Journal of Thermal Analysis and Calorimetry, Vol. 85 (2006) 3, 643–649

INVESTIGATION OF ACCIDENTAL EXPLOSION OF RAW GARBAGE COMPOSTING SYSTEM

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In November 2003 an explosion occurred at a shopping center in a room where organic waste including raw garbage is treated. Eleven people were injured including firefighters on duty and the explosion destroyed the walls of the room. To obtain a better understanding of self-heating and gas evolution processes thermal analysis, gas products analysis, spontaneous ignition test and bacterial analysis were carried out. Based on the experimental results accident scenario was investigated and it was considered that the flammable gases generated during a self-heating and combustion in a fermentation tank caused the gas explosion.

Keywords: *explosion, fermentation, garbage composting, gas analysis, spontaneous ignition, thermal analysis*

Introduction

In November 2003 an explosion occurred at a shopping center in Kanagawa prefecture in a room where organic waste including raw garbage is treated. The explosion destroyed the walls of the room and 11 persons were injured, including firefighters who were battling the fire. Although, according to the implementation of the Food Recycle Law, industrial scale garbage composting system becomes popular recently especially at food courts or shopping centers, the contents of garbage from restaurants or shopping center including meet or vegetable stores change day by day and the composting system is not easy to operate. Since the practice of effectively utilizing organic waste by composting is widespread, an understanding of the cause of this accident would be a useful contribution to the safety of such composting processes. To this end, using high temperatures, pressure analysis and heat flux measurements, we performed basic measurements relating to the ignition temperature and behavior of heat generation for materials collected from the fermentation tank in which the fire occurred. We also attempted to qualitatively and quantitatively evaluate the gases generated by thermal decomposition and combustion. Next, we determined the spontaneous ignition temperature under adiabatic conditions using a spontaneous ignition test apparatus, and investigated the effects of this on fires and explosions due to microbial fermentation.

Finally, based on these experimental results and verification of operating conditions, we investigated the mechanism by which the explosion occurred.

Operation of equipment and outline of the accident

Operation of equipment [1]

The organic waste including raw garbage discharged from a supermarket is mixed continuously in the composting system. Heated air is supplied to the bottom of the fermentation tank in order to maintain temperatures at levels that are conducive to microbial activity, thereby promoting the composting process. The length, width, height and volume of the machine was 8000, 2800, 2135 mm and 19.8 m^3 respectively, and six screw augers were equipped for mixing the contents. The standard daily input of organic waste was 1000 kg, and once a week approximately 2100 L of processed material is removed from the system. Sawdust (wood meal) and slaked lime are added to control the pH, are then added to the mix to dry the raw garbage and promote microbial activity.

Operation of the system began in November 2001, but due to problems such as excessive unpleasant odors being generated due to high moisture content of material in the fermentation tank, the temperature of the air blown into the bottom of the fermentation tank was gradually increased.

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1388–6150/$20.00

Akadémiai Kiadó, Budapest, Hungary
Springer, Dordrecht, The Netherlands

Outline of the accident [1]

Sequence of events leading up to the explosion

- 4:48 am The fire alarm sounds. The security guard tries to open the door to the waste treatment room, but is forced to close the door due to excessive smoke. The 119 emergency services (fire station) number is dialed from the disaster prevention center.
- 4:56 am Fire brigade arrives
- 4:57 am Firefighters put on respiratory protective gear and enter the waste treatment room of the organic waste storage area. The room is filled with smoke and, upon sighting flames, the firefighters spray water and leave the room. To clear the smoke, the security guard is instructed to open the shutters on the south side of the building.
- 5:09 am An explosion occurs in the raw garbage processing room

Damage

The external wall panels of the organic waste processing room were severely damaged over 20 m, injuring eleven people, one seriously. However, the composting system itself hardly incurred any damage.

Investigation after the accident

It was found that the stirrer in the fermentation tank had stopped operating some time before the accident occurred. Continued supply of heated air of 130 to 150°C resulted in an increase of the temperature inside the fermentation tank for several hours before the fire occurred.

Materials and methods

Table 1 shows the typical composition of the raw organic waste. This composition of the waste was not found to vary considerably from month to month.

Thermal analysis

After the accident, samples of materials from different places in the fermentation tank were removed and evaluated for their heat generation ability and ignitability using a high-pressure differential thermal analyzer Rigaku HP-TG/DTA and a heat flux calorimeter Setaram C80.

