Estimating source strengths of HCl and SO$_2$ emissions in the flue gas from waste incineration

Hua Zhang[1,2,3], Siyuan Yu[1,2,3], Liming Shao[2,3,4], Pinjing He[2,3,4,*]

1. *State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai 200092, China*
2. *Institute of Waste Treatment & Reclamation, College of Environmental Science and Engineering, Tongji University, Shanghai 200092, China*
3. *Shanghai Institute of Pollution Control and Ecological Security, Shanghai 200092, China*
4. *Centre for the Technology Research and Training on Household Waste in Small Towns & Rural Area, Ministry of Housing and Urban-Rural Development, Shanghai 200092, China*

ARTICLE INFO

ABSTRACT

HCl and SO$_2$ emission is one of the major concerns related to municipal solid waste incinerator (MSWI). In this study, a material flow analysis model was developed to estimate the HCl and SO$_2$ concentrations in the MSWI flue gases (FGs), and their concentrations in the full-scale MSWI were monitored. The calculated concentrations of HCl and SO$_2$ in the FG were 770–1300 mg/Nm^3 and 150–640 mg/Nm^3, respectively, in close agreement with the monitored values. More than 99% of Cl and 92% of S from the FG were captured into solid residues by the air pollution control (APC) systems. Moreover, since only 48.4%–67.5% of Cl and 21.3%–53.4% of S were transferred to the FG from the municipal solid waste (MSW), it was more reliable to estimate the source strengths and release amounts of HCl and SO$_2$ in the FG based on the amounts of Cl and S in the APC residues (AR) and exhaust gas rather than in the MSW. This simple method is easily applicable and the estimated results could provide scientific basis for the appropriate design and operation of the APC systems as well as corrosion control of heat recovery systems.

© 2018 The Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Published by Elsevier B.V.

Introduction

Modern incineration has been widely used for waste treatment, and in recent years, the amount of incinerated municipal solid waste (MSW) has been increasing significantly in both developing and developed countries. In China, the percentage of the collected MSW in 660 cities being incinerated increased from 14.5% in 2006 to 37.5% in 2016 (NBSPRC, 2017). In the USA, around 29.0–33.7 million tons of MSW have been incinerated for energy recovery since 2000, accounting for about 13% of the generated MSW (USEPA, 2016). In the European Union (EU) (27 countries), the amount of incinerated MSW went from 75 kg per capita in 1999 to 127 kg per capita in 2015 (Eurostat, 2017).

The increasing amount of the incinerated MSW is accompanied by a higher generation of flue gases (FGs), which puts tremendous pressure on the control of pollutants emission from the FG.

The use of chlorine-containing plastics and table salt leads to high contents of organic chlorides (such as polyvinyl chloride) and inorganic chlorides (such as NaCl, KCl) in MSW, resulting in a total chlorine (Cl) content of 0.2%–2.5% (Belevi and Moench, 2000; Dal Pozzo et al., 2016; Shanghai Environmental Engineering Design Institute of Science and Technology Co., 2017; Zhou et al., 2015). During incineration, the Cl present in MSW is transformed in the presence of hydrogen or moisture into hydrogen chloride (HCl) (Wang et al., 1999), which is highly soluble in water and can affect the growth of plants (JRC, 2017).

---

* *Corresponding author. E-mail:* solidwaste@tongji.edu.cn (Pinjing He).

Waste paper and rubber, instead, contain sulfur (S), which forms sulfur dioxide (SO_2) in the furnace and is released with the FG, which can cause acidification and is also one of the secondary aerosol precursors (JRC, 2017). Therefore, from the perspective of air pollution reduction, it is necessary to control the concentrations and total emissions of HCl and SO_2 in exhaust gases. The initial reaction rates of HCl and SO_2 with slaked lime or other reagents added into the air pollution control (APC) systems are influenced by the source strengths of HCl and SO_2 (Chyang et al., 2010); it is therefore necessary to have fast and accurate information regarding their values in order to improve the efficiency of the APC systems for both source control and end-of-pipe control of acid gases.

One of the main sources of income for MSW incineration plants with systems for energy recovery from high-temperature FG is represented by the electricity produced through turbine generators. Compared with coal, MSW contains high amounts of Cl, potassium, sodium and other alkali metals, and lower amounts of S (Ruth, 1998). In the MSW incinerator furnace, these elements form alkali metal salts, HCl, SO_2, sulfate and other pollutants and emit a high-temperature FG (Demirbas, 2005), causing fouling of and depositions on the heat recovery systems, thus accelerating corrosion of the boilers. Therefore, the operating steam temperature and pressure in MSW incinerators are generally maintained low, at around 400°C and 4 MPa (Nielsen et al., 2000), limiting the conversation to electricity power to only 11%–36% of the heat produced (JRC, 2016). To control the corrosion of the heat recovery systems by the FG and increase the energy recovery efficiency, it is necessary to know the source strengths of the corrosive gases, HCl and SO_2. This allows the development of tailored counter-measures such as the use of corrosion-resisting coatings and novel steel materials (Bala et al., 2010).

Due to the complex composition of MSW, the ranges of HCl and SO_2 strengths in the FG may vary significantly. Recent researches (Antonioni et al., 2012; Chen et al., 2010) mostly focused on developing and improving FG treatment methods, verified whether the concentrations of pollutants in exhaust gas reached emission standards. Field operating parameters are also controlled by feedback of the concentrations in exhaust gas. Given the increasingly stringent emission control standards, however, the FG treatment system has become more and more intricate and usually combined unit processes are adopted (Dal Pozzo et al., 2017), making it difficult to optimize each unit through feedback control. When a new incineration plant is planned, the APC systems are usually designed based on the designed values of HCl and SO_2 concentrations in the FG from the boiler and the operating parameters adopted in previous plants or in lab experiments. Field observations have been conducted only in a few cases, since they are expensive and difficult to carry out for the high-temperature FG. Some researchers (Guo et al., 2001; Wey et al., 2008) studied the effects of the MSW composition and other factors on the emission of HCl and SO_2 through lab-scale incineration experiments, but the differences between lab experiments and field operation are still not clear. Therefore, it is of great value to develop a feasible method to estimate the source strengths of acid gases in practical applications.

