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An integrated process investigation of self-sustaining incineration in a novel waste incinerator: Drying, pyrolysis, gasification, and combustion of sludge-plastic blends

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Utilization of waste-water sludge is one of the most difficult processes of environment protection because of the high moisture and contents of harmful substances. Incineration is the effective method of utilization of such waste mater. To deal with these issues more effectively, a novel sludge incineration technology was developed in this study. The results showed sludge drying, pyrolysis, gasification and incineration were achieved as a spectrum of combustion by a pilot screw model incinerator in one step. In practice, the primary chamber of this technology actually acted as both gasifier for organic matter and vitrifying reactor for ashes, and the combustion process was mainly completed in the secondary chamber. The pre-dried sludge blended with plastic successfully realized self-sustaining incineration in the incinerator, and the incineration temperature reached about 1000°C with complete combustion. The study primarily demonstrated co-incineration might be realized by mixing sludge and waste plastic in the novel incinerator, some adverse effects due to single sludge or waste plastic combustion may be avoided in co-incineration process in this way.

Key words: Incinerator, sewage sludge, waste plastic, self-sustaining incineration.

INTRODUCTION

In China, more than 600 wastewater treatment plants are currently operating, and consequently, about 5000 million kg of dry sewage sludge are produced annually. Furthermore, according to national planning, the municipal wastewater treatment rate is expected to increase to 40 to 50% by 2010, which will result in a considerable increase in sewage sludge production (Wang, 1997; Shanghai City Government, 2004; Tang and Zhao, 2005; Jiang et al., 2010). The growing shortage of suitable land for disposal sites strengthens the preference for sludge incineration in China. With the increasing cost of sewage sludge disposal which has

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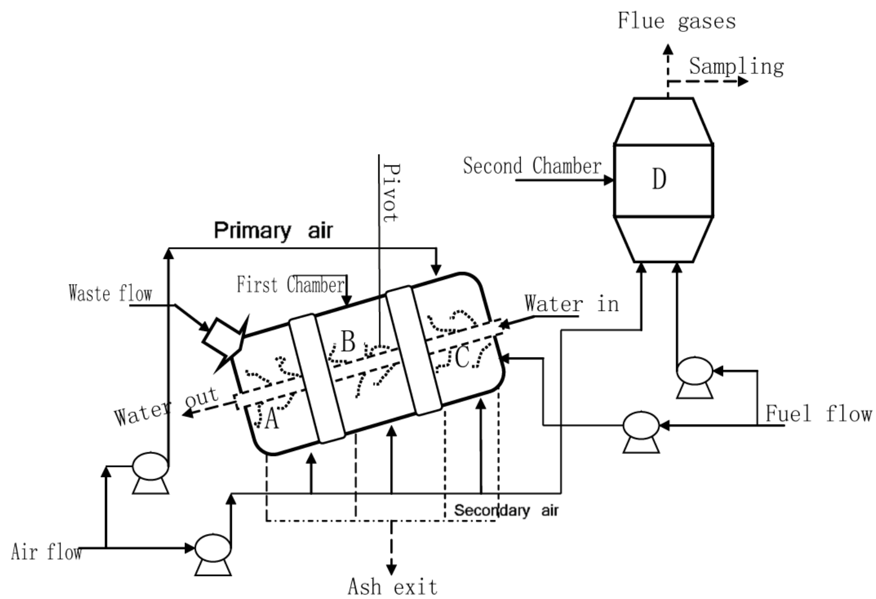

Figure 1. Flow chart of the new model screw incinerator.

posed a serious problem (Holmes et al., 1993; Kiely, 1997; Jimenez et al., 2004; NEPA, 1999; Zhang et al., 2002; Lowe, 1993). It may be expected that the role of incineration as a route for sludge disposal will also increase.

At the same time, waste plastic has become an environmental problem. For sustainable development, new ways of environmentally friendly waste plastic recycling have been of interest, and among them, the use of waste plastics as a supplemental fuel with coal has attracted interest (Jan and Weiss, 1996; Arapaima, 1996; Kim et al., 2002), plastics has greater fuel energy content than the sludge wastes. Therefore, co-incineration technology is a promising technique that offers a number of economical and environmental benefits, developments in national and international biomass waste recycling and reuse programmes have led to the process engineering design of an integrated unit.

The objective of this work is to investigate the operations in a novel integral type waste incinerator during the co-combustion of blends consisting of sludge and waste plastic, as an effort to improve and optimize the successful combustion with several processing variables, to obtain information about the running conditions, emissions and ashes of the biomass waste incinerator and evaluate the technological feasibility of the novel incinerator.

