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Life Cycle Assessment of the Environmental Impacts of Typical Industrial Hazardous Waste Incineration in Eastern China

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ABSTRACT

The environmental impacts of rotary kiln incineration, which is widely used in China for treating industrial hazardous waste (IHW), is evaluated in this work through life cycle assessment (LCA). Emissions data of key pollutants, along with energy and material inputs and outputs of rotary kiln incineration, were collected from a commercial-scale operating IHW incineration plant located in Hangzhou city in eastern China, and the corresponding environmental impacts were analyzed based on the LCA model. It is concluded that the IHW incineration process has the greatest impact on human toxicity, followed by global warming. Heavy metals, especially Pb and As, are the main contributors to human toxicity, while CO_2 is the main cause of global warming. PCDD/Fs have a relatively small contribution to human toxicity and overall environmental safety. This study has two improvement suggestions based on the assessment results: An energy recovery system and a $DeNO_x$ system should be added to the IHW incineration process, since the former would reduce the contribution of IHW incineration to global warming, while the latter would enable incineration plants to minimize the emissions of NO_x; Fly ash and bottom ash should be stabilized and further treated to mitigate the problems caused by heavy metals.

Keywords: Life cycle assessment; Industrial hazardous waste; Incineration; Environmental impact.

INTRODUCTION

The industrial waste which meets hazardous waste identification criteria for toxicity test, corrosivity test, ignitability test and some special character test, like radioactivity test is defined as industrial hazardous waste (IHW) (Ministry of Environmental Protection of China, 2008; U.S. Environmental Protection Agency, 2009). Resulting from fast economic development, the generation of IHW in China has increased dramatically in the past few years from 8.3 million tonnes in 2000 (National Bureau of Statistics of China, 2001) to 34.31 million tonnes in 2011 (National Bureau of Statistics of China, 2012). Because of the contained toxic and dangerous components, all IHW must be treated environmental friendly to avoid secondary pollution to environment and human health. Compared with traditional landfill, incineration can reduce the volume of IHW by more than 70%, convert all residues into inert materials and recover heat (Dorn *et al.*, 2012). Due to the high flexibility to different forms of waste, rotary kiln incinerator is recommended for IHW mass burning according to the technology specifications for HW incineration facility construction (HJ/T176-2005). However, waste incineration also generates many pollutant species, including dusts, acid gases, polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), waste water, etc. For example, solid waste incineration facilities in China have emitted 8,500 tons of SO_2, 11,200 tons of dusts, 14,100 tons of NO_x in 2010 (Ministry of Environmental Protection of China, 2010) and 610.47 g I-TEQ of dioxins in 2007 (China National Implementation Plan, 2007). These pollutants may impose serious impacts on surrounding environment and such impacts should be quantitatively examined to assess the influence on human health. In this paper, such examination will be presented through life cycle assessment (LCA).

LCA is a promising method to evaluate the environmental footprint of a product, an industrial process or activity throughout its life cycle or lifetime. It can identify and quantify all steps involving energy and materials consumption, as well as pollutant emission, to evaluate the environmental impact and to find the chance of improving negative impacts (SETAC, 1997). During the early stage of the development, LCA was mostly applied to products manufactures (Burgess and Brennan, 2001). In the last few

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years, it has been employed to characterize municipal solid waste management process (Blengini *et al.*, 2012) and also been extended to help developing sustainable integrated waste management systems. Unfortunately, only a few LCA researches have been carried out on IHW. Saft compared the pyrolysis and gasification treatment of hazardous paint packaging waste with rotary kiln incinerators in Netherlands (Saft, 2007). Vermeulen *et al.* (2012) compared the rotary kiln incineration and cement kiln co-incineration of automotive shredder residue and meat and bone meal. However, previous LCA researches are mainly focused on the influence of single hazardous waste instead of the incineration system. So the present study evaluated the whole incineration systems which is fed with mixed IHW and uses rotary kiln as primary incinerator.

In 1997, International Organization for Standardization (ISO) enacted the ISO14040 standard (Environmental management-LCA-principles and framework) as the LCA technology framework and principle (International Organization for Standardization, 1997). Currently, the LCA procedure is divided into four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. This paper implements the ISO14040 standard and builds the assessment model and inventory, based on the typical IHW incineration plant in China. The model and inventory are also used for analyzing environmental impact.

METHODS

The framework and principle of LCA have been prescript by ISO. Nonetheless, a number of different assessment methods are available to LCA practitioners, such as Environmental Design of Industrial Products 1997 (EDIP97), Eco-indicator 99 and Life Cycle Assessment-An Operational Guide to ISO standards 2001 (CML2001) (Dreyer *et al.*, 2003). EDIP97 is a Danish LCA methodology originally developed in the 1990s (Wenzel *et al.*, 1997) and revised in 2003 (Stranddorf *et al.*, 2005). It is popular used in the LCA field (Dreyer *et al.*, 2003). EDIP97 is in accordance with the general LCA framework in both SETAC and ISO recommendations (Wenzel *et al.*, 1997). So in this paper EDIP97 is used as the assessment method.