Sommersacher et al. (2012) and Obernberger (2014) estimated the HCl and SO_2 concentrations in the FG generated from biomass incineration based on the contents of Cl, S and other

elements in biomass, and the results coincided with the values resulting from the lab-scale incineration. However, considering the differences between MSW and traditional fossil fuels or biomass fuels in terms of organics and inorganics contents, heat values and other physicochemical properties (Demirbas, 2004; Ruth, 1998), the pollutant release rules of coal and biomass may not be the case for MSW completely. Furthermore, the heterogeneity and complexity of the MSW composition make it more difficult and uncertain to calculate the HCl and SO_2 concentrations in the FG merely on the basis of elemental composition of MSW.

The objective of this paper is to establish a reliable method for estimating the source strengths of HCl and SO_2 in the FG from MSW incineration through a material and substance flow analysis model for the APC systems. The estimated values were compared with field monitoring values to prove its feasibility and applicability. The result is expected to provide a basis for emission control of HCl and SO_2, as well as for research on the corrosion mechanism of heat recovery systems and other facilities in MSW incineration plants.

1. Material and methods

1.1. Flow analysis model

The material flow in the MSW incineration process is shown in Fig. 1. On the basis of the law of mass conservation, the flow balance of materials and substances can be described with Eqs. (1) and (2).

$$\sum_i M_{\text{Input } i} = \sum_j M_{\text{Output } j} \tag{1}$$

$$\sum_i F^x_{\text{Input } i} = \sum_j F^x_{\text{Output } j} \tag{2}$$

where $M_{\text{Input } i}$ (kg/day) and $M_{\text{Output } j}$ (kg/day) are the mass flux of input i and output j, respectively, $F^x_{\text{Input } i}$ (kg/day) and
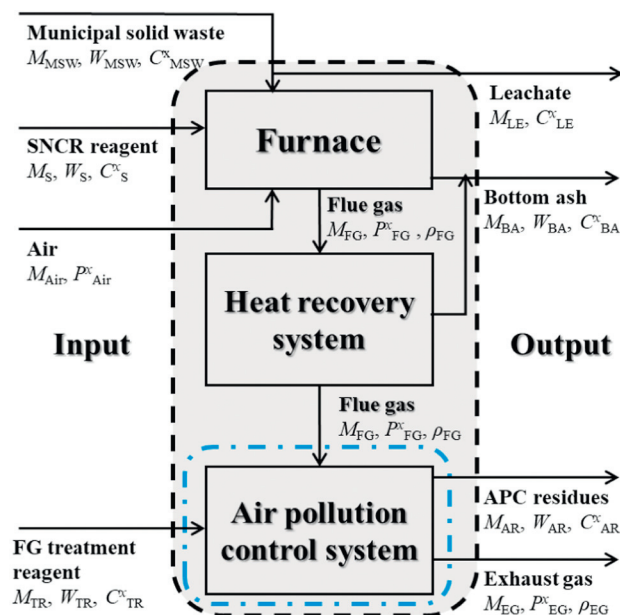

Fig. 1 – Material flow in the MSW incineration process.

$F^x_{\text{Output } j}$ (kg/day) are the mass flux of element x contained in input i and output j, respectively; and x refers to either Cl or S.

The substance flow balance of Cl and S in the APC systems can be described with Eq. (3).

$$F^x_{\text{TR}} + F^x_{\text{FG}} = F^x_{\text{AR}} + F^x_{\text{EG}} \tag{3}$$

where F^x_{TR}, F^x_{FG}, F^x_{AR}, F^x_{EG} (kg/day) are the mass flux of element x in the added treatment reagents (TR), the FG, the APC residues (AR), and the exhaust gas (EG), respectively.

Slaked lime, sodium hydroxide and other reagents are added to the APC systems to remove HCl, SO_2 and other acid gases, while activated carbon is added to adsorb heavy metals and dioxins. The total amount of TR added into the APC systems only occupies around 0.25%–1.6% of the mass of incinerated MSW (China GDE Engineering Co., 2006; College of Environmental Science and Engineering, 2015; China Wuzhou Engineering Group, 2013; Zhang et al., 2008), and the Cl and S contents in the added reagents are low (<1%) (Ministry of Industry and Information Technology of the People's Republic of China, 2009; National Bureau of Petroleum and Chemical Industry of the People's Republic of China, 1999), so the amount of x contained in the reagents may be neglected, i.e., $F^x_{\text{TR}} \approx 0$ kg/day.

The total amounts of Cl and S in the AR can be calculated from Eq. (4). Based on the monitored HCl and SO_2 emission in the EG, Eq. (5) can be applied to obtain the total amounts of Cl and S emitted with EG. TR added into the APC systems only remove HCl, SO_2 and other acid gases as well as some trace heavy metals, thus bringing negligible changes to the normal volume of the FG (Wang, 2016). Meanwhile, because of the variable amount of the incinerated MSW, large differences can be observed between the actual and designed FG volumetric flow, when estimating the HCl and SO_2 concentrations in the FG, since the normalized volumetric flow of the FG from the furnace is approximately equal to that of the EG (Eq. (6)). Then the HCl and SO_2 concentrations can be deduced from Eq. (7).