EXPERIMENTAL APPARATUS AND MATERIALS

Experimental setup

A process flowchart of the experimental apparatus is presented in Figure 1. The pilot screw model incinerator consists of two chambers. A primary chamber is 50 cm inside diameter and 5.0 m total length, a secondary chamber formed of two deformed cubes is 80 cm total height. The two chambers were connected with a transformative column integrated a whole and a long throat on the primary chamber for feeding. The primary chamber, a rotating cylindrical reactor with inner rotating helix fins, where drying (A zone), pyrolysis and gasification (B zone), combustion of sludge-plastic wastes and vitrification of residues occur (C zone), the primary chamber of the furnace is inclined, adjustable and rotatable at a low speed. Pre-dried solid waste can be turned and conveyed by screw, and consequently passed through varying temperature zones where drying, volatilising, combusting and cooling can take place. A hollow pivot with helix fins located in center of the primary chamber, which may regulate temperatures with cooling water, the helix fins are used to screw the waste forward and transfer the heat; the secondary combustion chamber (D zone), a deformed cube reactor with a fuel nozzle, where the yielded flue gases in the primary chamber were burnt out to completely destroy toxic organic compounds contained in the fuel gas.

For the newly installed pilot incineration unit, the ignition process was needed. At first, pre-drying blends was feed into the grate, and then gasoline was sprayed onto the waste blends. The flame-thrower was fixed on the top of the primary chamber ignited. Simultaneously, the auxiliary fuel was injected into the secondary chamber and ignited by another flame-thrower fixed on the top of the secondary chamber. After about 30~60 min, sludge-plastic waste was added. It took about 1 h to keep the combustion temperature higher than 850°C in the secondary chamber and about 2~3 h to make various parameters stable in the primary chamber.

Materials and analysis

The sewage sludge used in this study was obtained from an urban wastewater plant located in Suzhou and Guangzhou (China), which was treated with chemical softening and mechanical dehydration. The sewage sludge was dried and grounded into fine particles

Table 1. Main Characteristics of sludge and waste plastic used in the experiment.

Item	Proximate analysis (wt %)		Ultimate analysis (dry basis, wt %)	
Sludge	Volatile matter	59.23	C	41.87
			H	6.00
	Fixed carbon	8.63	N	5.79
			O	24.44
	Ash	39.14	S	1.83
			Cl	0.085
	Heating value (MJ/kg)	15.38	Others	19.985
Plastic	Volatile matter	80.12	C	59.14
			H	2.12
	Fixed carbon	0.023	N	0.40
			O	7.70
	Ash	19.91	S	0.61
			Cl	23.40
	Heating value (MJ/kg)	41.23	Others	6.63

before using in the experiments. The Poly (Vinyl Chloride) (PVC) used in this study was commercially available by Kaida waste recycle company, China (Its diameter <400 mm). Ultimate analyses of samples were determined using a CHN-600 LECO elemental analyzer. Table 1 shows the proximate analysis and ultimate analysis of test wastes, respectively. Thermo-gravimetric analyses (TGA) were carried out with the prepared samples using a LECO TGA-500. K-thermocouples were used to measure the temperatures and flue gas analyzer (Germany, Test 0330-2) was used to monitor gas concentrations, nine points in the primary chamber and three points in secondary chamber. For the nine points in the primary chamber, one was located on the top of the furnace body in each zone, other two points on the middle of both sides of the furnace body in each zone, respectively. For the secondary chamber, the three monitor points are located on the bottom, middle and top of the furnace wall, respectively. The raw waste and residues were characterized by scanning electron microscopy (SEM) to evaluate the alterations of surface morphology by the incineration.

RESULTS AND DISCUSSION

Pyrolysis characterization of waste

Figure 2 shows TGA results of sludge, waste plastic and their blends. For the sludge, three different behaviors were conducted in range 170 to 220°C, 300 to 400°C and 420 to 500°C. A primary weight loss was apparently taken place within range 170 to 220°C, two weight losses in range 300~500°C showed short transitions from volatilization to burn-off in sludge combustion, therefore, the two processes may be considered to take place parallel to each other (Gomez-Rico et al., 2005). Two main loss stages were observed in the PVC result. The primary weight loss within the range of 280 to 300°C was mainly due to HCl elimination in PVC and a polyenes structure formation (Makherjee and Gupta, 1983; et al., Szakacs 2004), the second weight loss stage within the range of 450 to 500°C was due to the thermal degradation of carbon chain of PVC that produced flammable volatiles (Troitskii and Troitskaya, 1999). For the blend sample, it showed that for the combustion, there was no marked separation between the drying ending and volatilizing beginning at temperatures, blend sample shortly burned after the volatilizing.