Goal and Scope Definition

The goal of this study is to analyze the environmental performance of the incineration process for IHW. The functional unit is defined as to dispose one ton of IHW. The functional unit provides the reference to which all inputs and outputs are normalized (International Organization for Standardization, 1997). The IHW are collected from companies located in the industrial development zone at East of Hangzhou city and most of these companies have business of painting and chemical refining. So the IHW may contain flammable hydrocarbon or acids/alkali components or heavy metals, etc. It is difficult to make an accurate analysis of the compositions of IHW because the physical and chemical properties of IHW vary with originating source. In the paper, the average statistics are obtained by calculating ten kinds of IHW according to industry analysis, elemental analysis and calorific values of different hazardous wastes sent to the incineration plant (Li, 2011). Table 1 shows the average elemental analysis and low heat value of mixed IHW together with standard deviation of each calculated value.

The incineration model used to estimate emissions inventory for the reference flow of one ton of waste is shown in Fig. 1. This model is built based on a running incineration plant for treating IHW in Hangzhou city, China. The plant with a capacity of 50 ton per day, is using a rotary kiln as primary combustion chamber and the flue gas is cleaned by air pollution control system for removal of acid gases, heavy metals and PCDD/Fs (Wu *et al.*, 2012). The LCA analysis discussed in this paper is based on the stable operating scenarios. The data under abnormal conditions are ignored because: first, the relevant data under the abnormal operating conditions are not easy to obtain and second, LCA is more reliable for evaluating the long term environmental impacts of incineration system for example, a period of 20 years.

System Description

IHW incineration system is subdivided into three processes: IHW pretreatment, combustion and flue gas cleaning. In order to ensure the safe operation of incineration system and the effective control of pollution emissions, IHW from different sources need to be blended before entering the furnace. During blending, the nature of different IHW is considered to prevent violent reaction and the contents of S, Cl are also controlled. The proportion of fractions with higher contents of S, Cl should be decreased in co-firing (Zhejiang Environmental Monitoring Center, 2009). After blending, IHW will be crushed into small particles and then sent into the primary rotary kiln incinerator for burning and assistant fuel (diesel) will be used to maintain the temperature. After combustion flue gas is drafted into the cleaning system and acid species are removed through lime injection. PCDD/Fs and heavy metals are absorbed by activated carbon and captured in bag-house filter along with fine fly ash particles. Finally, the cleaned flue gas is induced into air through the stack and the unburned residues are collected at the bottom of the rotary kiln. The bottom ash and fly ash are sent to landfill after stabilization. The detailed processes are illustrated in Fig. 2.

Life Cycle Inventory

Before LCA evaluation, it is important to build a life-cycle inventory including quantitative energy and raw

Table 1. Average element analysis and low heat value (as-received basis) of IHW with the standard deviation.

Element	C/%	H/%	O/%	N/%	S/%	Cl/%	Moisture/%	Ash/%	LHV/(MJ/kg)
IHW	38.31	4.38	12.19	2.63	0.89	0.28	29.32	12.00	12.9
σ	3.80	1.62	4.35	0.85	0.31	0.05	3.03	2.89	1.44

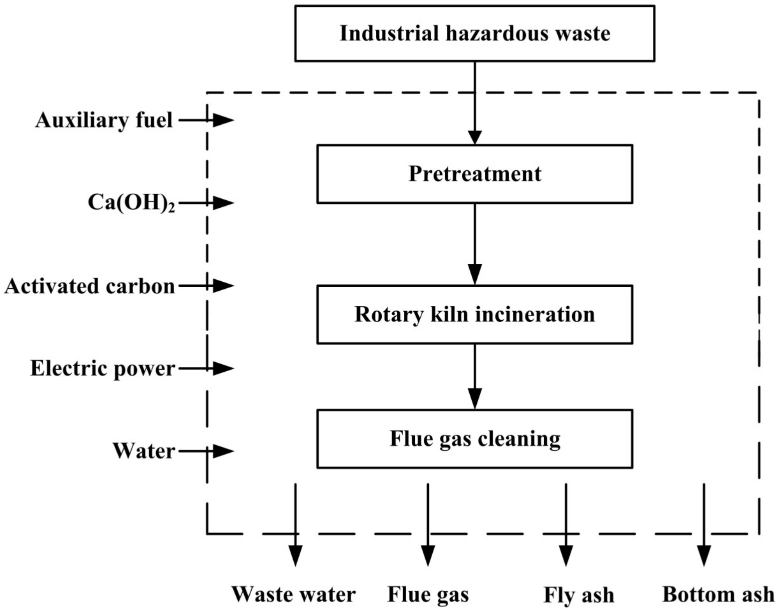

Fig. 1. Model of IHW incineration system.