$$F^x_{\text{AR}} = M_{\text{AR}} \times \left(1 - \frac{W_{\text{AR}}}{100}\right) \times C^x_{\text{AR}} \times 10^{-6} \tag{4}$$

$$F^x_{\text{EG}} = M_{\text{EG}}/\rho_{\text{EG}} \times P^x_{\text{EG}} \times 10^{-6} \tag{5}$$

$$M_{\text{FG}}/\rho_{\text{FG}} \approx M_{\text{EG}}/\rho_{\text{EG}} \tag{6}$$

$$P^y_{\text{FG}}(\text{mg/Nm}^3) = r^y \times \frac{F^x_{\text{FG}}}{M_{\text{FG}}/\rho_{\text{FG}}} \times 10^6 = r^y \times \frac{F^x_{\text{AR}} + F^x_{\text{EG}}}{M_{\text{FG}}/\rho_{\text{FG}}} \times 10^6 \tag{7}$$

$$= r^y \times \frac{M_{\text{AR}} \times \left(1 - \frac{W_{\text{AR}}}{100}\right) \times C^x_{\text{AR}} + M_{\text{EG}}/\rho_{\text{EG}} \times P^x_{\text{EG}}}{M_{\text{EG}}/\rho_{\text{EG}}}$$

where M_{AR}, M_{EG}, and M_{FG} (kg/day) are the mass flux of generated the AR, the EG, and the FG, respectively; W_{AR} (%) is the moisture content of the AR; C^x_{AR} (mg/kg) is the content (dry basis) of element x in the AR; P^x_{EG} (mg/Nm³) is the normalized concentration of element x in the EG; ρ_{EG} and ρ_{FG} (kg/Nm³) are the normalized density of the FG and the EG respectively; P^y_{FG} (mg/Nm³) is the normalized concentration of y (HCl or SO_2) in the FG; and r^y is the molar mass ratio of HCl to Cl or of SO_2 to S, i.e., 1.028 and 2.000, respectively.

The standard deviation of the above calculation can be obtained from Eqs. (8)–(12) using the error of each item.

$$\begin{aligned} s_{F^x_{\text{AR}}} = 10^{-6} \\ \times \sqrt{\left(1 - \frac{W_{\text{AR}}}{100}\right)^2 \times C^{x\,2}_{\text{AR}} \times s^2_{M_{\text{AR}}} + \left(1 - \frac{W_{\text{AR}}}{100}\right)^2 \times M^2_{\text{AR}} \times s^2_{C^x_{\text{AR}}} + M^2_{\text{AR}} \times C^{x\,2}_{\text{AR}} \times s^2_{\left(1 - \frac{W_{\text{AR}}}{100}\right)}} \end{aligned} \tag{8}$$

$$s_{M_{\text{EG}}/\rho_{\text{EG}}} = \frac{\sqrt{\rho^2_{\text{EG}} \times s^2_{M_{\text{EG}}} + M^2_{\text{EG}} \times s^2_{\rho_{\text{EG}}}}}{\rho^2_{\text{EG}}} \tag{9}$$

$$s_{F^x_{\text{EG}}} = 10^{-6} \times \sqrt{P^{x\,2}_{\text{EG}} \times s^2_{M_{\text{EG}}/\rho_{\text{EG}}} + (M_{\text{EG}}/\rho_{\text{EG}})^2 \times s^2_{P^x_{\text{EG}}}} \tag{10}$$

$$s_{F^x_{\text{FG}}} = \sqrt{s^2_{F^x_{\text{EG}}} + s^2_{F^x_{\text{AR}}}} \tag{11}$$

$$s_{P^y_{\text{FG}}} = r^y \times 10^6 \times \frac{\sqrt{(M_{\text{EG}}/\rho_{\text{EG}})^2 \times s^2_{F^x_{\text{FG}}} + F^{x\,2}_{\text{FG}} \times s^2_{M_{\text{EG}}/\rho_{\text{EG}}}}}{(M_{\text{EG}}/\rho_{\text{EG}})^2} \tag{12}$$

where $s_{F^x_{\text{AR}}}$, $s_{M_{\text{EG}}/\rho_{\text{EG}}}$, $s_{F^x_{\text{EG}}}$, $s_{F^x_{\text{FG}}}$, $s_{P^y_{\text{FG}}}$, $s_{M_{\text{AR}}}$, $s_{C^x_{\text{AR}}}$, $s_{\left(1 - \frac{W_{\text{AR}}}{100}\right)}$, $s_{M_{\text{EG}}}$, $s_{\rho_{\text{EG}}}$ and $s_{P^x_{\text{EG}}}$ are standard deviations of F^x_{AR}, $M_{\text{EG}}/\rho_{\text{EG}}$, F^x_{EG}, F^x_{FG}, P^y_{FG}, M_{AR}, C^x_{AR}, $(1 - \frac{W_{\text{AR}}}{100})$, M_{EG}, ρ_{EG} and P^x_{EG}, respectively.

Due to the negligible amount of Cl and S contained in the air fed to the furnace and in the reaction reagents added to the APC systems, Cl and S present in MSW are the sole source of HCl and SO_2 found in the FG. During incineration, a part of the Cl and S are converted into HCl and SO_2 and transferred to the APC systems along with the FG (Nielsen et al., 2000; Uemiya et al., 2001). The residual Cl and S are discharged with bottom ash (BA) and leachate, therefore, the material balance in furnace can be described by Eqs. (13)–(16).

$$F^x_{\text{MSW}} = F^x_{\text{FG}} + F^x_{\text{BA}} + F^x_{\text{LE}} \tag{13}$$

$$F^x_{\text{MSW}} = M_{\text{MSW}} \times \left(1 - \frac{W_{\text{MSW}}}{100}\right) \times C^x_{\text{MSW}} \times 10^{-6} \tag{14}$$

$$F^x_{\text{BA}} = M_{\text{BA}} \times \left(1 - \frac{W_{\text{BA}}}{100}\right) \times C^x_{\text{BA}} \times 10^{-6} \tag{15}$$

$$F^x_{\text{LE}} = M_{\text{LE}} \times C^x_{\text{LE}} \times 10^{-6} \tag{16}$$

where F^x_{MSW}, F^x_{BA}, and F^x_{LE} (kg/day) are the mass flux of element x in the MSW, the BA, and leachate (LE) respectively; M_{MSW}, M_{BA}, and M_{LE} (kg/day) are the mass fluxes of the MSW, the BA, and leachate respectively; W_{MSW} and W_{BA} (%) are the moisture contents of the MSW and the bottom ash respectively; and C^x_{MSW}, C^x_{BA}, and C^x_{LE} (mg/kg) are the contents of x in the MSW, the bottom ash and the leachate respectively.