Operation parameters of self-sustaining incineration

Due to variations of the characteristics of the feed waste, complete combustion conditions including continuous changeable incineration temperature and adjustable air excess ratio were observed during the process of the co-incineration. At the beginning of test, the temperature of the primary chamber was heated to 100°C with gas fuel, thereafter, the semi-dried sludge (40 to 50 wt% dry matter) and waste plastic powder blends were fed into the incinerator by means of the screw type feeder. Supply air and gas fuel were distributed through ducts and kept at a constant feed rate until the pyrolysis gases could be automatically combusted in the secondary chamber, after, the gas fuel tank was closed.

Air is one of the most important parameter in combustion processes. The air amount is approximately proportional to the calorific value of fuel. A change of fuel composition may result in a change of the air amount that must be supplied to the chambers. The parameters on co-incineration of sludge and waste PVC blends were discussed in this section, which might show combustion situation of the incinerator. Firstly, keep feed and supply air a constant value, frequently monitored temperature changes in each zone, their results are shown in Figure 3,

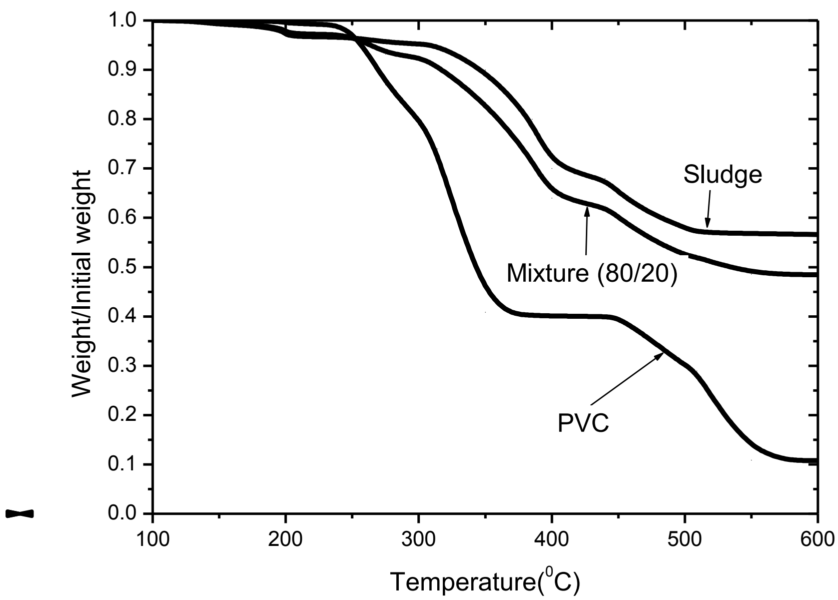

Figure 2. TGA profiles of the waste fuels.

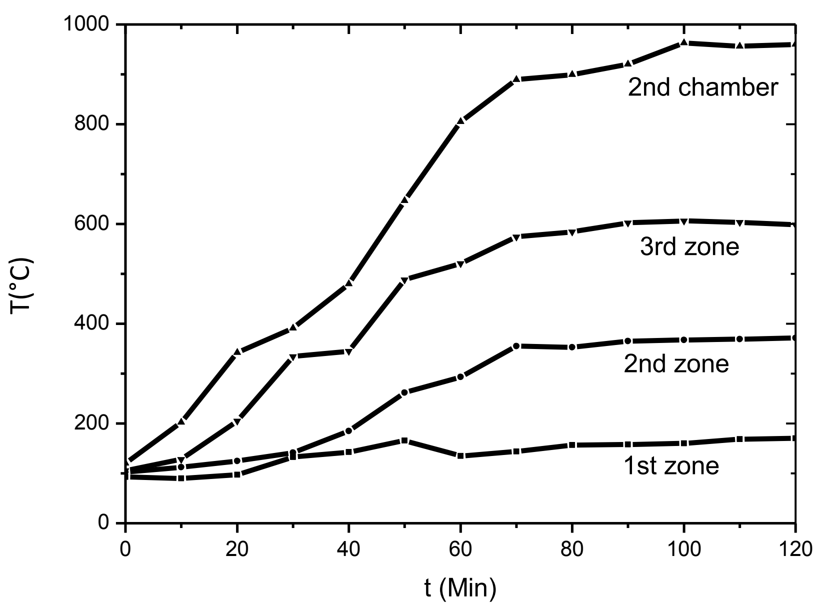

Figure 3. Distribution of temperatures in incinerator.

which shows the ranges of temperature distribution: 100~180°C in drying zone, 200~300°C in gasifying zone, and 400~600°C in combusting zone.

