Emission Characteristics and Formation Pathways of Polychlorinated Dibenzo-p-dioxins and Dibenzofurans from a Typical Pesticide Plant

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ABSTRACT

The emission characteristics of the polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) from a pesticide plant were well investigated. In the present study, the international toxic equivalent quantity (I-TEQ) value of the PCDD/Fs (0.087 ng I-TEQ Nm –3) in the flue gas at the outlet of stack can meet the emission limit (0.1 ng I-TEQ Nm –3). The I-TEQ value of the PCDD/Fs (3.25 pg I-TEQ g –1) in the fly ash is much lower than the permitted standard for disposal in sanitary landfill sites (3.0 ng of I-TEQ g -1). In addition, 1,2,3,4,6,7,8-HpCDD, OCDD and 1,2,3,4,6,7,8-HpCDF are the three main congeners in the PCDD/Fs for the outlet of both the secondary combustion chamber and the stack. 1,2,3,7,8-PeCDD, 1,2,3,6,7,8-HxCDD, 1,2,3,4,6,7,8-HpCDD and OCDD are the most dominant congeners for the PCDD/Fs from inlet of bag filter. PCDD/Fs may be formed through high temperature homogeneous synthesis and heterogeneous precursor synthesis in the flue gas. In addition, PCDD/Fs might be formed in bag filter via de novo synthesis. The main formation areas of PCDD/Fs are waste heat boiler and quenching/deacidification tower in this pesticide plant. The TEQ estimated emissions of PCDD/Fs reaches 9.3 g year –1. These findings are helpful for further controlling the formation and emission of PCDD/Fs in pesticide plants, yet more studies are still required.

Keywords: Polychlorinated dibenzo-p-dioxins and dibenzofurans; Chemical plant; Emission characteristics; TEQ emission factor; Formation pathways.

INTRODUCTION

Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), as major classes of persistent organic pollutants (POPs), have become serious problem threatening environment and human health (Tsai et al., 2014; Hsieh et al., 2018b; Hung et al., 2018; Lee et al., 2018) because of their properties such as neurotoxicity, carcinogenicity, immunotoxicity, and bioaccumulation. For the past decades, the international community has been trying to control the global pollution of POPs and to protect the environment and human health through the Stockholm Convention (Stockholm Convention 2001). There are 151 countries, including China, have joined the Convention to undertake the responsibility of reducing POPs, which requires studying and revealing the emission characteristics of PCDD/Fs in China.

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The emission characteristics of PCDD/Fs from industrial and thermal processes have been studied for over 40 years (Olie et al., 1977; Singh and Prakash, 2007; Mubeen et al., 2017), identifying several major sources of PCDD/Fs (McKay, 2002) such as municipal solid waste incinerators (MSWI) (Wei et al., 2016), cement kiln, the electric arc furnaces, and power plants (Tsai et al., 2014; Hsieh et al., 2018a; Xu et al., 2018; Zhan et al., 2018). In addition, advanced combustion technology and air pollution control devices (APCDs), including activated carbon injection and baghouse filter are widely used to control the emission of PCDD/Fs, meeting the limited standard (0.1 ng I-TEQ m–3) (GB18485-2014) (Lockwood and Ou, 1993; Karstensen, 2008; Shi et al., 2008; Aurell and Marklund, 2009). The emission of each source is quite different because of the differences in scale, technology, air pollution control devices (APCDs), and the awareness of environmental protection. It is estimated that the total emission of PCDD/F from all Chinese sources was 9.1 kg TEQ in 2013. Steel and other metal production industries made the largest PCDD/F emission with 45.6%, followed by waste incineration,
power generation and heating. The total discharge of these three accounted for 81%.