1.2. Sample collection and analysis

The AR (5–10 kg) and the BA (100–150 kg) samples were collected from four MSW incineration plants operating in stable conditions. The treatment capacities of the plants are shown in Table 1. The AR were collected from the ash tanks which contained the mixed ash from both semi-dry/dry scrubbers and bag filters. The moisture contents of the samples were analyzed by drying at 105°C until a constant mass was attained. The contents of Cl and S in the ash samples were analyzed with X-ray fluorescence spectrometry (XRF, UniQuant, Thermo, USA). Considering the variability in daily generation of the AR and the bottom ash, the

Table 1 – Treatment capacities of the four MSW incineration plants and the contents of Cl and S in the AR.

Plants	Treatment capacity (ton/day)	Content of Cl in the AR (mg/kg)	Content of S in the AR (mg/kg)
A	4 × 750	2.38 × 10^5	2.28 × 10^4
B	4 × 500	2.11 × 10^5	1.63 × 10^4
C	3 × 400	1.64 × 10^5	4.07 × 10^4
D	3 × 350	1.57 × 10^5	2.60 × 10^4

MSW: municipal solid waste; AR: APC residues.

average daily yields of AR and BA were obtained by dividing the total annual generation by 365 days. During stable operation of the incineration plants, 25 L of leachate were taken from the garbage pit of the plants. The concentration of Cl in the leachate was measured by AgNO$_3$ titration. The concentration of S in the leachate was analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES, ICP-720ES, Agilent, USA) after nitric acid digestion. The generated amount of leachate accounted for about 10%–25% of the total MSW amount (Chen and Christensen, 2010; Zhang et al., 2008). The HCl and SO$_2$ concentrations data in EG as well as the normalized volumetric flow of EG used were the average values calculated using the daily real-time results (Laogang Renewable Energy Utilization Center, 2017; Shanghai Liming Resource Recycling Co., 2017) monitored in four large-scale incineration plants throughout the whole year of 2016. The standard deviations were calculated as α = 0.05. The field concentrations of HCl and SO$_2$ in the FG from the boiler were monitored in the incinerator A (Wang, 2016).

2. Results

2.1. Mass fluxes of HCl and SO$_2$ in the FG

Table 1 shows the contents of Cl and S in the AR. The mass flux of Cl and S in the FG from the four incineration plants can be calculated from Eqs. (4)–(7). The distribution of the two elements in the EG and the AR is shown in Fig. 2. The mass fluxes of Cl and S were 4860–9470 kg/day and 570–1500 kg/day, respectively. More than 99% of the Cl present in the FG was captured into the residues by the APC systems, only 0.1%–0.7% of the total Cl was emitted into the environment with EG. Compared to Cl, the proportion of S captured by the APC systems was slightly lower, varying between 92.8%–99.8%. Antonioni et al. (2012) investigated the removal efficiencies of Cl and S in the APC system of an incineration plant in Europe, and the results were 99.7% and 97.5%, respectively, in line with those obtained in the present work. Jannelli and Minutillo (2007) reported the removal efficiencies of HCl and SO$_2$ to be 99% and 86% in a refuse derived fuel incineration plant, indicating that the removal efficiency of SO$_2$ was lower than that of HCl.

Lime or other alkaline absorbents are usually employed in the APC systems to remove HCl and SO$_2$ before the bag filter. The reaction rate of Ca(OH)$_2$ with HCl is much faster than with SO$_2$, so only a slightly over-stoichiometric of lime content is needed to convert HCl into CaCl$_2$ (Jannelli and Minutillo, 2007). The reaction products of lime and SO$_2$, namely CaSO$_4$ and CaSO$_3$, which may cover the surface of reagents, are weakly soluble in water and thus prevent SO$_2$ from diffusing into the pores of the absorbents (Chen et al., 2010). As a result, under the same reaction conditions (i.e., temperature, relative humidity, flow rate), the removal efficiency of SO$_2$ is lower than that of HCl (Garea et al., 1997), and the distribution of S in EG is a bit higher. Measurement of annual cumulative emission (Tian et al., 2012) also verify that the SO$_2$ emission in EG deriving from MSW incineration is higher than that of HCl.

Most of the Cl and S were captured by the APC systems (Fig. 2), therefore, even if information on the source strengths of HCl and SO$_2$ is lacking, the mass fluxes of Cl and S in the FG can be estimated from the data on the generation of the AR and their Cl and S contents. The amount of Cl released from the furnace can be estimated accurately by this method, but as for S, whose proportion in the AR fluctuates, the accuracy will be a little lower.

