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Life cycle analysis of sanitary landfill and incineration of municipal solid waste①

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[Abstract] Environmental consequences from sanitary landfill as well as incineration with power generation were compared in terms of life cycle analysis (LCA) for Laohukeng Waste-disposal Plant that is under consideration in Shenzhen. A variety of differences will be resulted from the two technologies, from which the primary issue that affects the conclusion is if the compensatory phase in power generation can be properly considered in the boundary definition of LCA. Upon the compensatory phase is taken into account in the landfill system, the negative environmental consequences from the landfill will be more significant than those from the incineration with power generation, although the reversed results can be obtained as the compensatory phase is neglected. In addition, mitigation of environmental impacts through the pollutant treatment in the incineration process will be more effective than in the landfill process.

[Key words] sanitary landfill; incineration; life cycle; compensatory phase
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1 INTRODUCTION

The rapid economic development and urbanization in China in recent years has resulted in substantial increase of solid waste. It was estimated that the total production of municipal solid waste (MSW) in 2000 has been up to 120~ 140 million tons. However, the treatment rate is very low, and thus the environmental consequence of MSW becomes a serious problem in more than 200 large cities[1].

Considering the negative impacts to living environments, landscapes and human health, more and more attention has been paid to the treatment and disposal of MSW. At the present stage, the MSW treatment technologies primarily include sanitary landfill, incineration, composting and recovery/recycling. By use of proper treatment and disposal technologies, the environmental impact of MSW could be greatly mitigated, although some secondary pollution could be still inevitable in the whole processes and the impact mechanisms or extents could be different for different technologies. Finnveden[2] studied some issues that must be considered in the life cycle assessment (LCA) for solid waste management systems, and five issues were indicated, i.e. the upstream and downstream system boundaries, the open-loop allocation problem, the multi-input allocation problem, the time as a system boundary and the life cycle impact assessment. Denison[3] compared the major options for managing MSW prevailed in the studies in North American on the basis of environmental considerations.

In order to evaluate the environmental consequences of MSW treatment/disposal in the whole life-cycle, a case study is made for Laohukeng Waste-disposal Plant under consideration in Shenzhen, where MSW treatment/disposal becomes one of the primary concerns by the local government. Two technologies are considered, i.e. the sanitary landfill or incineration with power generation. For comparison, the LCA is applied for both technologies with full consideration of the different processes and environmental consequences.

2 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA)[2, 4, 5] is a tool to quantify environmental burdens associated with products or activities throughout their life cycle, or "from cradle to grave". Since its birth and first application to industrial product in 1960s, many study cases have been developed in the world. LCA developed rapidly during the 1990s and has reached certain level of harmonization and standardization.

LCA[6~8] studied the overall environmental burdens generated by products, processes or activities during their entire life cycle, which includes the stages from the extraction and processing of raw materials, manufacturing, through production, packaging, transportation, distribution, use and reuse, and maintenance, recycling, to the final disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological considerations. There are four phases for LCA, which include: (1) goal definition and scoping; (2) inventory analysis; (3) assessment of potential environmental impacts; (4) interpretation or improvement analysis.

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3 LCA OF LANDFILL AND INCINERATION

3.1 Goal definition and scoping

The "functional unit" is taken as 600t MSW for both landfill and incineration technologies, which is determined according to the daily disposal capacity of the Laohukeng Waste Incineration Plant. For the definition of system boundaries for landfill and incineration of MSW[2], an equivalent amount of electricity generated from the incineration process is assumed to add to the landfill system, and the alternative heat source is assumed to be coal fuels. In general, the disposal capacity of 600t MSW per day in the incineration plant could meet the requirement of generating 1.918×10^5 kW·h electricity every day. For compensation of the equivalent amount of electricity, 81.32 t of standard coal is needed according to the average consumption rate of 0.424 kg standard coal per kW·h. The life cycle concerned herein includes the transportation, treatment/disposal and stabilization. Note that the different waste composition and environmental factors, the degradation rate of Chinese MSW is much higher. Therefore, a 10-year time-period is used herein[9].

