the facility after the accident.

Fig. 5 shows the generation of H_2, CO, methane, CO_2, ethane with the time detected by both the GC and gas detector tubes in the third measurement. The concentrations were $CO_2 \approx CO > H_2 >$ methane > ethane in order, and each built up markedly at the time of smoke outbreak but thereafter remained almost constant. Other detectable gases were acetaldehyde, acetic acid and H_2S.

Normally biotransformation is utilized for conversion of a wide variety of organic waste materials to useful end products [4–8]. The optimum thermophilic temperature for either aerobic or anaerobic activities was found to be at 50–60 °C [9]. Since fermentation is a weak exothermic process, it does not lead to self heating unless under some extreme conditions [9,10]. In the accident, several factors such as the local overheating due to failure of stirring and the higher local concentration of oil might lead to the occurrence of smoldering when the temperature reached to a value required for initiating a relatively active reaction of the garbage.

The appearances of the large amount of CO and smoke were the proof that smoldering had happened in the process. It is a slow, low temperature, and flameless form of incomplete combustion, sustained by the heat evolved from the reactions of the sample [10–13]. The temperature of heat source was confirmed as 150 °C or lower by the TG-DTA, depending on the oil concentration in the waste.

Fig. 6 shows the similar temperature profile by the thermal image when the smoldering happens. Because of radiation loss, the temperature measured by the thermal imaging was much lower than the actual temperatures detected by the thermocouples, in which the maximum temperature near these areas attained to 300 °C. But it illustrates more clearly that the smoldering initially started from the locations near the nozzles and had an upward propagation along the pathway of the imposed air.

Gas generation of H_2, CO, methane, CO_2, and ethane from the sample was confirmed. Furthermore, measurement by the flowmeter, which is usually used for measuring air flowing, showed that the flow at venting exit increased significantly when the smoke emission started, as in Fig. 7. Comparably, for the combustion of cellulose, the heat flux would increase by 10% at the outlet when the temperature increases. In the case of the garbage, the fluxes at the outlet in both the second and third tests increased much more significantly, by three

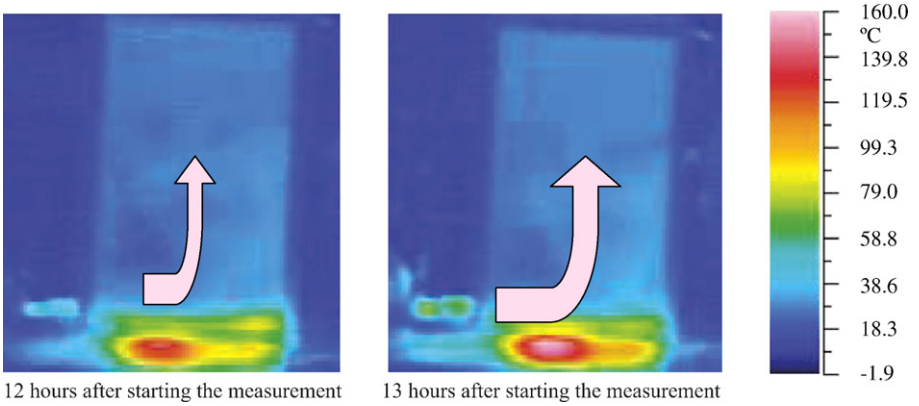


Fig. 6. Thermal image inside the equipment (in the third run).

Table 4
Gas explosion range

Gas	Explosion range (%) [14]	Maximum gas production during the measurement (%)
H_2	4.0–75.0	6.2
CO	12.5–74.0	11.2
Methane	5.0–15.0	2.9
Ethane	3.0–12.4	0.8

times. This suggested the generation of hydrogen from the system. The response of the flowmeter was greatly affected by the thermal conductivity of the gases. The thermal conductivity of hydrogen is 0.18 W/m/K, which is 7.5 times of that of air (0.024 W/m/K). This made the flux much larger than the actual airflow value when the hydrogen flowed out. The reproducibility of smoldering tests, such as the time corresponding to smoldering occurrence and the temperature distribution, is commonly poor [10], partly because the process is inordinately sensitive to air flow.