2.2. Estimated concentrations of HCl and SO$_2$ in the FG

Fig. 3 shows the HCl and SO$_2$ concentrations in the FG from the four incineration plants, as estimated by the material flow
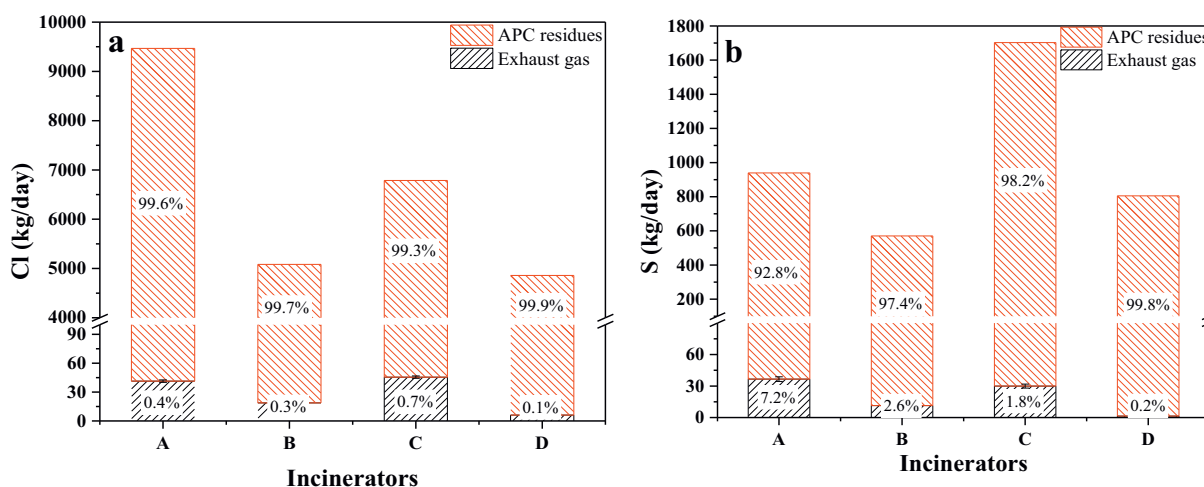
Fig. 2 – Flux and distribution of Cl (a) and S (b) in the outputs of the APC systems.
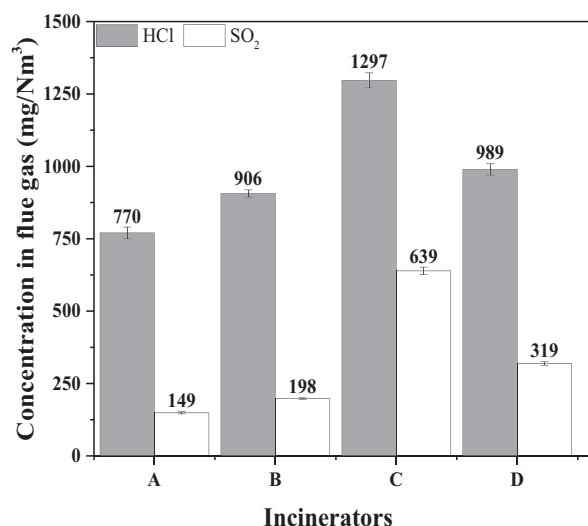
Fig. 3 – Estimated HCl and SO$_2$ concentrations in the flue gas from boiler in different plants.

and substance flow analysis model for the APC systems. The discrepancy between the HCl source strengths among different plants was small, and the estimated range was 770–1300 mg/Nm^3, close to the value (915 mg/Nm^3) determined by Antonioni et al. (2012). The differences in MSW composition, operation parameters, and incineration amount could be the cause of the variations of HCl concentration. Similar to the values present in literature (Antonioni et al., 2012; Chyang et al., 2010), the estimated SO$_2$ concentration in the FG was relatively low, varying in the 150–640 mg/Nm^3 range. The Cl content in the MSW is relatively higher than that of S (Zhou et al., 2015), and some of the Cl is present in the form of organic chloride, which is easily released (Chi et al., 2005; Wey et al., 2008). The temperature of around 850°C, at which the furnace operates, is sufficient for the transformation of most of the Cl contained in MSW into HCl and its release with the FG (Guo et al., 2001; Kuo et al., 2008). On the other hand, the fraction of S converted into gaseous SO$_2$ is low due to good thermal stability of sulfate (Frigge et al., 2016), the high moisture content of the MSW, the strong S retention of alkali metals such as K and Na, and the good SO$_2$ absorption capacity of humid substances (Wen et al., 2006). These are the main reasons for which the source strength of SO$_2$ was lower than that of HCl.

2.3. Verification of the estimated HCl and SO$_2$ concentrations

In plant A, the HCl and SO$_2$ concentrations in the FG from the boiler were monitored (Wang, 2016). The measured HCl concentration in the FG was lower than the estimated value by 29.0%–32.3%. This result may be due to the fluctuation in HCl concentration, and to the high solubility of HCl in condensate water, which may have caused a decrease in the concentration values, measured by FG analyzer. The estimated SO$_2$ concentration in the FG coincided with the monitored values, which indicates that it is rational to estimate the HCl and SO$_2$ concentrations in the FG from boiler from the total amounts of Cl and S contained in the AR.

3. Discussion

3.1. Migration of chlorine and sulfur in MSW during incineration

The flow analysis of Cl and S during incineration was also conducted. The inlet contents of moisture, Cl and S in the MSW were set to 51.86%–60.65% (Shanghai Environmental Engineering Design Institute of Science and Technology Co., 2017), 1.25%–1.52% (Zhou et al., 2015), and 0.28%–0.31% (Zhou et al., 2015), respectively. Fig. 4 shows the Cl and S amounts in MSW and in incinerator byproducts (plant C is not included due to the lack of data of Cl and S in MSW). For plants A and B, the total amounts of Cl and S in the MSW were approximately equal to the sum of Cl and S in the FG, the bottom ash and leachate, indicating that the estimated concentrations and fluxes of Cl and S in the FG met the material balance and were therefore, reliable. The estimation of Cl flow in plant D agreed with material conservation, while the amount of S in the MSW was lower than the sum of S in the FG and the bottom ash. This may be due to the variation in the MSW composition. The results can be influenced by the complexity and fluctuation of the MSW composition, elemental contents in the bottom ash, the AR and the leachate, and some deposition of alkali chlorides in furnace (Demirbas, 2004; Schumacher et al., 2016).