3.2 Inventory analysis

The content percentages of MSW components such as C, H, N, S, Cl, F and H_2O are 39.43%, 6.24%, 1.41%, 0.81%, 0.069%, 0.017% and 38.46%, respectively. Transportation distance is assumed to be 40 km. Diesel consumption is about 0.04 L/(t·km), so 960 L diesel will be consumed by conveying 600 t MSW. With regard to the emissions, two conditions could be considered: treatment or not. In this paper, the gas from landfill is assumed to release into the air directly without gas recovery. The pollutant content of landfill leachate depends on if it is treated or not before discharged into surface water bodies. The flue gas of incinerator could be released into the air directly or be treated with semi-dry process. The average total leachate from landfill is about 163 m^3 for 600 t of MSW during the life cycle. The total mass of bottom slag and fly ash is about 150 t. The emission data during the life cycle are shown in Table 1.

3.3 Impact assessment

According to the life-cycle characteristics of waste treatment/disposal, its environmental impacts are classified into five kinds[10, 11]: energy depletion potential (EDP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical oxidant potential (POCP). The equivalent relationship[12] between environmental factors and reference basis is shown in Table 2. The overall potential impacts of different kinds, under two situations, are listed in Table 3.

For the case without treatment before discharge, the level for any specific potential environmental impact from the landfill is assumed to be 1.0 unit for reference, then the relative levels of standardized potential environmental impacts, including those of the incineration process with power generation are evaluated respectively. The results are shown in Table 4. The relative weight coefficient for any impact could be obtained according to the analytic hierarchy process (AHP). The importance level[11] of each factor is shown in Table 5. The weight coefficients of EDP, GWP, AP, EP and POCP are 0.43, 0.35, 0.13, 0.03 and 0.06, respectively. The integrated standardized factors of the environmental impacts from the two treatment processes are obtained with the following index

$$Q = \sum_{i=1}^{5} q_i \times \eta_i \tag{1}$$

where Q is an index that integrates various environmental impacts, q_i the value of a factor for any specific impact, η_i the weight coefficient for a factor. It should be indicated that any of the two processes discussed here could result in new pollutants. For reference, assume $Q_1 = 1.0$ for the landfill process, then Q_2 would be 0.78 for incineration in case of no treatment at all. Similarly, if pollutant treatment were considered, Q'_1 would be equal to 0.98 for landfill, and Q'_2 would be 0.49 for incineration. Therefore, it is clear that the landfill process would result in more significant environmental consequences than those from incineration with power generation in both cases discussed above.

3.4 Improvement analysis

Table 1 Pollutant production during life cycle (t)

Process	Treatment	CO_2	CO	CH_4	NO_x	SO_2	H_2S	HCl	HF	C_xH_y	COD	NH_3-N
Landfill	No	230.01	0.078	17.19	0.30	4.89	0.0077			0.41	3.26	0.082
	Yes	230.01	0.078	17.19	0.30	4.89	0.0077			0.41	0.033	0.0057
Incineration	No	869.08	1.09		1.07	9.73		0.43	0.11	0.0040	0.0025	0.0016
	Yes	869.08	0.55		0.30	0.19		0.072	0.0036	0.0040	0.0025	0.0016

Table 2 Relative significance of pollutants

Impact	Pollutant	Reference constituent	Significance
GWP	CO_2	CO_2	1
	CO		2
	CH_4		25
EP	NO_x	NO_3^-	1.35
	NH_3-N		3.64
	COD		0.23
AP	NO_x	SO_2	0.70
	SO_2		1.00
	HCl		0.88
	HF		1.60
	H_2S		1.88
POCP	C_xH_y	C_2H_2	0.398

It is assumed that impact significance of reference constituents be 1.

The pollutant treatment would be helpful to further improve environmental conditions in both processes. From comparison of the reduction of negative environmental consequences, it is found that the treatment in the incineration is more effective than in the landfill process. With the treatment consideration, the integrated index for overall environmental impacts could be reduced 37% (from 0.78 to 0.49) in the incineration process, whereas only 2% (from 1.0 to 0.98) reduction could be obtained in the landfill process. Another aspect that is not considered herein is the reuse of produced gases such as CH_4, which is beneficial to both environmental protection and effective use of energy.