However, emission characteristics from chemical plants, especially pesticide plants, are still obscure. In 2004, the emission of PCDD/Fs from chemical plants accounted for 2.6% of the total emissions. In recent years, due to the rapid increase of chemical plants constructed annually, emission of toxic pollutions from chemical plant has been given considerable attention (Xue et al., 2006; Černá et al., 2007; Hou et al., 2013; Tan et al., 2013). From an international perspective, with the in-depth development of economic globalization, the production of the pesticides in developed countries has been gradually shifted to developing countries. Approximately, in the past five years during 2013–2017, the production of pesticide in China has exceeded 3 million tons year−1, and it is estimated that pesticide production will also be over 2.8 million tons in 2018 (National Bureau of Statistics of China, 2018). During the production of pesticides, persistent organic pollutants can be generated in huge amounts (Weber and Varbelow, 2013). The fine particles and organic chlorides (such as HCl, methyl chloride and so on) (Weber et al., 2008a, b) in the flue gas significantly facilitate the production of PCDD/Fs generally through heterogeneous (solid-gas phases) reaction (200–400°C) and homogeneous (gas phase) reaction (500–800°C) (Choudhry et al., 1982; Stanmore, 2004; Karstensen, 2008). De novo and precursor synthesis are two major pathways of the heterogeneous reaction. For the formation pathway, the PCDD/Fs are synthesized from carbon matrix through a series reactions of oxidation and chlorination (Iino et al., 2000), while the precursor synthesis indicates that the PCDD/Fs are formed by the transformation of dioxin-like precursors on the particle surface with the assistant of metal catalysts (Addink and Olie, 1995). Besides, it has been demonstrated that the homogeneous reaction of PCDD/Fs synthesis is also associated with the precursors. The PCDD/Fs content in the flue gas from a municipal solid waste incinerator is highly related to the concentration of various possible precursors (Kaune et al., 1994). However, the emission characteristics of PCDD/Fs in pesticide plants have not been investigated in detail, and the formation mechanisms have not yet been revealed by now.

In this study, the samples of flue gas and fly ash are collected from different positions in a pesticide plant. The main objective of this work is to study the emission characteristics and the formation pathways of PCDD/Fs in the pesticide plant. Specifically, the PCDD/Fs in the flue gas of cooling system is worthy of attention, which are the basis of emission control.

**MATERIALS AND METHODS**

**Experimental Design**

The experiments are conducted in a typical pesticide plant in eastern China, consisting of two main parts of directional conversion furnace and APCDs. The directional conversion furnace can also be referred to as Regenerative Thermal Oxidizer (RTO), which includes a two-stage directional converter. Phosphate mixture is rapidly dewatered and shaped in the first-stage directional converter and then free fall to the second-stage directional converter. Phosphate mixture is basically converted to crude phosphate in the second-stage directional converter. Meanwhile, the volatile organic compounds waste gas (HCl, methanol, chlorine, formaldehyde, triethylamine, methyl chloride, etc.) is continuously fed into the directional conversion furnace for treatment. The APCDs include the cyclone separator, the secondary combustion chamber, the waste heat boiler, the quenching/deacidification tower, and the baghouse filter. The emitted volatile organic compounds (VOCs) from the directional conversion furnace are burned out in the secondary combustion chamber for over 2 s at temperature of about 800°C. The quenching/deacidification tower is applied to remove acidic gas and to decrease flue gas temperature. Activated carbon is used to absorb PCDD/Fs from flue gas and then is collected in bag filter efficiently together with other particles. Following the flow of flue gas, the gas samples are collected at the outlet of the secondary combustion chamber (FG1), the inlet of the baghouse filter (FG2), and the outlet of the stack (FG3), respectively. The fly ashes (FA) are collected from the baghouse filter. The details of sampling position are shown in Fig. 1. Samples are stored in sealed plastic pots prior to analysis.

Three parallel samples are collected at each position to ensure the reliability of the results. The concentration of PCDD/Fs in the outlet of the second combustion chamber

![Fig. 1. Scheme of sampling positions.](image-url)
(FG1) can reflect the influence of combustion situation on the formation of PCDD/Fs. The regeneration of PCDD/Fs in cooling system can be studied by comparing the PCDD/Fs in FG2 (from the inlet of baghouse filter) to those in FG1. In addition, the removal efficiency of PCDD/Fs for baghouse filter can be identified by comparing FG3 (from stack) to FG2.

In this pesticide plant, the average volume of dry flue gas is 20000 Nm$^3$ h$^{-1}$, the average moisture content in the flue gas is 35%, the average fly ash discharge rate is 3 kg h$^{-1}$, and the concentration of CO which is normalized to dry air at 11% of O$_2$ is 258.56 mg Nm$^{-3}$.