High-pressure differential thermal analyzer [2]

The HP-TG/DTA measures the ignition temperature of a material by employing oxygen or air pressure. This method has been used by the U.S. Bureau of Mines to measure the ignition temperature of coal, and by the U.S. Air Force to evaluate the risk of ignition of lubrication oil. Example of measurement applications is given in Fig. 1. A 20 mg of garbage sample was heated from room temperature up to 500°C at a heating rate of 20 K min^{-1} under 1 MPa oxygen atmosphere. The onset temperature for heat generation is indicated by point B where the differential temperature curve (DTA curve) begins to rise, and the ignition temperature is indicated by point A where there is a sudden rise in the temperature curve.

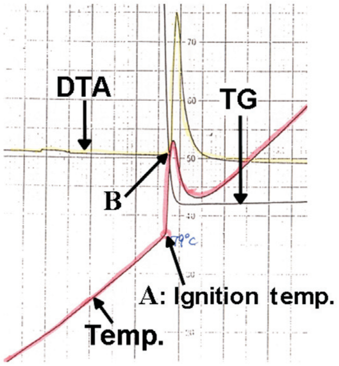

Fig. 1 HP-TG/DTS curve of raw garbage sample

Heat flux calorimeter

Since the quantity of sample used in measurements with the TG/DTA is low, it is difficult to measure the initial microscopic heat generation behavior. Consequently, a high-sensitivity calorimeter, the C80, was used to determine the thermal behavior between the onset of heat generation and the time of ignition. The C80 works on a principle analogous to that of a differential scanning calorimeter (DSC) by measuring heat flow of exothermic/endothermic reactions of samples resulting from temperature increase or isothermal maintenance. A cylindrical stainless steel or hastelloy C sample container (outer diameter of 17 mm, height 80 mm) was loaded with samples of up to 10 mL. A 1 g of sample was loaded under 1MPa oxygen atmosphere in a stainless steel closed container and heated from room temperature up to 180°C at a heating rate of 2 K min^{-1}.

Table 1 A typical composition of garbage (March, 2002)

Material	vegetable	fish paste	meet	fruit	bread, rice	bean	fish	deep fried
(mass.%)	32	24	18	16	7	2	1	0.2

Method of gas analysis

Analysis of heat generation behavior shows that samples can generate heat and reach ignition temperature. In addition, in the incident reported here, an explosion also occurred. From the nature of the damage to the facility caused by the explosion, it is thought that the explosion occurred inside the processing system or close to it. However, it does not appear that the organic waste in the equipment itself exploded. It therefore seems likely that the explosion resulted from gases formed by thermal decomposition in the air-filled upper part of the waste treatment tank and nearby. Thus, we analyzed the products associated with thermal decomposition and the combustion of the organic waste and investigated the gases that were generated.

To analyze the gases produced by thermal decomposition we used a headspace gas chromatograph mass spectrometer Shimadzu GC17A/QP-5000 and Tekmar headspace autosampler 7000 with CP-Silica plot column. Also, to analyze combustion gases we inserted samples in ULVAC gold image furnace under various atmospheric conditions such as air, nitrogen or oxygen, combusted them under air flow conditions, and then measured the amounts of carbon monoxide, carbon dioxide and other gaseous components produced with Shimadzu IR absorption type CO–CO_2 meter and detection tubes

Spontaneous ignition test [3]

Spontaneous ignition is a phenomenon that occurs when a mixture is left at a temperature lower than its ignition point for long hours. A spontaneous ignition test is a method of evaluating this phenomenon. The device used here was a spontaneous ignition tester Shimadzu SIT-2, a diagram of which is given in Fig. 3. A sample of the substance to be tested is placed at atmospheric pressure under adiabatic conditions and the time taken to reach ignition (adiabatic induction time) is measured. According to thermal ignition theory, it is possible to infer the reaction mechanism by which the sample reaches spontaneous ignition from the change in adiabatic induction time at the set initial temperature. This apparatus is useful for evaluating the hazard associated with accumulated metals, organic powders or refuse derived fuels (RDF) [4, 5].

After drying the samples taken from the fermentation tank, 1.0 g was weighed in a quartz sample container and then heated in a nitrogen gas stream at a prescribed temperature. At the point where 60 min after the temperature becomes constant, the circulating gas is switched from nitrogen to air, and the heat generated by oxidation is observed. Figure 4 shows the result obtained at the initial set temperature of 150°C. The graph confirms that the temperature rises about 390 min (=18000 sec) after air inflow commences, and that the temperature continues to rise until ignition occurs.

Results and discussion

Thermal analysis

Using the HP-TG/DTA, we compared the ignition temperature of fermentation tank samples after the fire. These results are summarized in Table 2 in relation to their position within the fermentation tank. Ignition temperature was observed to vary considerably relative to position within the tank, with some samples only igniting at approximately 170°C such as at the bottom in the center of the tank. This could be explained by the fact that after the stirrer stopped, high-temperature air for drying was still supplied to the tank, thereby greatly increasing the risk of ignition.