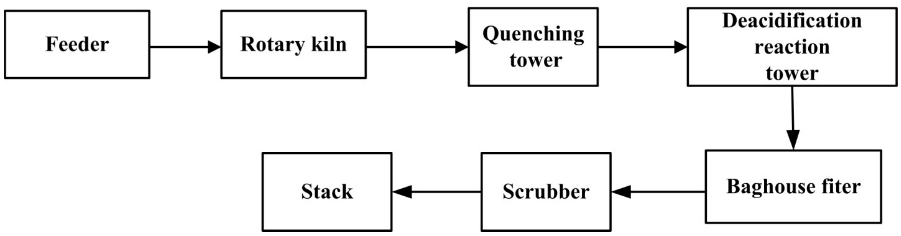

Fig. 2. The system diagram of IHW incineration process.

material requirements, atmospheric emissions, waterborne emissions, solid wastes and other releases for the entire life cycle of a product, process or activity (Curran, 2008). In this paper, the inventory for the IHW incineration system should contain the emission of pollutants to environment and the amount of energy and material consumed. According to the assessment object and LCA model, basic assumptions are set to identify the most important processes from an environmental perspective and exclude the insignificant ones without affecting LCA results. Some assumptions are made for setting the boundary and initial conditions:

a. Generation, collection and transportation processes of IHW are not considered.
b. Energy recovery is not considered because this plant is not equipped with heat recovery facility.
c. Landfill is assumed to be the final process for all solid-waste streams.

As shown in Fig. 1, the inputs of the materials and energy include assistant fuel, calcium hydroxide ($Ca(OH)_2$), activated carbon, electricity and water. Without energy recovery, there are no outputs except emissions coming from incineration process. Inputs and outputs of the incineration system are shown in Table 2. The data are collected from the paper of Lin *et al.* (2014) and operational reports provided by the incineration manager (Zhejiang Environmental Monitoring Center, 2009).

Table 2. Inputs and outputs for the treatment of one ton of IHW in incineration plant (Zhejiang Environmental Monitoring Center, 2009; Lin *et al.*, 2014).

Input	Units	Value[a]
Assistant fuel	kg/ton waste	45
$Ca(OH)_2$	kg/ton waste	50
Activated carbon	kg/ton waste	2.3
Electricity	kWh/ton waste	232
Water	kg/ton waste	455
Output	**Units**	**Value**
Flue gas	Nm^3/ton waste	12040
Bottom ash	kg/ton waste	128
Fly ash	kg/ton waste	169
Waste water	kg/ton waste	200

[a] Based on the annual average.

According to previous research (Tian *et al.*, 2012), the pollutants generated from IHW incineration process can be classified into four categories: acid gaseous species (NO_x, SO_2, HCl, etc.), incomplete combustion pollutants (CO, PCDD/Fs, etc.), particulate matter and toxic heavy metals (Sb, Hg, Pb, Cr, Ni, etc). All these pollution are considered in present study and the emission inventory is listed in Table 3. The concentrations of all pollutants are determined based on the emission monitoring reports provided by the Environmental Monitoring Center (China National Environmental Monitoring Station, 2009; Zhejiang Environmental Monitoring Center, 2009) and Li (Li, 2011). The pollutants contained in waste water during IHW incineration are also considered. The specific emissions are listed in Table 4.

Life Cycle Impact Assessment

In the impact assessment phase, the goal is to understand and evaluate the magnitude and significance of the potential environmental influence of a system (Goedkoop *et al.*, 2010). Firstly, impact categories must be identified. In EDIP97 method, the impact categories are identified based on the problem-oriented approach driven by environmental problems (the so-called mid-point of the cause-effect chain) (Guinée *et al.*, 2002). According to the emissions listed in Tables 3 and 4, this paper chooses five impact categories: global warming (GW), human toxicity (HT), ecotoxicity (ET), acidification (AC) and nutrient enrichment (NE) as briefly introduced in Table 5.

The impact assessment consists three steps: characterization-calculating potential contributions to various impact categories, normalization-comparing impact potentials, weighting of the normalized impact potentials (Yang and Nielsen, 2001). In characterization, for each individual emission to the environment, a calculation is made to determine the contributions to all impact categories. These contributions are called the emission's environmental impact potentials (Wenzel *et al.*, 1997). These potentials indicate the extents of various environmental impacts of pollution from incineration system. The positive impact potentials indicate incineration cause negative effects on the environment; on the contrary, negative potentials mean beneficial effects. In normalization, for reflecting the relative importance of the different impact categories, the impact potentials are compared with basic scenario called normalization reference (listed in Table 5). Normalization references are selected as the background impact which

Table 3. Emission inventory of the incineration referenced to one ton waste.