During the storage in incineration plants, 9.2%–16.1% of the Cl and 5.2%–9.0% of the S contained in the MSW were released into the leachate (Fig. 5). During the incineration process, 48.4%–67.5% of the Cl and 21.3%–53.4% of the S initially present in the MSW migrated into the FG; while the remaining contents of Cl and S were retained in the form of more stable compounds in the BA (Li et al., 2009). By analyzing behavior of the elements in an incineration plant Switzerland, Belevi and Moench (2000) found that around 89% of Cl and 67% of S were transferred into the FG, whereas around 11% of Cl and 33% of S were discharged with the BA. The migration features observed in this study were similar, although the proportions of Cl and S migrating into the FG were lower, due to the high moisture content of MSW, which
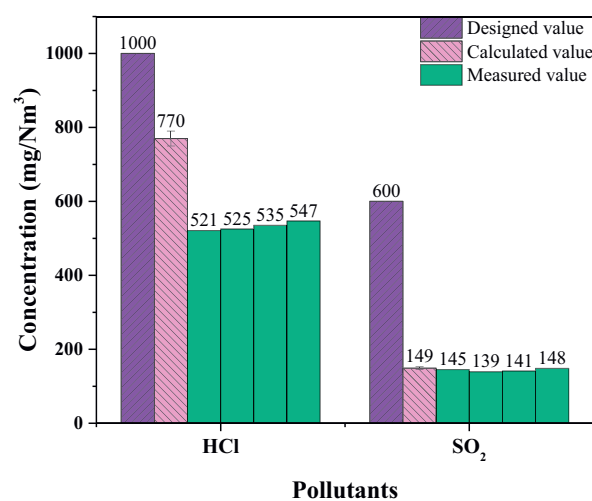

Fig. 4 – Comparison of the monitored HCl and SO$_2$ concentrations with estimated values in the flue gas from boiler.
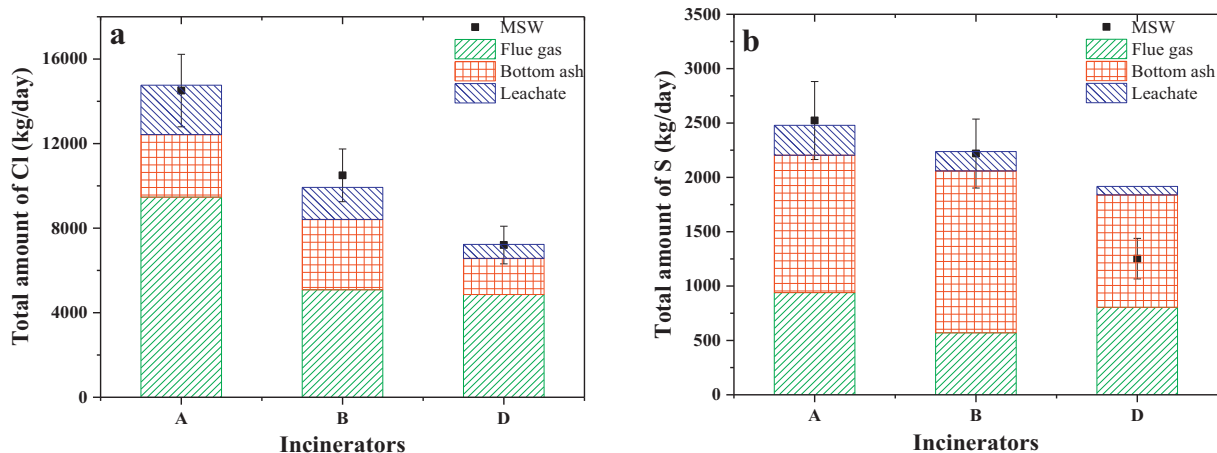
Fig. 5 – Material flow of Cl (a) and S (b) in MSW incineration plants.

produced big amounts of leachate and reduced the Cl and S contents in the incinerated waste. The element Cl is more easily transferred into the FG, while S prefers to remain in the BA. The majority of organic chlorides in the MSW decomposes in the furnace forming HCl (Guo et al., 2001). In addition, because of their lower stability during incineration compared to metal oxides (Nielsen et al., 2000), alkali chlorides and heavy metal chlorides formed during incineration are more volatile. As the temperature increased from 600°C to 800°C, the proportion of Cl migrating into the FG increased from 59% to up to 90% (Liu et al., 2000). Part of the S contained in the MSW exists as sulfates, which has a good thermal stability and low volatility, the incineration temperature is not sufficient for S to pass to gas phase (Frigge et al., 2016). At the same time, HCl in the FG promotes the conversion of SO_2 to SO_3 to some extent (Liu et al., 2000), making it easier for S to be captured by water vapor in the FG and to deposit as sulfate. It can be concluded that because of the fluctuation in Cl and S migration to the FG, the MSW composition and leachate production, the flow analysis based on the composition of more stable and uniform products

(the AR and the FG) is more reliable to estimate the source strengths of HCl and SO_2 in the FG.

3.2. Rationality of designed values for HCl and SO_2 concentrations in the FG

Fig. 6 shows a comparison between designed and estimated HCl and SO_2 concentrations in the FG from waste heat boiler in plants A, C and D. For plant C, the designed HCl and SO_2 concentrations were close to the estimated ones, with a deviation of 2.47% and 6.10%, respectively. The designed HCl and SO_2 values for plants A and D were 1000 mg/Nm^3 and 600 mg/Nm^3, and 1265 mg/Nm^3 and 580 mg/Nm^3, respectively, much higher than the estimated values. These differences caused a great deviation in the selection of gas cleaning process and operating parameters of the APC systems, which in turn greatly affect the removal efficiency of SO_2. An accurate estimation of the source strengths of HCl and SO_2 will have a positive effect on the adjustment and optimization of technological parameters of the APC systems.
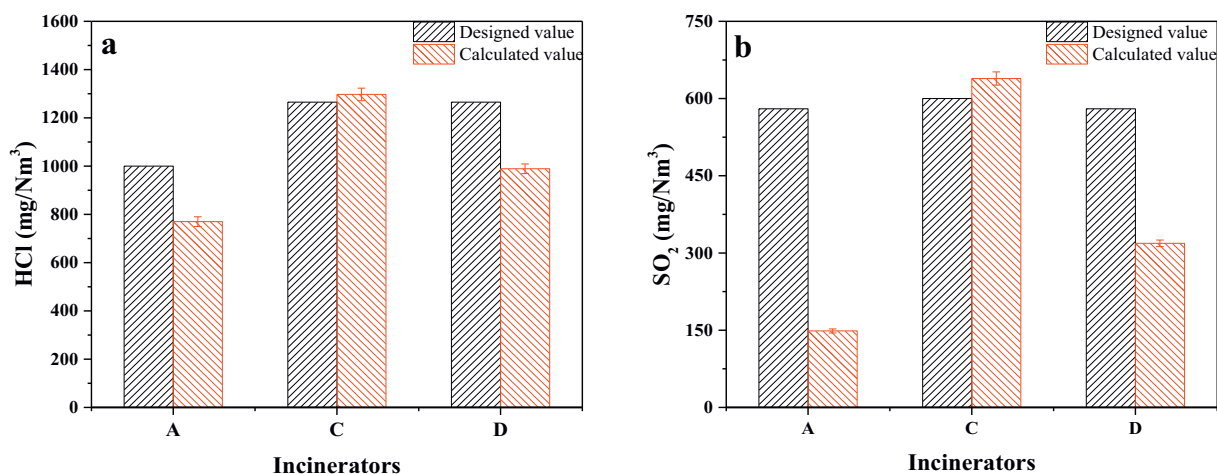