**Sample Analysis**

According to United States Environmental Protection Agency (U.S. EPA) Methods 23A and 1613 (EPA, 1994) to pretreat PCDD/Fs samples in the flue gas and fly ash, respectively. The fly ash needs to be soaked for 4 h in 2 mol L$^{-1}$ hydrochloric acid with a solid/liquid ratio of 1 g 40 mL$^{-1}$ to eliminate the metal salts in the fly ash before the cleanup procedure. The high-resolution gas chromatography and high-resolution mass spectrometry (HRGC/HRMS) on a 6890 Series gas chromatograph (Agilent, USA) coupled with a JMS-800D Ultrafocus mass spectrometer (JEOL, Japan) was used to identify and quantify the PCDD/Fs. A DB-5 ms (60 m × 0.25mm inside diameter, 0.25 µm film thickness) capillary column was used to separate the PCDD/F congeners. The detailed PCDD/Fs analysis can be found in other papers (Wu et al., 2012; Chen et al., 2017).

The toxic equivalent quantity (I-TEQ) were calculated using Eqs. (1) and (2):

$$C_g = \frac{\sum_{i=1}^{n} C_{ni} V_{sid}}{n}$$

$$C_f = \frac{\sum_{i=1}^{n} M_i}{n}$$

where $C_g$ is the average I-TEQ concentration of PCDD/Fs in the flue gas, $C_{ni}$ is the I-TEQ value of PCDD/Fs in either gas or ash sample $i$ (ng I-TEQ), $V_{sid}$ is the volume of flue gas for collecting sample $i$ (m$^3$), $C_f$ is the average I-TEQ concentration of PCDD/Fs in the fly ash (ng I-TEQ), $M_i$ is the mass of the fly ash conducted to PCDD/F analysis (g), and $n$ is the number of parallel samples.

**RESULTS AND DISCUSSION**

**Emission Characteristics of PCDD/Fs in Flue Gas**

The Concentrations of PCDD/Fs in the Flue Gas

The I-TEQ value, the homologue distribution, the weight ratio of PCDF/PCDD and the weight average level of chlorination (Cl-PCDD/Fs) in the flue gas from different positions are shown in Table 1. The concentration and I-TEQ value of PCDD/Fs at the outlet of the secondary combustion chamber (FG1) are 0.69 ng m$^{-3}$ and 0.056 ng I-TEQ m$^{-3}$, respectively, which shows that PCDD/Fs has been formed initially. As is well known, temperature and chlorine are the most critical factors for the formation of PCDD/Fs (Addink and Olie, 1995; Wikström et al., 2003), and PCDD/Fs are easily produced during incomplete combustion (Wikström et al., 2004). Some scholars investigated the homogeneous synthesis of PCDD/Fs in high-temperature areas of chambers, suggesting that pollutants of incomplete combustions (PIC) provide precursors and produce PCDD/Fs in the gas phase at the temperatures between 600–800°C (Sidhu et al., 1995). The content of CO is one of the most important parameters reflecting the condition of combustion (Weber et al., 2002). The concentration of CO in the

<table>
<thead>
<tr>
<th>FG1</th>
<th>FG2</th>
<th>FG3</th>
<th>FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>∑PCDDs</td>
<td>0.30</td>
<td>4.47</td>
<td>0.30</td>
</tr>
<tr>
<td>∑PCDFs</td>
<td>0.39</td>
<td>2.44</td>
<td>0.38</td>
</tr>
<tr>
<td>∑PCDD/Fs</td>
<td>0.69</td>
<td>6.92</td>
<td>0.68</td>
</tr>
<tr>
<td>PCDF/PCDD</td>
<td>1.31</td>
<td>0.55</td>
<td>1.28</td>
</tr>
<tr>
<td>PCDF/PCDD</td>
<td>3.14</td>
<td>0.41</td>
<td>3.29</td>
</tr>
<tr>
<td>Cl-PCDD</td>
<td>7.22</td>
<td>6.43</td>
<td>7.26</td>
</tr>
<tr>
<td>Cl-PCDF</td>
<td>6.21</td>
<td>5.95</td>
<td>6.22</td>
</tr>
<tr>
<td>Cl-PCDD/Fs</td>
<td>6.65</td>
<td>6.26</td>
<td>6.68</td>
</tr>
<tr>
<td>I-TEQ (11% oxygen)</td>
<td>0.056</td>
<td>1.412</td>
<td>0.087</td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td>0.08</td>
<td>1.8</td>
<td>0.06</td>
</tr>
<tr>
<td>Stand. Dev.</td>
<td>0.01</td>
<td>0.08</td>
<td>0.02</td>
</tr>
</tbody>
</table>

a The concentration ratio of PCDF to PCDD.