Emissions	Units	IHW	
Emissions to air[a] (China National Environmental Monitoring Station, 2009; Zhejiang Environmental Monitoring Center, 2009)			
Particulate matter	mg/Nm^3 flue gas	40.4	
HCl	mg/Nm^3 flue gas	25.1	
SO_2	mg/Nm^3 flue gas	46	
NO_x	mg/Nm^3 flue gas	150	
CO	mg/Nm^3 flue gas	2.5	
HF	mg/Nm^3 flue gas	2.2	
PCDD/Fs	ng EQ/Nm^3 flue gas	0.04	
Hg	mg/Nm^3 flue gas	0.022	
Cd	mg/Nm^3 flue gas	2.78×10^{-3}	
Pb	mg/Nm^3 flue gas	0.46	
As	mg/Nm^3 flue gas	0.672	
Ni	mg/Nm^3 flue gas	0.064	
Cr	mg/Nm^3 flue gas	0.028	
Cu	mg/Nm^3 flue gas	0.015	
Sb	mg/Nm^3 flue gas	0.142	
Emissions to soil (Li, 2011)			
Emissions	Units	Bottom ash	Fly ash
PCDD/Fs	ng EQ/g ash	NA	19.7
Hg	mg/kg ash	11.52	1.2
Cd	mg/kg ash	NA	6.4
As	mg/kg ash	1.66	374
Ni	mg/kg ash	724.34	24.5
Pb	mg/kg ash	193.39	800
Cr	mg/kg ash	1399.06	39.5
Cu	mg/kg ash	3765.03	460.5
Zn	mg/kg ash	869.27	NA
Sb	mg/kg ash	NA	141.1

[a] Oxygen content in flue gas has been converted into 11%.
NA = Not available.

Table 4. Pollutant concentrations in waste water (unit: mg/L).

Pollutant	COD_{cr}	BOD_5	SS	Cu	Cr^{6+}	As	Pb	Zn	Total-P	Total-N
Concentration	150	80	40	1	0.1	0.05	0.1	2	10	30

Table 5. Life cycle impact categories and reference substances (Stranddorf *et al.*, 2005).

Category	Pollutants from incineration	Reference substance	Normalization references
Global warming	CO_2,CO	CO_2	8700
Acidification	SO_2, NO_x, HCl, HF	SO_2	101
Nutrient enrichment	NO_x, total-N, total-P	NO_3^-	260
Ecotoxicity to water, chronic	PCDD/Fs, heavy metals	water	7.91×10^5
Ecotoxicity to soil		soil	6.56×10^5
Human toxicity to air	PCDD/Fs, heavy metals, particulate	air	5.56×10^{10}
Human toxicity to water	matter, SO_2, NO_x, CO	water	1.79×10^5
Human toxicity to soil		soil	157

society and human imposes on the environment each year. They are calculated over the course of one year per person in the area for which the impact is computed (Wenzel *et al.*, 1997). In weighting, the normalized impact potentials are multiplied by weight factors. However, weighting factors reflecting the degree of interest of different countries in different impact categories (Chen and Christensen, 2010) are not considered here since they are often influenced by non-technological factors and not developed in China. The detailed calculation methods of these three steps are further described in *Environmental assessment of products* by Wenzel *et al.* (1997).

RESULTS AND DISCUSSION

Fig. 3 shows the normalization result of the IHW incineration process based on EDIP97 method. All impact potentials are positive which indicate emissions from incineration plant contribute to environmental pollution. This is consistent with the research results of literatures (Saft, 2007; Nouri *et al.*, 2012; Vermeulen *et al.*, 2012). To clearly demonstrate the impact of IHW incineration to different aspects of environment safety, the impact potentials are respectively divided by the yearly personal contribution to the same aspect of environment safety. For example the impact of IHW incineration to global warming is about 17% of that of one person per year. Other figures are expressed in the same way.

Human Toxicity

Human toxicity can be classified into three types: human toxicity to soil (HTs), human toxicity to water (HTw) and human toxicity to air (HTa), based on different emission space (Wenzel *et al.*, 1997) and pathways. After incineration, the pollutants existing in flue gas, bottom ash, fly ash and waste water contaminate respectively air, soil and water and then harm the human health. This paper considers all types of human toxicity. It is clear from Fig. 3 that HT has the largest impact potential. The contributions of different emissions sources are shown in Fig. 4.

In Chinese IHW incineration plant, waste water is emitted into the urban sewage pipe network after a physico-chemical treatment in plant to meet the Chinese integrated waste water discharge standard (GB8978-1996). So the concentrations of heavy metals in waste water are very low. And EDIP97 considers the harm of pollutants in waste water is lower than that in flue gas and ashes. Hence, pollutants in waste water contribute little to human toxicity.