Representative results obtained with the C80 are given in Fig. 2. The measurements made with the high sample volumes permitted by the C80 show that heat generation started at lower temperatures – from approximately 110°C – than was possible with the HP-TG/DTA. It was found that the temperature of the drying air in the composting system, 130–150°C, was sufficient for starting an exothermic reaction. Furthermore, at the point where the temperature reaches 160°C, the pressure and heat generation curves rise

Table 2 Ignition temperatures of garbage samples measured by HP-TG/DTA

	Inlet side/°C	Center/°C	Outlet side/°C
Upper	244	255	208
Middle	201–226	216	217
Lower	210–220	174	260

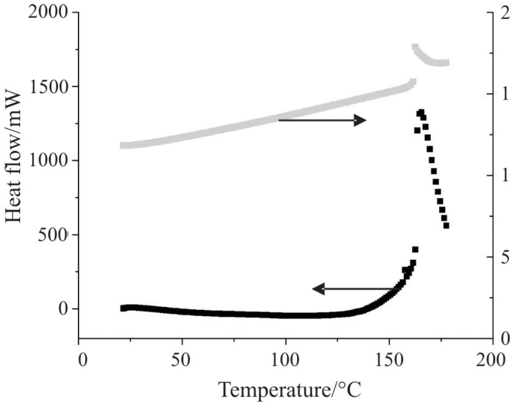

Fig. 2 Temperature and pressure profiles of raw garbage sample measured by C80

Table 3 Major gas products of raw garbage determined with GC-MS

No	Retention time/min	Area/μV sec	Name of substance	
1	7.5	1.1E+09	O_2	Oxygen
2	9.1	7.4E+09	CO_2	Carbon dioxide
3	11.6	7.6E+08	COS *	Carbonyl sulfide
4	12.1	7.7E+08	C_3H_8 *	Propane
5	13.0	2.5E+09	H_2S	Hydrogen sulfide
6	15.1	7.5E+08	C_3H_6	Propylene
7	16.0	1.1E+09	i-C_4H_{10}	Isobutane
8	16.6	1.3E+09	n-C_4H_{10} *	*n*-Butane
9	17.2	1.9E+09	CH_3Cl	Methyl chloride
10	17.8	1.1E+09	CS_2 *	Carbon disulfide
11	18.9	2.4E+09	SO_2 *	Sulfur dioxide
12	20.0	2.5E+09	n-C_4H_8	*n*-Butene
13	20.5	1.6E+09	n-C_5H_{12} *	*n*-Pentane
14	21.9	4.3E+09	CH_4S	Methanethiol
15	25.308	4.5E+09	n-C_7H_{16}	*n*-Heptane
16	26.875	6.5E+09	$C_5H_{10}O$	2-Methylfuran
17	27.322	2.2E+09	C_6H_6	Benzene
18	28.021	3.8E+08	C_2H_4O	
19	29.492	6.5E+09	$C_2H_4O_2$	
20	30.651	3.7E+09	n-C_8H_{18}	*n*-Octane

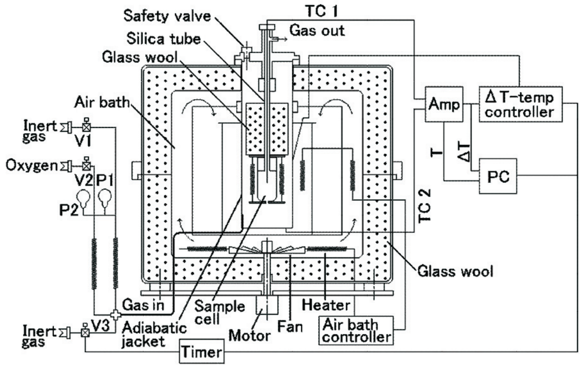

Fig. 3 Schematic diagram of SIT-2

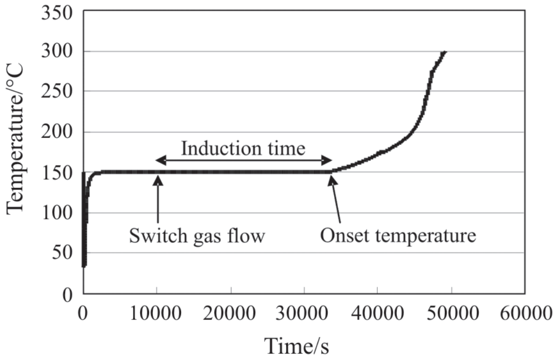

Fig. 4 Typical self-heating curve of raw garbage under adiabatic condition

suddenly and this is the point at which the sample ignites. Pressure also rises as a result of the accumulation of gases generated during combustion.