b The I-TEQ ratio of PCDF to PCDD.

c Weight average chlorination level was calculated as follows:

$$C_l = \frac{\sum_{j=4,5,6,7,8} C_j \times n_j}{C}$$

where $C_j$ is the concentration of each 2,3,7, 8-substituted PCDD/Fs, $n_j$ is the amount of chlorine atom of each 2,3,7,8-substituted PCDD/Fs; C is the total concentration of PCDD/Fs.
directional conversion furnace has reached 258.56 mg Nm$^{-3}$, indicating an incomplete combustion to some extent. PCDD/Fs produced at this position may be attributed to the formation of PCDD/Fs in high temperature gas phase conditions. The formation mechanism is that the precursors synthesize PCDD/Fs under high temperature conditions. The precursors are mainly derived from the organic chloride waste gas in the glyphosate mother solution, which is produced from the thermal reaction process of the directional conversion furnace. This is similar with other researchers who believe that precursors should be responsible for the homogeneous formation of PCDD/Fs under high temperature (600–1200K) (Zhang et al., 2009; Pan et al., 2013; Zhang et al., 2014). We can see the proportion of PCDFs and PCDDs from Fig. 2. The PCDFs and PCDDs accounted for 57 and 43%, respectively, which means that more PCDF is generated at high temperature.

The concentration and I-TEQ value of PCDD/Fs in the flue gas at the inlet of the baghouse filter (FG2) are 6.92 ng m$^{-3}$ and 1.412 ng I-TEQ m$^{-3}$, respectively, which shows that PCDD/Fs have been produced dramatically in the area (from the outlet of secondary combustion chamber to the inlet of baghouse filter). This area consists of a waste heat boiler with temperature range of 800–500°C and a quenching/deacidification tower with temperature range of 400–200°C. It is identified that high-temperature (500–800°C) homogeneous reaction mainly happening in gas phase leads to the formation of PCDD/Fs and their precursors (Yang et al., 1998; Ryu et al., 2006). Low temperature (200–400°C) catalytic heterogeneous routes, taking place at the surface of solid carbon (such as soot and charred materials) on fly ash particles and being catalyzed by some metal ions (such as Cu and Fe), usually have the largest contribution to the formation of PCDD/Fs (Benfenati et al., 1991; Stanmore, 2004). This area is also rich in O, Cl and organochlorinated matters, which are the most important factors for the formation of PCDD/Fs and can significantly influence the PCDD/F yields (Babushok and Tsang, 2003; Peng et al., 2016). Some researchers have already discovered that the waste heat boiler plays a very important role in the formation of PCDD/F from municipal solid waste incinerator (MSWI) (Düwel et al., 1990; Zhang et al., 2018). The quenching/deacidification tower section covers the optimum temperature range (250–400°C), which is conducive to heterogeneous catalytic reactions and has been repeatedly accused of promoting the formation of PCDD/F (Wang et al., 2010). Heterogeneous production of PCDD/Fs mainly includes (1) de novo synthesis, beginning from carbon matrix or polycyclic aromatic hydrocarbons (PAH) and (2) precursor pathways, beginning from chemicals with similar structure to PCDD/Fs. With the temperature range of 400–200°C in quenching/deacidification tower, the PCDD/Fs can mainly be formed through the rearrangement/condensation of precursors in the pesticide plant. This is different from municipal solid waste incinerators, in which de novo synthesis is considered to be the main formation pathway (Huang and Buekens, 2000; Zhan et al., 2019). The ratio of PCDF to PCDD is related to the importance of de novo and precursor pathways, respectively (Altwickner, 1996).

In this study, the PCDF/PCDD ratio is 0.55 for FG2, and the proportion of PCDDs reaches 65% (Fig. 2). One possible reason is that the precursor pathways become stronger at the quenching/deacidification tower and result in more production of PCDD than PCDF. Chlorophenols (CP) would produce the most abundant PCDD homologues through the rearrangement and condensation reactions (Chen et al., 2018a, b; Ryu et al., 2006; Zhang et al., 2018). Another reason is that the presence of water vapor will increase the yield of PCDDs (Christelle et al., 2007). The average moisture content in the flue gas is 35%. The formation of PCDDs will be facilitated at 300°C when water vapor is introduced into the flue gas stream (Stieglitz et al., 1990; Christelle et al., 2007). This feature is supposed to be further studied in pesticide plant.