Flue gases have the largest contribution to HTa (up to 98.32%). The main reason is that pollutants in flue gases directly are emitted to the atmosphere so that the influence on HTa is the most significant. Pollutants in bottom ash and fly ash are kept in soil after emission and difficult to dissipate into air, making the contributions to HTa small which are respectively 1.48% and 0.2%.

The greatest contributor to HTw is bottom ash instead of waste water. EDIP97 method considers that only Hg in bottom ash can harm the human safety through water. So Hg has the impact factor of HTw and other heavy metals are zero. According to normalization result, the impact potential of Hg in bottom ash to HTw is 0.906. Also the concentrations of heavy metals in waste water are very low so that the impact potential of heavy metals in waste water is 9.9×10^{-5}. The result indicates that even if Hg is discharge to soil, its toxicity to human health through the aquatic environment is great.

It is found that the pollutants leading to human toxicity are heavy metals, PCDD/Fs, SO_2, NO_x and particulate matter through further analysis of the data on Table 5 and Fig. 3. Hence, this paper also analyzes the contributions of these pollutants to human toxicity, displayed in Fig. 5, which indicates the contribution ratio of single pollutant to the total HT by summing up its contributions of HTa, HTs and HTw. In all pollutants, the greatest contributions are Pb and As, respectively 82.57% and 11.46%. As explained above, IHW, mainly from chemical companies, contain very high ratios of heavy metals than general solid wastes. For LCA assessment, the impact of Pb is larger than that of other heavy metals because first, Pb has relative high concentration in original waste; and second, as a volatile metal, during incineration, a large part of Pb will evaporate especially when chlorine is presented and gaseous Pb species will condense to fine ash particles during flue gas cooling process. These fine particles have very high possibility of escaping from the air pollution control system and causing secondary pollution. This explains the largest contribution of Pb to HT. Nonetheless most of heavy metals are present in fly ash and bottom ash which should be well treated and stabilized for landfilling to avoid any harm to human.

PCDD/Fs are widely concerned by the public because of its great harm to human health. But the contribution of dioxins is only 0.002% in the assessment result, indicating IHW

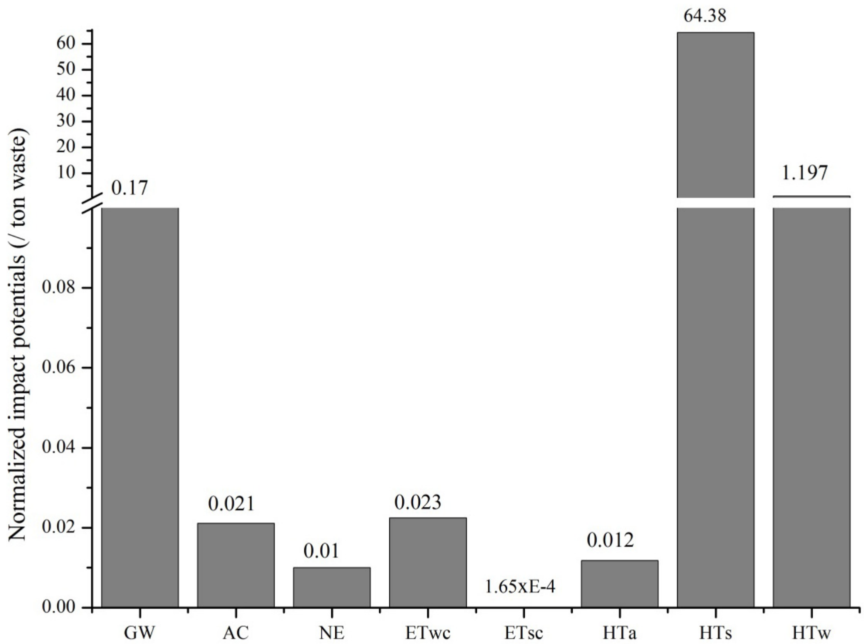

Fig. 3. Normalization result of IHW incineration process.