When the lighter wastes were screwed to the third segment with the helix fins, the furnace temperature rose up rapidly, and reached 400°C. Here, a heat balance was held among the newly ingoing wastes, the fume and the incineration. Table 2 shows that relation between the supply air and incineration temperatures in the incinerator. Experimental results showed the amount of supply air in the primary chamber was too small to complete incineration, the heat could not realize auto-incineration in the secondary chamber. Certainly, the secondary incineration could not be obtained for enough air in the third zone and less combustible gases in the secondary chamber. Incinerating temperatures and the total air excess ratio showed a negative and positive correlation in four zones.

Table 2. Effect of feed air on combustion.

Primary chamber						Secondary chamber		
First sect		Second sect		Third sect		Chamber		Out-flue
Air (m^3/h)	T(°C)	Air (m^3/h)	T(°C)	Air (m^3/h)	T (°C)	Air (m^3/h)	T(°C)	T(°C)
2.2	97.3	5.2	110.4	8.1	403.2	14	446.4	441.4
1.8	110.5	5.5	130.3	9.2	430.9	15	615.4	595.2
1.4	140.5	1.6	265.2	6	448.1	10	929.1	723.0
1.2	85.6	2.4	210.6	6	519.3	10	697.5	691.2
1.2	109.7	3.2	188.0	6	641.4	10	855.5	819.5
1	127.2	2.5	228.5	8	331.2	10	844.9	804.3
1	153.0	3	300.4	8	591.0	10	1020.1	875.1

The changes of the combustion temperatures are caused by the varies of oxygen contents in the air excess ratios, only when the total amounts of the oxygen in the supplied air can be reached to balance, and the produced heating energy cannot be flowed away due to a higher air excess ratio. Then the incinerating temperatures might be constantly maintained in each part in the whole system (Inguanzo et al., 2002). Another influencing factor of auto-incineration is that a right distribution of the supplied air in the primary chamber can burst violently out the combustible gases in the 3rd zone of the primary chamber. The operation conditions were optimized during the experiments: First stage air ratio: 0.5~0.7; Feed rate: 6~8.5 kg/h; Screw speed: 2~3r/min.

Incinerator temperatures with combustion

All operating conditions were kept constant except the temperatures in the experiments. At the beginning, the incinerator was heated, and upon attaining the temperature of 100°C, then, the blend samples were fed into the incinerator. The average temperatures of the nine points in the primary chamber and three points in the secondary chamber were calculated. Figure 3 shows experimental curves corresponding to drying, pyrolysis and combustion in dynamic runs. The drying curve showed the demanded temperature characteristic within a 150-200°C range. Based on the sludge dry studies (McGhee, 1991), the sludge moisture was characterized as free moisture which could be removed during a constant drying rate period. The blend wastes appeared to have some differences compared with single waste for pyrolysis property, sludge and waste plastic had a significantly high content of volatiles, its volatile carbon was up to 80% (Heo et al., 2000).

The pyrolysis in the secondary zone and combustion in the third zone showed approximately consistent results with the designed requirements. The blast starts of volatilization and the combustion beginning lead to a rapid increase of the chamber temperature within 70 min, consistent with the TGA results at 400 and 600°C, respectively. For the secondary chamber, the rapidly pyrolyzed gases cannot be completely combusted for having not enough time and air in the primary chamber, so the larger quantity of combustible gases flowed into the secondary chamber, subsequently auto-thermal combustion was realized successfully within a high temperature (about 1000°C), which definitely might destroy pollutants effectively in such a waste incinerator (Nottrodt et al., 1990).