![Fig. 2. I-TEQ concentration of PCDD/Fs and the proportion of PCDD/Fs in the flue gases.](image-url)
Activated carbon injection coupled with baghouse filters are effective for PCDD/Fs control (Hung et al., 2011). Thus, the concentration of PCDD/Fs decreases sharply from 6.92 to 0.68 ng m\(^{-3}\) at the outlet of the stack (FG3) after going through the baghouse filters. Also, the I-TEQ value reduces from 1.412 to 0.087 ng I-TEQ m\(^{-3}\), which meets the Chinese emission limit of 0.1 ng I-TEQ m\(^{-3}\) for pesticide industry. The activated carbon adsorbs PCDD/Fs from flue gas but also provides additional reaction areas and carbon sources which might produce PCDFs via de novo synthesis in bag filters (Atkinson et al., 2015; Bai et al., 2017). The removal efficiencies of PCDD/Fs for both concentration and I-TEQ value are 90% (93% for PCDDs and 84% for PCDFs) and 94%, respectively, yet are lower than designed values (98% and 99%). The main reasons includes (1) the quality of activated carbon does not meet the requirements, (2) the activated carbon is not injected continuously, (3) the deficient operation of baghouse filters, and (4) the memory effects (Chen et al., 2011). In addition, the ratio of PCDF/PCDD rises from 0.55 to 1.28, which can be attributed to either the promotion of de novo synthesis (in favor of PCDFs formation) (Atkinson et al., 2015; Bai et al., 2017) or the preferable absorption of PCDD by activated carbon. The latter speculation is supported by the fact that the vapor pressure of PCDD is lower than that of PCDF (Lin et al., 2018; Chen et al., 2019a) and the desorption enthalpy of PCDD is higher (Zhang and Buekens, 2016; Zhang et al., 2018). This feature worth further studies by sampling PCDD/Fs from both gas and solid phases simultaneously in pesticide plant.

For controlling PCDD/Fs emission from this pesticide plant, some effective management strategies are proposed as: (1) increasing temperature to promote complete combustion in the secondary combustion chamber, (2) injecting the activated carbon with high quality continuously, (3) avoiding backflush in baghouse filter and reducing the air induced from the quenching part, (4) decreasing the residence time of flue gas in the quenching/deacidification tower, (5) trying to avoid shut-down of the furnace for mitigating the memory effect (Guo et al., 2014).

**Congener Profiles of PCDD/Fs in Flue Gas**

The congener profiles of PCDD/Fs is useful for determining their sources and speculating on its underlying formation mechanisms (Zhao et al., 2017). The congener profiles of 17 toxic 2,3,7,8-substituted PCDD/Fs in three flue gases are shown in Figs. 2 and 3, respectively. For PCDD/Fs in FG1 and FG3, the congener profiles exhibit the same distribution tendency. The percentage of PCDFs in the PCDD/Fs is 57 and 56% for FG1 and FG3, respectively. The reason has been illustrated in previous section of 3.1.1. Particularly, the proportion of PCDFs in the PCDD/Fs is merely 35% for FG2, indicating the dominant formation pathway of precursors synthesis. Specifically, 1,2,3,4,6,7,8-HpCDD, OCDD and 1,2,3,4,6,7,8-HpCDF are three main congeners in the PCDD/Fs for FG1 and FG3, and the total percentage of them reaches 48%. OCDD has the biggest proportion among all congeners for FG1 and FG3. In addition, although 2,3,4,7,8-PeCDF does not contribute a lot to the total concentration, it is the biggest component of the I-TEQ value (Fig. 3(b)). Also, the strong positive correlation between the concentration of 2,3,4,7,8,PeCDF and the I-TEQ value has been revealed (Fiedler et al., 2010). The most abundant congeners found in FG2 are 1,2,3,7,8-PeCDD, 1,2,3,6,7,8-HxCDD, 1,2,3,4,6,7,8-HpCDD and OCDD. These four congeners account for 50% of total concentration. The major contribution to the I-TEQ value is 1,2,3,7,8-PeCDD, because of its relative abundance and high I-TEF of 0.5.