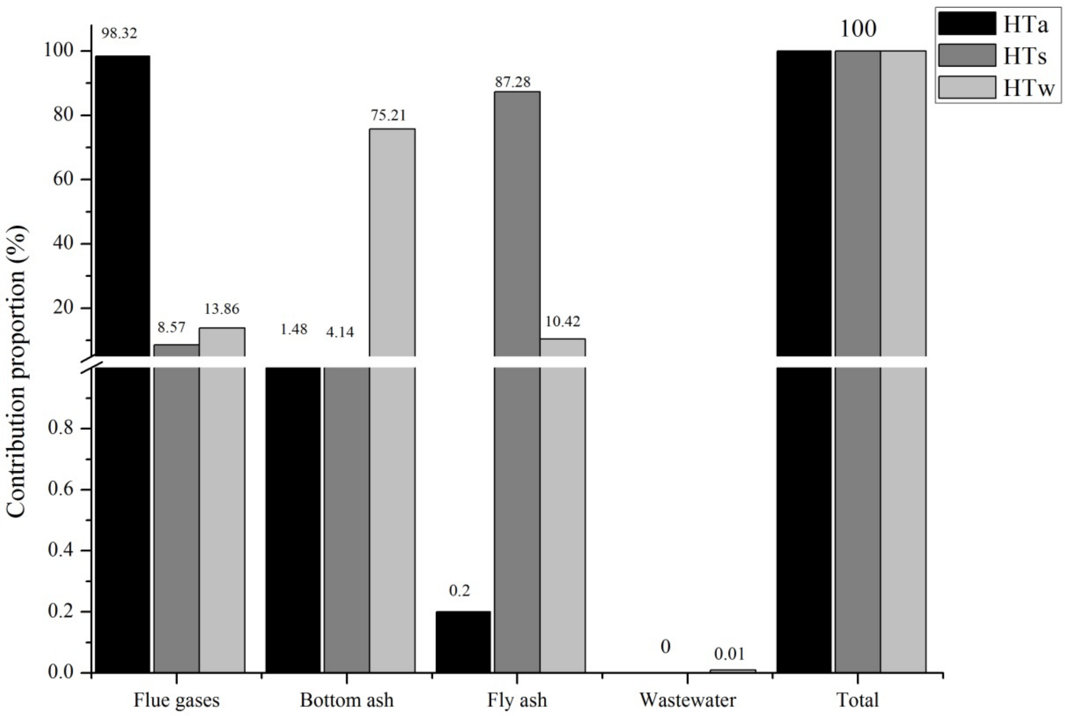

Fig. 4. The contributions of different emissions sources to HTa, HTs and HTw.

incineration plants in China well control dioxins emission by using '3T' (temperature, time and turbulence) principium controlling furnace combustion conditions and the method of activated carbon adsorption in the tail of flue gases.

Global Warming

In Fig. 3, the potential of GW ranks third in all environmental impacts. The main reason is that CO_2 emission is much higher than other pollutants; moreover, GW is nearly all caused by CO_2. However, CO_2 emission is not only from IHW incineration, also from combustion of assistant diesel, accounting for 5.1%. Usually, equivalent GW is relative lower for solid waste incineration when heat is recovered (Zhao *et al.*, 2008). However, the heat is not used in the incineration plant discussed in this paper.

Acidification

Substances, such as SO_2, NO_x, HF, HCl, contribute to

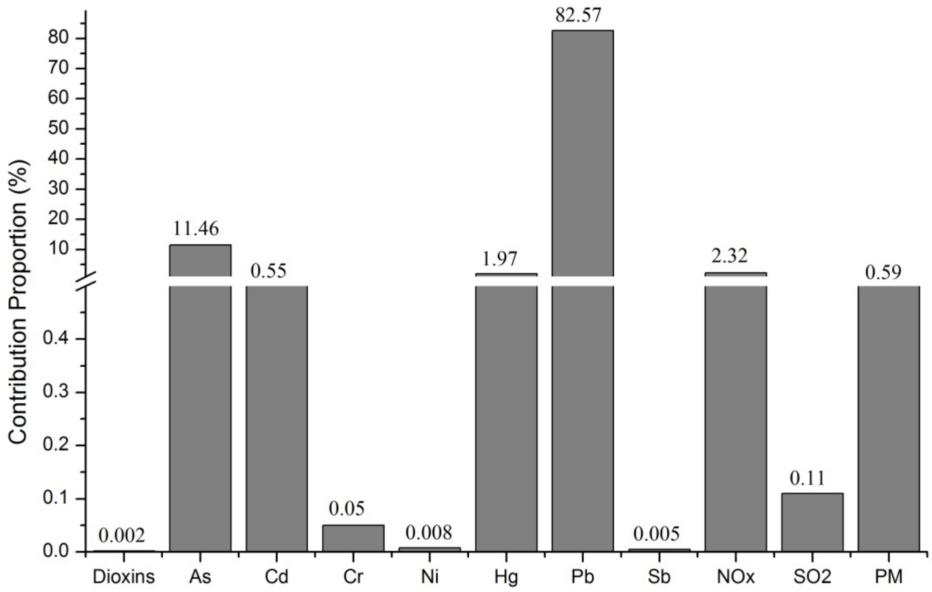

Fig. 5. The contributions of various pollutants to human toxicity.

the acidification of the environment (Yang and Nielsen, 2001). In this section, SO_2, NO_x, HCl and HF are chosen, all of which have strict emission standards. The impact potential of acidification is relatively small compared with other impact potentials indicating IHW incineration plants well control the acid gases emissions. The contribution of different pollutants to acidification is shown in Fig. 6. NO_x has the largest effect comparing with SO_2, HCl and HF because currently the acid gases removal devices have much high removal efficiency for SO_2, HCl and HF and low removal efficiency for NO_x. So a $DeNO_x$ system should be added to the flue gas cleaning system to reduce the harm of NO_x to the surrounding environment.