Fig. 6 – Comparison of designed and estimated HCl (a) and SO_2 (b) concentrations.

3.3. Implication for waste incineration

The source strength calculation is based on the mass balance of Cl and S in the APC systems. The on-line monitoring data for EG are usually available and analyzing the Cl and S contents in the AR is much easier than measuring the composition of the high-temperature FG from incinerators. The method is applicable not only to MSW incineration, but also to incineration systems of other wastes such as sewage sludge, hazardous waste.

4. Conclusions

The complexity of MSW composition, heterogeneity of waste samples, and the fluctuation of migrations and distributions of Cl and S during incineration process make it difficult and uncertain to calculate the HCl and SO_2 concentrations in the FG deriving from MSW incineration. A material flow and substance flow model was developed, through which the amount and concentrations of HCl and SO_2 emitted with the FG from MSW incineration plants were estimated based on the Cl and S concentrations in the AR and EG. The source strengths of HCl and SO_2 were found to be 770–1300 mg/Nm^3 and 150–640 mg/Nm^3, respectively. The results meet material conservation in incinerators and coincide with the monitored values, indicating that the method developed is accurate and reliable. About 99% of Cl and 92%–99% of S initially present in the FG were deposited in the AR when emission control was correctly performed. Therefore, the composition and flux of acid gas can be easily estimated based on the amounts of Cl and S in the AR. The results can provide a basis for the APC systems optimization and high-temperature FG corrosion control.

Acknowledgments

R E F E R E N C E S

Antonioni, G., Guglielmi, D., Stramigioli, C., Cozzani, V., 2012. MSWI flue gas two-stage dry treatment: modeling and simulation. Chem. Eng. Trans. 26, 213–218.

Bala, N., Singh, H., Prakash, S., 2010. Accelerated hot corrosion studies of cold spray Ni-50Cr coating on boiler steels. Mater. Des. 31 (1), 244–253.

Belevi, H., Moench, H., 2000. Factors determining the element behavior in municipal solid waste incinerators. 1. Field studies. Environ. Sci. Technol. 34 (12), 2501–2506.

Chen, D., Christensen, T.H., 2010. Life-cycle assessment (EASEWASTE) of two municipal solid waste incineration technologies in China. Waste Manag. Res. 28 (6), 508–519.

Chen, G., Gao, J., Gao, J., Du, Q., Fu, X., Yin, Y., et al., 2010. Simultaneous removal of SO_2 and NO_x by calcium hydroxide at low temperature: effect of SO_2 absorption on NO_2 removal. Ind. Eng. Chem. Res. 49 (23), 12140–12147.

Chi, Y., Wen, J.M., Zhang, D.P., Yan, J.H., Ni, M.J., Cen, K.F., 2005. HCl emission characteristics and BP neural networks prediction in MSW/coal co-fired fluidized beds. J. Environ. Sci. 17 (4), 699–704.

China GDE Engineering Co., L, 2006. Preliminary Design Description of Changzhou Municipal Solid Waste Incineration Project. China GDE Engineering Co., Ltd., Guangzhou, China.

China Wuzhou Engineering Group, 2013. Feasibility Study Report of 1 × 12MW Waste Incineration and Power Generation Project of Xinjiang Tianfu Thermoelectric Co., Ltd. China Wuzhou Engineering Group, Beijing, China.

Chyang, C., Han, Y.L., Wu, L.W., Wan, H.P., Homti, L., Chang, Y.H., 2010. An investigation on pollutant emissions from co-firing of RDF and coal. Waste Manag. 30 (7SI), 1334–1340.

College of Environmental Science and Engineering, 2015. Executive Summary of Laogang Renewable Energy Utilization Project (3000t/d). Peking University, Beijing, China.

Dal Pozzo, A., Antonioni, G., Guglielmi, D., Stramigioli, C., Cozzani, V., 2016. Comparison of alternative flue gas dry treatment technologies in waste-to-energy processes. Waste Manag. 51, 81–90.

Dal Pozzo, A., Guglielmi, D., Antonioni, G., Tugnoli, A., 2017. Sustainability analysis of dry treatment technologies for acid gas removal in waste-to-energy plants. J. Clean. Prod. 162, 1061–1074.

Demirbas, A., 2004. Combustion characteristics of different biomass fuels. Prog. Energy Combust. 30 (2), 219–230.

Demirbas, A., 2005. Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. Prog. Energy Combust. 31 (2), 171–192.

Eurostat, 2017. Municipal waste generation and treatment, by type of treatment method. Available:. http://ec.europa.eu/eurostat/data/database, Accessed date: 27 December 2017.

Frigge, L., Ströhle, J., Epple, B., 2016. Release of sulfur and chlorine gas species during coal combustion and pyrolysis in an entrained flow reactor. Fuel 201, 105–110.