4 DISCUSSION

Just assume that the compensatory power generation in landfill system is not considered, then potential environmental impacts would be quite different, the relevant results are shown in Table 6. With the same references for various impacts as used in the aforementioned, the calculated results for no-compensatory case are given in Table 7. For landfill system, we have the integrated index $\overline{Q}_1 = 0.28$, and $\overline{Q}_2 = 0.78$ for incineration system, if neglecting the pollutant treatment. However, $\overline{Q}'_1 = 0.26$ and $\overline{Q}'_2 =$

Table 3 Major potential environmental consequences

Process	Treatment	EDP/GJ	GWP/kg	AP/kg	EP/kg	POCP/kg
Landfill	No	2 412.59	660 022.35	5 118.06	1 453.32	163.42
	Yes	2 412.59	660 022.35	5 118.06	435.15	163.42
Incineration	No	34.27	871 253.56	11 028.81	1 446.83	1.58
	Yes	34.27	870 173.56	470.024	406.79	1.58

Table 4 Standardized results of environmental factors with compensatory phase

Process	Treatment	EDP	GWP	AP	EP	POCP
Landfill	No	1.0	1.0	1.0	1.0	1.0
	Yes	1.0	1.0	1.0	0.299 4	1.0
Incineration	No	0.014 2	1.320 0	2.154 9	0.995 5	0.009 7
	Yes	0.014 2	1.318 4	0.091 8	0.279 9	0.009 7

Table 5 Important level of different environmental factors

Impact factor	EDP	GWP	AP	EP	POCP
EDP	1	2	3	9	7
GWP	1/2	1	6	8	6
AP	1/3	1/6	1	5	3
EP	1/9	1/8	1/5	1	1/3
POCP	1/7	1/6	1/3	3	1

$\lambda_{max} = 5.31$, RI = 1.12, CI = 0.077 5, CR = 0.069 < 0.1

Table 6 Environmental consequences from landfill and incineration

Process	Treatment	EDP/GJ	GWP/kg	AP/kg	EP/kg	POCP/kg
Landfill	No	34.27	480 098.97	33.74	1 058.100	1.58
	Yes	34.27	480 098.97	33.74	39.919 4	1.58
Incineration	No	34.27	871 253.56	11 028.810	1 446.83	1.58
	Yes	34.27	870 173.56	470.024	406.79	1.58

Table 7 Standardized results of factors without compensatory phase

Process	Treatment	EDP	GWP	AP	EP	POCP
Landfill	No	0.014 2	0.727 4	0.006 6	0.728 0	0.009 7
	Yes	0.014 2	0.727 4	0.006 6	0.027 4	0.009 7
Incineration	No	0.0142	1.320 0	2.154 9	0.995 5	0.009 7
	Yes	0.014 2	1.318 4	0.091 8	0.279 9	0.009 7

0.49 could be obtained once pollutant treatment is considered. It is obvious that overall potential environmental impact from the landfill is lower than that from the incineration with power generation. This conclusion is totally reversed to the results from the aforementioned analysis where compensatory power generation in landfill system is considered.

One of the primary challenges in LCA is the proper definition of the system boundary. For the two disposal processes for MSW, the boundary determination is focused on whether the compensatory power generation should be involved in the landfill system. Once this matter is made clear, the controversy about environmental consequences from the incineration and the landfill by different investigators[12] could be well explained. Although there are many alternatives for compensatory considerations, they do not change the conclusion qualitatively and the choice made in the present paper is no doubt one of the effective ways. In addition, taking coal as fuel is also proper for most cases in China.

5 CONCLUSION

LCA and AHP are used to compare the potential environmental impacts of landfill and incineration with power generation. It is shown that more negative environmental consequences would be resulted from the landfill than from the incineration with power generation if the compensatory phase for power generation were taken into account in the landfill system. Otherwise, the former would be much better than the latter in terms of environmental considerations. The functional unit requires the similar functions for comparison of two different technologies for MSW treatment/disposal in the whole life cycle. Therefore, the compensatory consideration of power generation in landfill system gives a good basis for boundary definition in LCA and is of significance to other relevant studies. As for the pollutant treatment, it does not change the aforementioned conclusion, but alters the environmental consequences to certain degree particularly for the incineration process.

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