White smokes were observed after 5 h in the second measurement and 11 h in the third test, respectively. After then it became thicker, and the flame could be seen in the smoke 15 h after the start of the test. When a small LP burner, which was used as a pilot igniter, was held up near the venting gases, the flame was enlarged and developed to blaze. This implies that certain amounts of flammable gases were gathered during the processing. The limitations for explosion [14] and maximum values produced during the measurement of the gases are shown in Table 4. The concentration of H_2 and CO almost reached to the range of explosion. The concentration of methane was also high. Therefore, under such circumstance there was a likelihood of the conversion of smoldering to blaze or explosion if the flammable gases were accumulated.

4. Conclusions

The TG-DTA results showed that raw garbage firstly underwent weight loss below 100 °C due to evaporation of moisture, which hindered to some extent the happening of the active exothermic reaction thereafter. The onset temperature of visible reactions was about 150 °C, as the results of the oxidation and the pyrolysis of the organic components. With the increase of the oil concentration, the onset temperature of the exothermic reaction tended to decrease.

The risk involving in the disposal process was demonstrated in a laboratory-scale facility, being heated by hot air of 150 °C at its bottom. The local overheating made the local temperature of the garbage approach to a value required for initiating a relatively active reaction of the garbage once the moisture was driven out. In the runs with 14.1% oil contained dry waste, white smoke emitted and temperature rose rapidly near the air supply nozzle after several hours. It suggests that smoldering was developed in the facility. In addition to its characteristics of weak combustion and being self sustained by successive supply of hot air, smoldering emitted large quantities of flammable gases, like carbon monoxide and hydrogen, which could later be ignited in the gas-phase, trigger the transition to flaming combustion or reach to the limit of explosion.

References

[1] K. Yoshino, An explosion at a shopping mall, Association of dangerous materials, 2205.3 (in Japanese).
[2] M. Miyake, T. Wakakura, T. Uchida, A. Ushikubo, Investigation of accidental explosion of raw garbage compositing system, J. Therm. Anal. Calorim. 85 (3) (2006) 643–649.
[3] K. Komamiya, Heat accumulation at a large materials, Saf. Dig. 50 (2004) 30–38 (in Japanese).
[4] R.J. Branconnier, D.B. Cumming, R.L. Jackman, Process for thermophilic aerobic fermentation of organic waste, US Patent 5, 810,903, 1998.
[5] E.R. Vieitez, J. Mosquera, S. Ghosh, Kinetics of accelerated solid-state fermentation of organic-rich municipal solid waste, Water Sci. Technol. 41 (3) (2000) 231–238.
[6] J.T. Pfeffer, Temperature effects on anaerobic fermentation of domestic refuse, Biotechnol. Bioeng. 16 (6) (2004) 771–787.
[7] A.A. Bertschi, R.J. Yokelson, D.E. Ward, R.E. Babbitt, R.A. Susott, J.G. Goode, W.M. Hao, Trace gas and particle emissions from fires in large diameter and belowground biomass fuels, J. Geophys. Res. 108 (D13) (2003) 8.1–8.12.
[8] Q. Wang, J.-Y. Narita, W. Xie, Y. Ohsumi, K. Kusano, Y. Shirai, H. Ogawa, Effects of anaerobic/aerobic incubation and storage temperature on preservation and deodorization of kitchen garbage, Bioresour. Technol. 84 (3) (2002) 213–220.
[9] X.-R. Li, H. Koseki, M. Momota, Evaluation of danger from fermentation-induced spontaneous ignition of wood chips, J. Hazard. Mater. A135 (1–3) (2006) 15–20.
[10] V. Babrauskas, Ignition Handbook, Fire Science Publishers, Issaquah WA, 2003.
[11] T.J. Ohlemiller, Smoldering combustion, in: SFPE Handbook of Fire Protection Engineering, third ed., Society of fire protection engineers & National Fire Protection Association, Section 1, 2002, pp. 352–359.
[12] K. Sato, S. Sega, The Mode of burning zone spread along cylindrical cellulosic material, J. Fire Sci. 3 (1985) 26–34.
[13] D. Drysdale, An Introduction to Fire Dynamics, second ed., John Wiley & Sons Ltd., 1998, pp. 263–289.
[14] T. Hikita, K. Akita, Outline of Combustion–Physics and Chemistry of Flames, Corona Publishing Co., Ltd., Tokyo Japan, 1971 (in Japanese).