Waste blend ratio with combustion

The energy is required for the evaporation of the moisture in the sludge. If the net energy is not sufficient for auto-thermal combustion, then supplementary fuel must be supplied the use of recycled plastic as a secondary substitute fuel for its high energy efficiency (Oral et al., 2005; Werle and Wilk, 2010). Figure 4 shows the plastic requirements as the supplementary fuel to maintain auto-thermal incineration. At 6 wt. % of PVC in the mixed waste, the average temperatures in the two combustion chambers were about 563.5 and 839.5°C, respectively. This began to maintain auto-thermal incineration, which means that the incinerator operating conditions were at acceptable levels. The blended waste, which is mixed with PVC and sludge, has the higher heating value as the higher co-incineration percentage. For example, the co-incineration percentage was 7 wt.%, the low heating value of the mixed waste was 17.19 MJ/kg, the average temperatures in the two combustion chambers were about 601.2 and 899.8°C, respectively. But, when the co-incineration percentages were 10 and 12 wt.%, the low heating value of the mixed waste was 17.83 and 18.48 MJ/kg, respectively. The average temperatures in the two combustion chambers were about 569.2 and 809.8, 435.7 and 646.8°C.

Therefore, as the co-incineration percentage increased, the combustion chamber temperature decreased and dropped to less than 435.7 and 646.8°C, respectively. The result shows that sludge, and 6 to 10% waste plastic blends might maintain auto-thermal incineration, however

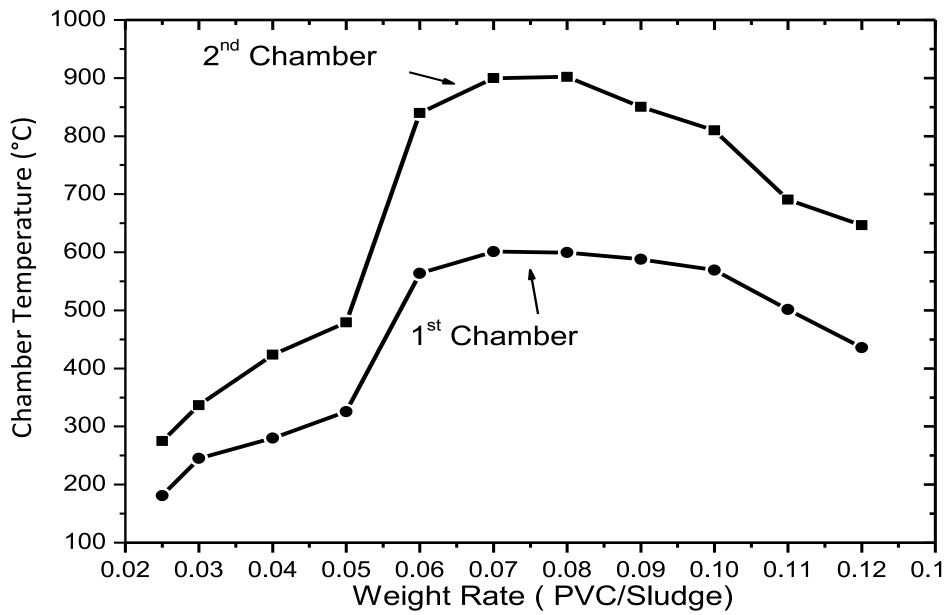

Figure 4. Blend ratio of waste fuels with combustion.

Table 3. Effect of feed rate on combustion (Gas: Vol.-%).

Feed (kg/h)	5	6	7	8	9
T (°C)	495.4	523.1	567.3	532.7	483.4
Burnout (%)	87.4	86.9	86.4	86.0	76.3
O_2	10.2	8.5	8.3	7.9	5.4
CO_2	6.2	7.3	8.8	8.9	9.2
CO	0.94	1.0	1.4	1.9	2.1

the overfull waste plastic in blend wastes would agglomerate with showing a burnt and sintered surface. Whereas the inside remains were unburned, because plastic materials were generally melt from surface to core due to low thermal conductivity, the problem of the ‘‘sticky phase’’ must be solved in the combustion systems (Oral et al., 2005). The amount of air is approximately proportional to the calorific value of the mixing waste fuel. For air flow below the stoichiometric requirement an oxygen deficient combustion regime is established within the waste matrix. This regime is characterized by low reaction temperatures, favors endothermic pyrolysis. The stoichiometry controls the reaction temperature, a PVC enhancement leads to a decrease in temperature for a constant total air.