Generally, as the volume of the sample increases, the heat loss per unit mass decreases, thereby reducing the onset temperature. Without high-capacity stirring, the composting garbage gets deposited, and the material in the center of the fermentation tank reaches almost adiabatic conditions. As a result of self-heating, the risk of spontaneous ignition in response to the continued supply of drying air increases.

Decomposition and combustion gas analyses

Table 3 shows the chemical substances detected according to retention time. A '*' indicates identification by standard samples, while others were identified from libraries. The main chemical compounds were aliphatic hydrocarbons, hydrogen sulfides, ketones and aldehydes.

It is thought that hydrocarbons and sulfur compounds are generated by the breakdown of proteins, and hydrocarbons, ketones and aldehydes are generated by the decomposition of celluloses. The lower explosion limit of these gases is approximately 1.5–2%. It is assumed that the gases were formed by thermal decomposition, ignition and fire, eventually making explosion possible. For example, peak 8 indicates a threshold concentration of approximately 1% for butane, while peak 13, representing pentane in the measurement vessel, indicates a concentration of 3%. Since the explosion threshold for butane is 1.5% and that of pentane is 1.4%, the gas in the container can be considered to be in the range of explosion. Though this cannot strictly be compared with the real composting process, it does show that it was possible for gases generated within the system to enter the ranges of being capable of causing an explosion.

Spontaneous ignition test

The experimental results were organized as shown in Table 4. The adiabatic induction time in the table is defined as the time taken for the sample temperature, measured at 10-second intervals, to rise by 2.5°C after air inflow to the experimental device is allowed. In the spontaneous ignition test with SIT-2, tests were terminated as soon as the sample temperature reached 300°C due to the safety limitations of the equipment.

From Table 4, it can be seen that high initial temperatures were associated with low values for adiabatic induction time (Δt), the time taken for the temperature to rise by 2.5°C from the start of heat generation under adiabatic conditions. Based on the theory of reaction kinetics under adiabatic conditions, approximate values for these quantities are given by the relationship below.

$$\Delta t = A\exp(-E/RT) = 5.0\cdot 10^{-11}\exp(12544/T) \qquad (1)$$

where A is the pre-exponential factor [–], E is the apparent activation energy [kJ mol^{-1}], R is the gas constant [8.31 J mol^{-1} K]. From the experimental results E is determined to be 104 kJ mol^{-1}.

Given that the components and composition of the organic waste samples in this study were not uniform, identification of the various factors that contributed towards spontaneous heat generation and ignition behavior was difficult. It is clear, however, that if air is maintained at temperatures exceeding 125°C for more than several hours, after a certain induction time of moderate heat generation, reactions characterized by violent heat generation can commence and the likelihood of ignition occurring is markedly increased under certain conditions.

Evaluating the influence of fermentation

Method of bacterial phase analysis [6]

Along with a chemical analysis of target samples using elemental composition, pH, electrical conductivity, we also performed bacterial phase analysis on various bacteria that are capable of influencing the generation of heat and combustible gases, such as the hydrogen-generating eubacteria (EUB), and the methane-generating archaea (ARC). The assay methods listed below were used for all the bacteria.

(1) Direct count method:

Determines total bacterial counts in a test sample with a wet mass of 1 g.

(2) FISH method:

Determines the proportion of eubacteria and archaeabacteria communities in a sample.

(3) PCR: PCR-DGGE method

Evaluates the diversity of the eubacteria community in a test sample. Also, examines the probability of the presence of methane-generating archaeabacteria.

Results

Representative results from the bacterial phase analysis are shown in Table 5 according to where samples were collected. Based on these results, the probability of methane-generating archaeabacteria being present was considered low, and compared to the methane bacteria count in the methane fermentation tank. Similarly, the quantity present per gram was also considered low.

Table 4 Summary of spontaneous ignition test

Set temp/°C	Sample mass/mg	Gas flow	Induction time/min	Judgement
120	1003	air	–	No
125	1014	air	2528	Self-heat
130	1002	air	1802	Self-heat
135	1011	air	1068	Ignition
140	1025	air	849	Self-heat
150	1017	air	391	Ignition

Table 5 Summary of bacterial analysis of raw garbage samples

	Inlet side				Center						Outlet side			
	Upper		Lower		Suraface		Upper		Lower		Upper		Lower	
	EUB	ARC	EUB	ARC	EUB	ARC	EUB	ARC	EUB	ARC	EUB	ARC	EUB	ARC
A	< 0.001		0.1 - 30		37		0.05		41		0.03		0.02	
B	0–10	90–100	54–61	39–46	24	76	44	56	17	83	28	72	0	100

A: Total number of cells/*10^7 cells g^{-1}; B: Ratio of existence %

Assumed explosion mechanism [1]

In addition to the experimental results discussed above, we examined the factors underlying the explosion after considering various aspects related to the construction and operating conditions of the composting system. We then attempted to infer the cause of the accident.