Nutrient Enrichment

IHW incineration will cause NE due to the emissions of NO_x, total-N, total-P. The contributions of these pollutants are shown in Fig. 7. Among the pollutants causing NE, the contribution of NO_x is largest. In the IHW incineration process, 98.9% of N in IHW is transferred to NO_x (Zhao *et al.*, 2008). Since the IHW incineration plant discussed in this paper is not equipped with a $DeNO_x$ system, NO_x, SO_2, HF, HCl are removed simultaneously by alkaline reaction which have very low efficiency on removing NO_x. These explanations further indicate the necessity of adding the $DeNO_x$ system.

Ecotoxicity

Ecotoxicity can be classified into two types: chronic ecotoxicity to water (ETwc) and ecotoxicity to soil (ETs). In all pollutants from IHW incineration, PCDD/Fs and heavy metals in flue gas, bottom ash, fly ash and waste water can harm the ecosystem. From a view of life cycle assessment, PCDD/Fs and heavy metals are more easily accumulated in human body though food chain, contact and exposure, etc. The harm to ecosystem caused by PCDD/Fs and heavy metals is largely transferred to the human body. So impact potentials of ETwc and ETs are very low. But the impact of ecotoxicity is significant in EDIP97. The contribution for ETwc and ETs are also analyzed shown in Fig. 8.

Although the pollutants in waste water can cause ETwc directly though the surface water, low concentrations of them lead to the relatively small contribution to ETs and ETwc. Rainwater transfers heavy metals and dioxins from flue gases into water, thus making pollutants in flue gases have the largest contribution to ETwc. ETs is mainly caused by dioxins and heavy metals in bottom ash and fly ash. There is no contribution proportion from waste water to ETs. In EDIP97, the pollutants in the water have small influence on ecotoxicity to soil by default. Only Hg in waste water has contribution to ETs which is the same reason explained in the section of human toxicity. However, before being released to the surrounding environment, harmful substances have been well treated wherefore the concentration of Hg is not detected. Hence the contribution proportion of waste water is zero.

CONCLUSIONS

In this paper, life cycle assessment is used to evaluate the incineration process of industrial hazardous waste (IHW). As the recommended incineration technology, the rotary kiln is chosen as the waste treatment option. Its incineration model and data inventories are established based on the running incineration plant in Hangzhou city, the eastern of China. In order to comprehensively understand the impacts of incineration process on the environment and human, process specific emissions (emissions to air, water and soil) are considered. The environmental impacts are classified to five categories: global warming, acidification, nutrient enrichment, ecotoxicity and human toxicity. The assessment results indicate that IHW incineration has the largest contribution to human toxicity, followed by global warming. Since the data and emissions inventory used in this paper

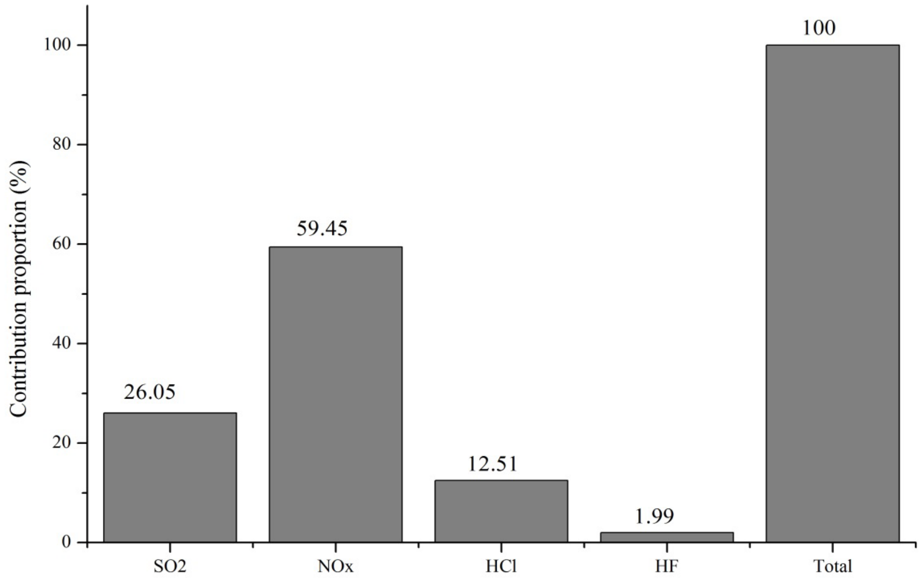

Fig. 6. The contributions of different pollutants to acidification.