Feed and screw rates with combustion

Incineration experiments were conducted in keeping constant operating parameters except variable feed rate in the incinerator, their temperatures, burnout rates and O_2 CO_2; CO vol.% were measured in each round at the third zone, the CO concentration is one of important parameters in combustion processes indicating the efficiency (Shi et al., 2009). The results are shown in Table 3. Experimental results suggested the temperature played a key index for the auto-thermal combustion, automatic combustion was difficult in happening when the temperature of the third zone was lower than 500°C. When the mixed waste was gradually supplied to the incinerator with a increase rate, the chamber temperatures and the CO contents were increased with the enhancement of the mixed waste, the burnout rate was maintained at similar levels, then the feed rate reached at 9 kg/h, the chamber temperatures in the 3rd zone was under 500°C, the co-combustion of the variations of the feed rate have also affected the emissions of gases and burnout rates. So, an optimal value of feed rate was set at 6 to 8.5 kg/h. For the rotation speed, keeping constant operating parameters except variable screw rates in the incinerator, the temperatures, burnout rates and O_2, CO_2; CO vol.% were measured in each round at the third zone, the experimental

Table 4. Effect of screw speed on combustion (Gas: Vol.-%).

Rotation speed (rpm)	Temperature(°C)	Burnout (%)	O_2	CO_2	CO
2	524.8	79.4	7.2	6.3	1.6
3	589.0	84.3	6.5	7.2	0.4
4	435.9	69.9	7.8	5.7	2.8

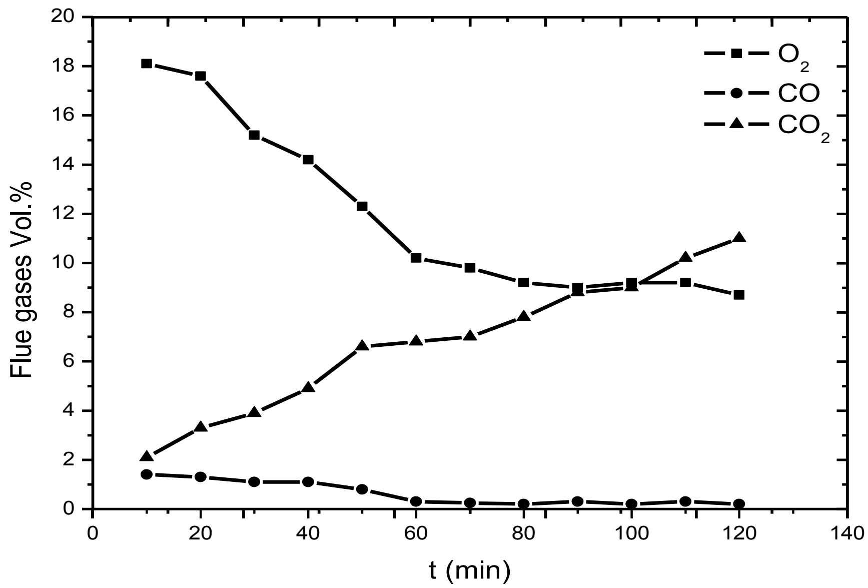

Figure 5. Variations of O_2, CO_2 and CO compositions in the secondary chamber.

Table 5. Combustion status in the incinerator (Mean; Gas: vol.-%).

Item	Zones			2nd chamber	Flue gas
	1st	2nd	3rd		
T(°C)	172.3	343.4	589.5	974.6	646.5
O_2	5.8	6.7	7.2	10.8	9.7
CO_2	2.3	4.6	6.2	8.9	8.2
CO	1.1	2.3	5.0	0.14	0.13

results, as shown in Table 4. With no change in the quantities of the mixed waste, the burnout rates and combustion temperatures were increased as the increase of the rotation speed from 2 to 3 rpm. If the rotation speed continued to increase to 4 rpm, the CO content was sharply increased to 2.8 vol. %, and the combustion temperature was only 435.9°C. This indicated that a rate in 4 r/min could decrease the temperatures and burnout rates in the third zone, and a significant change in O_2, CO_2 and CO values, so an optimal screw rate was set at 2~3 r/min.

Combustion efficiency

The O_2, CO_2 and CO concentrations were inspected in different parts of the incinerator for indicating combustion. In general, CO concentration can be used as a surrogate indicator for combustion efficiency. The results are shown in Figure 5 and Table 5. Curves in Figure 5 show the combusting situation according to the changes of O_2, CO_2 and CO concentrations in the secondary chamber. The CO_2 generation at the O_2 expense directly shows the combustion reactions, the profiles lead to an insight of the combusting process in the incinerator, oxygen concentrations were decreased with an increase of CO_2 composition, the CO behavior was associated with the imperfect combustion of hydrocarbons under a constantly supplied air. The measured temperatures in different sections showed that the mixtures were heated up slowly as they passed through from the primary zone to the third

Table 6. Evaluation of the designed combustion zones (rate, wt %).