**Discharging Characteristics of PCDD/Fs in the Fly Ash**

Fly ash is classified as hazardous waste in many countries, including China, because of its high content of PCDD/Fs and heavy metals (Chen et al., 2016; Chen et al., 2019b; Zhiliang et al., 2019). Therefore, special attention to fly ash from pesticide plant is both necessary and important for fly ash management. The concentration and I-TEQ of PCDD/Fs are 38.87–45.31 pg g\(^{-1}\) (with an average value of 43.29 pg g\(^{-1}\)) and 2.75–3.33 pg I-TEQ g\(^{-1}\) (with an average value of 3.25 pg I-TEQ g\(^{-1}\)), respectively. The I-TEQ values are far below Chinese limits for disposal in sanitary landfill sites (3 ng I-TEQ g\(^{-1}\)) (GB16889-2008). The order of magnitude of these values is less than those found in MSWI fly ashes (Bie et al., 2007; Chang et al., 2011). The diversification of PCDD/F contents in fly ash is caused by reactants (primary factor), incineration conditions and APCDs performance.

From the results obtained in this study, the distribution of 17 toxic congeners in fly ash is shown in Fig. 4(a). OCDD contributes the most (24%) to the total PCDD/Fs concentration. Other congeners with higher proportion are 1,2,3,4,6,7,8-HpCDD (15%), 1,2,3,4,6,7,8-HpCDF (12%) and 2,3,4,6,7,8-HxCDF (10%). Because of the different vapor pressure of PCDFs congeners, higher chlorinated congeners may be more dominant than others in the fly ash for PCDDs, but the trend of PCDFs is not obvious. Normally, higher chlorinated congeners with lower vapor pressures have higher solid phase fractions at a specific temperature (Chang et al., 2011). In term of I-TEQ, the distribution of 17 toxic congeners in fly ash is shown in Fig. 4(b). It is obvious that the highest contribution (38%) to I-TEQ value is 2,3,4,7,8-PeCDF, which is agree with results from municipal solid waste incinerators (Wang and Gao, 2007). The PCDF/PCDD ratio is a general and practical indicator for identifying PCDF/F features. The I-TEQ ratio of PCDF to PCDD is 2.96 (Table 1), indicating a much more contribution for I-TEQ value by PCDFs than by PCDDs in the fly ash from pesticide plants.

**TEQ Estimated Emissions of the Investigated Pesticide Plant**

The formula for calculating the TEQ estimated emissions of PCDD/Fs is:

\[ T = C_g \times V_g + C_a \times V_a \]  \tag{3}

where T is the TEQ estimated emissions of PCDD/Fs, g year\(^{-1}\), \(C_g\) is the PCDD/Fs concentration in the flue gas,
CONCLUSION

This study investigated the emission characteristics and the formation pathways of the PCDD/Fs in both flue gas and fly ash in different position of a pesticide plant. The results are as follows:

1. Incomplete combustion facilitates PCDD/Fs formation within secondary combustion chamber. PCDD/Fs concentration and I-TEQ value in flue gas at the outlet of secondary combustion chamber (FG1) reach 0.69 ng m$^{-3}$ and 0.056 ng I-TEQ m$^{-3}$. The PCDF/PCDD ratio of 1.31 indicates the preferable formation of PCDF than PCDD during high temperature synthesis.

2. The main formation areas of PCDD/Fs are waste heat
boiler and quenching/deacidification tower in this pesticide plant. The concentration and I-TEQ value of PCDD/Fs in the flue gas increase sharply at the inlet of the baghouse filters (FG2). The PCDF/PCDD ratio of 0.55 indicates the major formation pathways of rearrangement and condensation of precursors.

(3) The I-TEQ value (0.087 ng I-TEQ m$^{-3}$) in flue gas at outlet of stack meets the Chinese emission limit of 0.1 ng I-TEQ m$^{-3}$ with the utilization of activated carbon injection coupled with baghouse filter. The major contribution to the I-TEQ value is 1,2,3,7,8-PeCDD.

(4) The I-TEQ value of PCDD/Fs (3.25 pg I-TEQ g$^{-1}$) in fly ash is much lower than both that in MSWI fly ashes and Chinese emission limits (3 ng I-TEQ g$^{-1}$). The I-TEQ is contributed by PCDFs far more than PCDDs for the fly ash from pesticide plants. Some management strategies have been proposed for controlling PCDD/Fs in pesticide plant.

(5) The TEQ estimated emissions of the investigated pesticide plant reaches 9.3 g year$^{-1}$ in the pesticide plant.

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