Garea, A., Viguri, J.R., Irabien, A., 1997. Kinetics of flue gas desulphurization at low temperatures: fly ash/calcium (3/1) sorbent behaviour. Chem. Eng. Sci. 52 (5), 715–732.

Guo, X.F., Yang, X.L., Li, H.B., Wu, C.Z., Chen, Y., 2001. Release of hydrogen chloride from combustibles in municipal solid waste. Environ. Sci. Technol. 35 (10), 2001–2005.

Jannelli, E., Minutillo, M., 2007. Simulation of the flue gas cleaning system of an RDF incineration power plant. Waste Manag. 27 (5), 684–690.

JRC, 2016. Best Available Techniques (BAT) Reference Document for Large Combustion Plant. The Joint Research Centre, European Commission.

JRC, 2017. Best Available Techniques (BAT) Reference Document on Waste Incineration (Draft 1). The Joint Research Centre, European Commission.

Kuo, J.H., Tseng, H.H., Rao, P.S., Wey, M.Y., 2008. The prospect and development of incinerators for municipal solid waste treatment and characteristics of their pollutants in Taiwan. Appl. Therm. Eng. 28 (17–18), 2305–2314.

Laogang Renewable Energy Utilization Center, 2017. Flue gas daily monitored data in the year of 2016. Available http://www.laogang-development.com/LGWeb/web/infoList.aspx, Accessed date: 27 December 2017.

Li, P.S., Hu, Y., Yu, W., Yue, Y.N., Xu, Q., Hu, S., et al., 2009. Investigation of sulfur forms and transformation during the co-combustion of sewage sludge and coal using X-ray photoelectron spectroscopy. J. Hazard. Mater. 167 (1–3), 1126–1132.

Liu, K., Pan, W.P., Riley, J.T., 2000. A study of chlorine behavior in a simulated fluidized bed combustion system. Fuel 79 (9), 1115–1124.

Ministry of Industry and Information Technology of the People's Republic of China, 2009. Calcium Hydroxide for Industrial Use. Standard HG/T 4120-2009.

National Bureau of Petroleum and Chemical Industry of the People's Republic of China, 1999. Chemical Reagents: Activated Carbon. Standard HG 3491-1999.

NBSPRC, 2017. 2017 China statistical yearbook. National Bureau of Statistics of the People's Republic of China. China Statistics Press, Beijing.

Nielsen, H.P., Frandsen, F.J., Dam-Johansen, K., Baxter, L.L., 2000. The implications of chlorine-associated corrosion on the operation of biomass-fired boilers. Prog. Energy Combust. 26 (3), 283–298.

Obernberger, I., 2014. Strategy for the application of novel characterization methods for biomass fuels: case study of straw. Energy Fuel 28 (2), 1041–1052.

Ruth, L.A., 1998. Energy from municipal solid waste: a comparison with coal combustion technology. Prog. Energy Combust. 24 (6), 545–564.

Schumacher, S., Lindermann, J., Stahlmecke, B., Khot, A., Zeiner, T., Zwaag, T.V.D., et al., 2016. Particle sampling in boilers of waste incineration plants for characterizing corrosion relevant species. Corros. Sci. 110, 82–90.

Shanghai Environmental Engineering Design Institute of Science and Technology Co., L, 2017. Physical and Chemical Characteristics of Municipal Solid Waste in Shanghai (2016). Shanghai Environmental Engineering Design Institute of Science and Technology Co., Ltd., Shanghai.

Shanghai Liming Resource Recycling Co., L, 2017. Flue gas daily emissions data in the year of 2016. Available. http://www.limingziyuan.com.cn/yqpfsj/list_34.aspx, Accessed date: 24 December 2017.

Sommersacher, P., Brunner, T., Obernberger, I., 2012. Fuel indexes: a novel method for the evaluation of relevant combustion properties of new biomass fuels. Energy Fuel 26 (1), 380–390.

Tian, H., Gao, J., Lu, L., Zhao, D., Cheng, K., Qiu, P., 2012. Temporal trends and spatial variation characteristics of hazardous air pollutant emission inventory from municipal solid waste incineration in China. Environ. Sci. Technol. 46 (18), 10364–10371.

Uemiya, S., Kobayashi, T., Kojima, T., 2001. Desulfurization behavior of Ca-based absorbents under periodically changing condition between reducing and oxidizing atmosphere. Energy Convers. Manag. 42 (15–17), 2029–2041.

USEPA, 2016. Advancing Sustainable Materials Management: 2014 Fact Sheet Assessing Trends in Material Generation, Recycling and Disposal in the United States. Environmental Protection Agency, Washington, DC.

Wang, H.T., 2016. Flue Gas Treatment Key Technologies and Applications to Meet the EU 2000 Standard in Municipal Solid Waste Incineration Plant. Tsinghua University, Beijing, China.

Wang, K.S., Chiang, K.Y., Lin, S.M., Tsai, C.C., Sun, C.J., 1999. Effects of chlorides on emissions of hydrogen chloride formation in waste incineration. Chemosphere 38 (7), 1571–1582.

Wen, J., Yan, J., Zhang, D., Chi, Y., Ni, M., Cen, K., 2006. SO_2 emission characteristics and BP neural networks prediction in MSW/coal co-fired fluidized beds. J. Therm. Sci. 15 (3), 281–288.

Wey, M.Y., Liu, K.Y., Yu, W.J., Lin, C.L., Chang, F.Y., 2008. Influences of chlorine content on emission of HCl and organic compounds in waste incineration using fluidized beds. Waste Manag. 28 (2), 406–415.

Zhang, H., He, P.J., Shao, L.M., 2008. Fate of heavy metals during municipal solid waste incineration in shanghai. J. Hazard. Mater. 156 (1–3), 365–373.

Zhou, H., Meng, A.H., Long, Y.Q., Li, Q.H., Zhang, Y.G., 2015. An overview of characteristics of municipal solid waste fuel in China: physical, chemical composition and heating value. Renew. Sust. Energ. Rev. 46, 107–122.