Zones			Combustibility (Fly ash)
Drying 1st	Volatilization 2nd	Burnout 3rd	
64.3%	69.8%	91.2%	7.45%

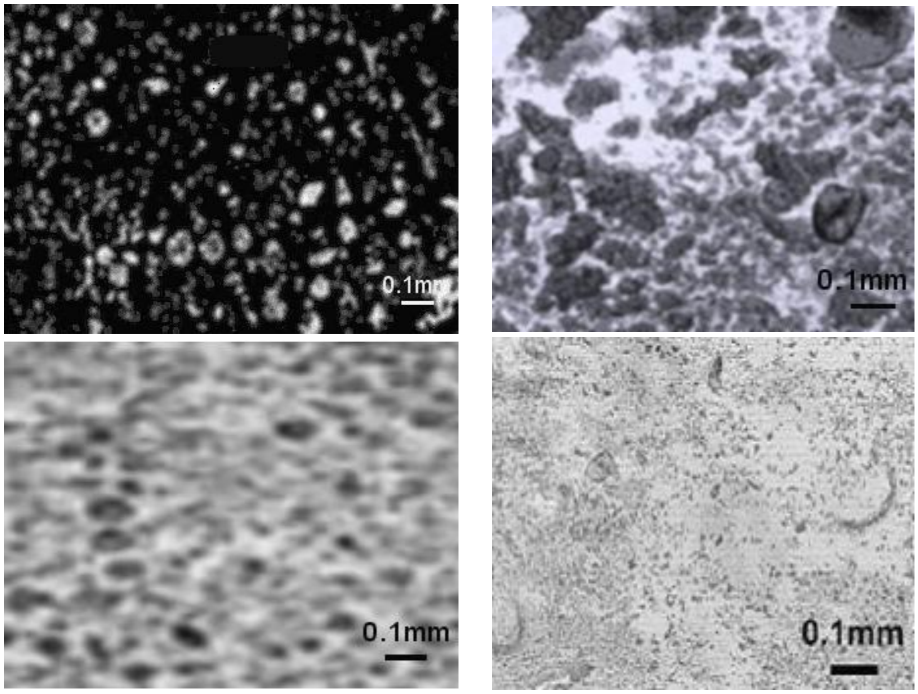

Figure 6. SEM micrographs of raw fuels and residues (In order: Raw wastes, Residues in volatile zone, Residues in burnout zone and Fly ash in secondary chamber).

zone. Table 5 shows constitution (%) of flue gases, under a constant total air excess ratio in the whole system, if the combustible gases from the primary chamber were incompletely incinerated and the formation of CO increased.

The emission of CO gradually decreased with enhancing the combustion efficiency. The results show that the residual O_2 was about 9.7 vol. %, CO, 0.13 and CO_2, 8.2vol. %. The contents of O_2 and CO_2 were slightly related to the waste feed period, but that of CO was more stabile, the combustion temperature in the secondary chamber was 974.6°C and a low CO emission was achieved. To understand drying, volatilizating and burnout in the incinerator, the overall combustion was analyzed with a selected case; the evaluated efficiency of co-combustion with corresponding measurement is presented in Table 6. In the heat balance system, the increase in char formation is the main reason for the reduction in temperature with the co-incineration. The residual oxygen increase under a constant total excess air can also be explained as being due to this large increase in the unburned char of waste. With the co-incineration of 7 wt.% PVC and 93 wt.% sludge waste, the unburned char fractions were 8.8 wt.% in the 3rd zone and 7.4 wt.% in fly ash from the secondary chamber, respectively, which was a low combustibility in fly ash.

The results showed a high efficient incineration and also indicated a successful process of drying and volatile release. Experiments provided the detected results with SEM on raw wastes and residues in the test, as shown in Figure 6. In contrast, the changes might be clearly observed among the raw wastes, residues in volatile zone, residues in burnout zone and fly ash in the secondary chamber, the obvious changes were shown from physical shapes to colors in the whole combustion process.

Pollutant control with incinerator characteristics

Although, combustion procedure may lead to the production of compounds like polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) (Wang et al., 1999). Two different process technologies have been adopted for waste incineration to reduce pollutants emission, namely, rotary kilns or thermal oxidizers. For instant, Dioxin emissions could be reduced below 0.1 ng I-TEQ/m^3 with rotary kilns (Rappe et al., 1992; McKay, 2002).