Safety design problems

The over-heating protection system of the composting system's air heater works by measuring the air temperature in the heater and turning off the heater when the air temperature exceeds a predefined limit by more than 30°C for three consecutive minutes. However, even after the heater was turned off, the air supply was observed to continue. Furthermore, as soon as the temperature in the heater exceeded 200°C, all of the heaters are turned off, but the air supply is not turned off. Conversely, while there were temperature sensors at three positions on the side of the fermentation tank, the temperature inside the tank is not measured. Consequently, even if the temperature in the tank reaches an abnormally high level, it cannot be detected, and the supply air continues to be directed into the tank. As a result, a fire, if it were to occur, could intensify and expand.

Problems related to the design of the system

It was clear from the beginning of the system's operation that it was intended for use with biological materials. However, due to the high water content of the wastes and the generation of strong odors, the temperature of the air supplied to the fermentation tank was slowly increased and controlled within the range of 130–150°C. It would appear that associated with the increase in the drying temperature and the change in operating mode, drying came to be a major concern of the system.

Problems related to waste composition

As a secondary material, large quantities of sawdust were supplied to the composting system. It is presumed that this increased the thermal inertia of the system, and may also have increased the quantity of carbon monoxide generated at the time of ignition. Conversely, according to daily records showing the wastes supplied to the system, no deviation was detected in the type of waste to be treated. Even in the waste collected after the accident no inappropriate types of garbage such as metals were found.

Heat generation and ignitability of the waste itself

The raw garbage supplied to the composting system contains a substantial amount of moisture. If stirring is conducted, this moisture is distributed evenly, making ignition very difficult. On the other hand, heat generation testing of a dried sample observed that heat generation starts occurring at approximately 120°C, which suggests that ignition can occur at 135°C in a spontaneous ignition device. Also, analyses performed under high-pressure and temperature revealed several instances of where ignition temperature was substantially lower than this level. Even now, air at 130–150°C is still blown into the fermentation tank, but since substantially moist raw garbage is added steadily and stirred up in the tank, the risk of significant heat build up is avoided.

Shut down of the stirrer and drying of organic waste

Essentially, the purpose of the stirrer was to promote fermentation and drying of the waste by enhancing the permeability of composting system contents. However, in effect, the raw waste that is supplied daily is stirred has the effect of dispersing the moisture of the waste which would serve to suppress heat generation. In addition, the temperature of the external walls of the composting system were measured and recorded over the 48 h preceding the explosion. It was found that the temperature of the middle part of the external wall increased for some hours prior to the explosion. If the stirrer were operating, the temperature would have remained uniform, and the temperature rise would have been prevented. It is therefore assumed that the stirrer stopped operating.

Inferred mechanism of fire outbreak

Even after the stirrer stopped working, hot air was supplied to the composting system, and the waste in the area around the air supply opening became progressively drier and hotter. The waste in the lower part of the fermentation tank was compacted so that the circulation of the supplied air became uneven. At the starting temperature of heat generation of the dry garbage, 120°C, there was insufficient heat removal from parts with little or no air circulation. This resulted in a further increase in the rate of heat generation and finally ignition temperature was reached.

Likelihood of inflammable gas generation from fermentation

It is likely that air circulation at solidified parts of material within the organic waste treatment tank was inadequate and that methane gas may have been generated due to fermentation. It was in response to this possibility that a bacterial phase analysis was performed. However, it is considered unlikely that any significant quantity of gases would have been generated or that these contributed to the explosion that was produced.

Presumed mechanism of the explosion

As the organic waste became progressively drier, a part of it ignited, resulting in a fire. Consequently, as a result of combustion and thermal decomposition, a substantial quantity of inflammable gases was produced. This explosive mixture of gases, located in airspaces within the organic waste treatment tank, eventually reached the lower explosion limit and was thus ignited by the flames of the fire.

Acknowledgements

Authors wish to express their thanks to Mr. C. Imura for his excellent management of research investigation, Mr. S. Yamauchi of Sumika Chemical Analysis Service, Ltd. for performing SIT test, and also Aeon Co. Ltd., for giving the permission to publish the work.

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DOI: 10.1007/s10973-006-7637-8