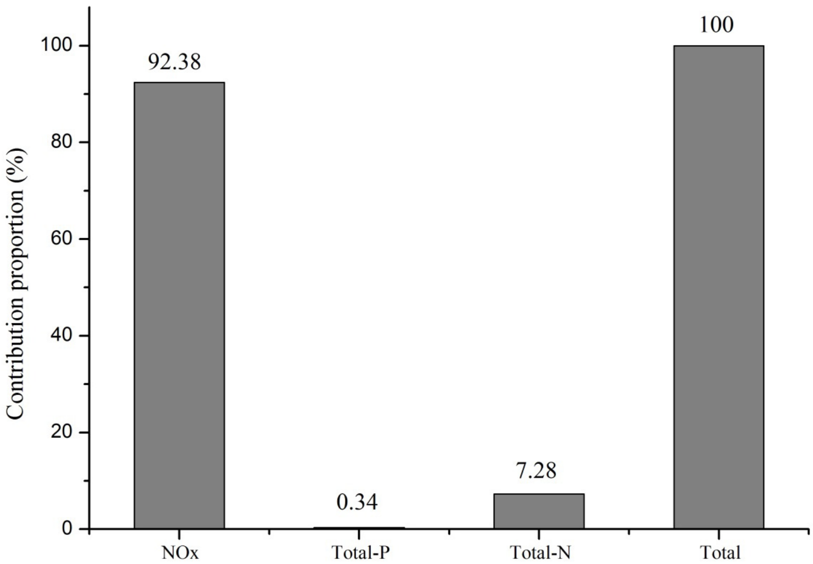

Fig. 7. The contributions of different pollutants to nutrient enrichment.

are provided by the IHW incineration manager and the environmental protection monitoring department, the assessment results are credible.

Heavy metals, specifically Pb and As, have the largest contribution to human toxicity. Heavy metals are mainly in bottom ash and fly ash. So bottom ash and fly ash should be well treated and stabilized for landfilling to avoid any harm to human. PCDD/Fs have small contribution to human toxicity and the whole environmental impacts, indicating Chinese IHW incineration plants can well control the dioxins emission. CO_2 is the main pollutant causing global warming. If energy recovery system is installed in incineration system, environmental impacts will be obviously decreased. In the gaseous pollutants, except CO_2, NO_x has relatively large contribution to environmental impacts. Although now flue gas cleaning system of IHW incineration plants enables NO_x concentration to meet the national emission standards, the environmental harm of NO_x does not fall below the minimum.

As a general conclusion, it can be stated that IHW incineration in China has negative effect on the environment and human health. However, there is still space for improvement according to the assessment results: Energy recovery system and $DeNO_x$ system should be added into incineration system and bottom ash and fly ash should be well treated and stabilized.

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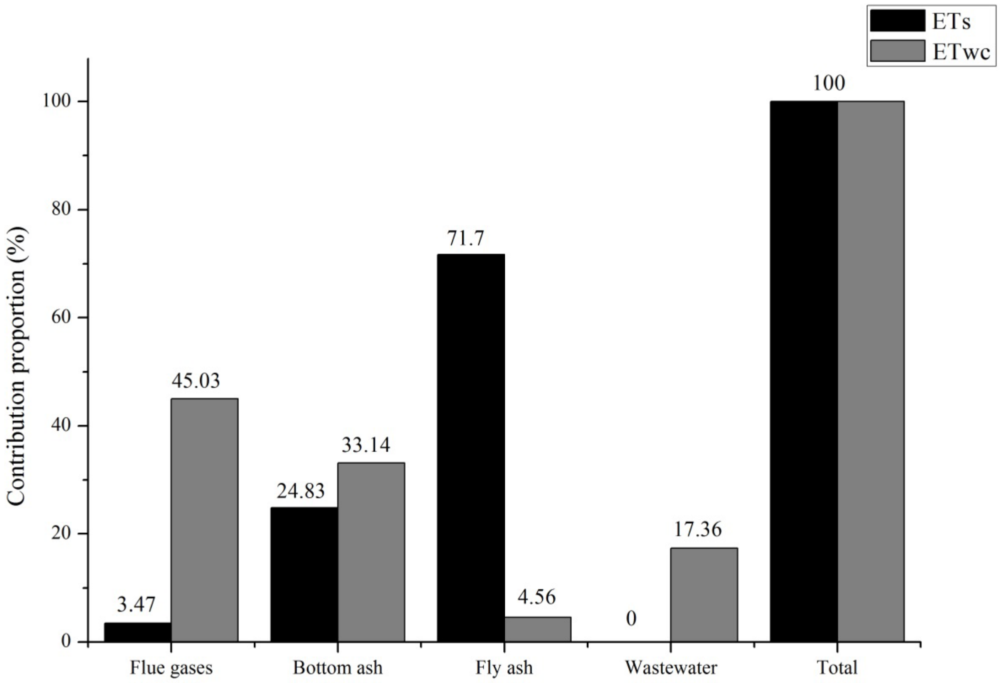

Fig. 8. The contributions of different emissions sources to ETs and ETwc.

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