To minimize these possibilities for dioxin formation, the optimum design of an incinerator must pay particular attention to the four cornerstones of high destruction efficiency–temperature, time, turbulence and excess oxygen, such that PCDDs and PCDFs were certainly destroyed after adequate residence times and temperatures above 800°C (WHO, 1986; Vogg and Stieglitz, 1986). These might exert a different influence on the PCDD/Fs formation. Furnace temperature is one of the key variables that determine the combustion condition in incinerator, and it exerted a large influence on PCDD/Fs formation in a waste incineration system (Hatanaka et al., 2000; Lenoir et al., 1991). High furnace temperature, which intended to promote combustion reactions, was generally recommended to reduce their release. It was generally agreed that combustion temperatures of 850°C and a gas residence time of 2s or 1000°C and a gas residence time of 1 s were necessary for total destruction of PCDD/Fs (McKay, 2002).

Figure 3 shows the results of the temperature change during the combustion, the temperature of third zone in the primary chamber reached 600°C, and that of the secondary chamber reached 1000°C, it was certainly effective to keep the temperature of the secondary combustion chamber high enough to reduce the PCDD/Fs release. Three slag exits and the upper part of the secondary chamber were designed to minimize contact between flue gas and ash, which definitely inhibited the PCDD/Fs formation in this incinerator. Poor combustion was shown to result in relatively high emissions of dioxin formation or other pollutants, some studies reported a correlation of CO emission to PCDD/PCDF concentration during combustion processes (Yde et al., 1994; Sato et al., 1994), the O_2, CO_2 and CO values were parameters indicating high quality of combustion in the incineration chamber. Further studies (Raghunathan and Gullett, 1996; Ogawa et al., 1996; Lindbauer et al., 1992; Gullett and Raghunathan, 1997) have shown the presence of sulphur dioxide reduces the level of PCDD/F formation during incineration processes. A number of mechanisms have been proposed but the basic concept was that sulphur (Verhust et al., 1996) could scavenge the chlorine molecule in the presence of moisture producing SO_3 and HCl and also sulphur might block the activity of metallic catalysts in the ash thus reducing their PCDD/Fs activity formation (Chen et al., 1997).

The municipal sewage sludge taken as potential inhibitors of PCDD/PCDF formation has been investigated by some researchers (Ruokojarvi et al., 2001; Mininni et al., 2004; Caneghem et al., 2010). Addition of waste plastic to sludge waste changed the fuel composition (S/Cl ratio). The increase of S/Cl ratio in wastes could inhibit formation of chlorinated pollutants by generating SO_2 which could convert the chlorine formed via the Deacon reaction back to HCl (Fullana et al., 2004; Hagenmaler et al., 1987), this slowed chlorination process as HCl was a much poorer chlorination agent than chlorine. Werther and Ogada (1999) suggested that the relative lower PCDD/Fs concentration (in comparison with municipal waste incineration) in sewage sludge was perhaps due to the high concentration of sulfur in the sewage sludge. There are competitive reactions with transition metals between sulfur oxides and chlorides, thus, the formation of transition metal sulfides may reduce the produce of chlorinated pollutants. We are combining removal of pollutants in integrated processes and conducting a series of experiments to evaluate the effects of additives ($CaSO_3$, $Ca(OH)_2$) on pollutant formations (HCl SO_2 and Dioxin). Several cleaning steps are being integrated into the incinerator to test the cleaning efficiency. The chlorine generated from PVC combustion is consumed by reaction with the SO_2 from sludge in the fume gases, add additional adsorbents to capture heavy metals as well as dioxins/furans and other harmful components (Fullana et al., 2004; Hagenmaler et al., 1987; Skodras et al., 2007; Pandelova et al., 2007).

The cleaning process based on the reactions among Cl_2, SO_2, $CaCO_3$ and $Ca(OH)_2$ according to self-sustaining incineration in the waste incinerator has been investigated and it is possible to study the relations among HCl, SO_2 and dioxin in the incinerator in the future. It is possible to study the relations among HCl, SO_2 and dioxin in the incinerator in the future.

Conclusions

A pilot screw incinerator with two chambers was designed and constructed for sludge incineration. The co-combustion possibility of using waste plastics as a source of secondary fuel was available in the incinerator, the experimental results showed self-sustaining combustion was successfully realized by drying, pyrolysing and combusting process of pre-dry sludge with waste plastic blends, the success of this process was critically dependent upon the optimization of operating conditions. This strongly suggests that the combustibility of sludge with waste plastic could be improved by controlling these variables such as temperature, air-excess and so on. The designed incinerator can be effective to keep the temperature of the secondary combustion zone high enough to reduce pollutant release. On the other hand, the combined designs (2 s residence time, incline, screw feed and multi-exits) might result in reducing the pollutant concentration with completing combustion.

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