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REVIEW ARTICLE

Development and prospects of municipal solid waste (MSW) incineration in China

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Abstract With the lack of space for new landfills, municipal solid waste (MSW) incineration is playing an increasingly important role in municipal solid waste management in China. The literatures on certain aspects of incineration plants in China are reviewed in this paper, including the development and status of the application of MSW incineration technologies, the treatment of leachate from stored MSW, air pollution control technologies, and the status of the fly-ash control method. Energy policy and its promotion of MSW-to-energy conversion are also elucidated.

Keywords municipal solid waste, incineration, air pollution control, stoker, fluidized bed

1 Introduction

With the sustained and rapid economic growth in the past three decades, China is undergoing massive urbanization. The total population increased from 9.626×10^8 in 1978 to 1.376×10^9 by the end of 2005, while the urbanization rates over the country increased from 17.4 to 41.8%. Along with the rapid urbanization, municipal solid waste (MSW) generation is increasing at annual rates of 8–10%, with more than 1.50×10^8 t of MSW generated each year. At the same time, the composition of MSW in China is also changing with kitchen waste replacing coal cinder as the largest component. This corresponds with the shift from coal to natural gas as a major source of fuel for domestic use. In addition, the proportion of both organic waste and recyclable waste continues to increase as living standards improve in most Chinese cities. In the middle of the 1980s, the content of coal cinder and ash was up to 60–70% and the content of combustible matter was less than 10% because coal was the main energy. Currently, the content of ash has decreased to less than 20%, while the content of combustible matter has increased to greater than 20% and the content of biodegradable organics has increased to about 50%.

However, the composition of the waste in China is extremely inhomogeneous.

In some of the large cities, the composition of the waste corresponds roughly to that in Western Europe. In the coastal areas, such as Guangdong, Zhejiang, Jiangsu, and Fujian provinces, some combustible industrial waste materials such as waste cloth, waste plastic, and waste rubble, are mixed into municipal solid waste. As for biodegradable organics, the content is about 31–36% in big cities, while in mid-sized and small cities it is 50% and 65%, respectively.

Currently, the average calorific value of MSW in China equals 5000 kJ/kg. The lower heating value of MSW in a typical city of China is above 4000 kJ/kg. Even in the larger cities, the calorific value only reaches to 6000–7000 kJ/kg. The reasons for the low calorific value are the high moisture and the high proportion of kitchen waste in the MSW, with calorific value of approximately 2000 kJ/kg due to the traditions of materials recovery and extensive picking, the food culture, and the mixed collection miner in China. The MSW's calorific values (4000–7000 kJ/kg) are typically less than half of those (8400–17000 kJ/kg) of the MSW in developed countries.

A growing number of cities in China are facing the problem of MSW disposal. China will not be able to further dump raw MSW because of the lack of space for new landfills. Some municipal authorities already have great difficulty in finding appropriate landfill sites for MSW. Thus, an increasing number of cities have constructed or are planning to construct incineration plants, in spite of the significant capital and operating costs involved. MSW incineration is playing an increasingly important role in municipal solid waste management in China.

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2 Development and status of MSW incineration

2.1 Development of MSW incineration

In China, MSW incineration (MSWI) started to be used at the end of 1980s. The first modernized incineration plant in China was built in Shenzhen, Guangdong Province, in 1988. Three sets of Martin MSW incinerators were installed and the disposal capacity of each incinerator was 150 t/d. With the operation of phase II of the project, MSW incineration began undergoing rapid development.

There were 36 municipal waste incineration plants in operation in China in 2001 with a total daily capacity of approximately 6520 t. These plants were used to incinerate 2.9% of all the treated municipal solid waste. By the end of 2005, China operated 67 MSWI plants with a total daily capacity of approximately 33010 t. This was about 12.9% of all the municipal solid waste being treated in China at the time.

In China, almost all of MSW incineration plants are designed to dispose of MSW and to produce electricity as a byproduct of the incinerator operation. The Pudong MSW incineration plant in Shanghai has three stoker incinerators and two 8500 kW power units. The average disposal capacity is 1200 t/d. The heating value of MSW was designed at 6060 kJ/kg, and fluctuates from 4600 to 7500 kJ/kg in actual operation.

At present, more and more incineration plants are under construction in China. Most of them are distributed in the big cities and the cities in the Yangtze River Delta and the Zhujian River Delta, which have more developed economies and higher population densities.

In Beijing, the Gao'antun MSW-to-energy plant has been constructed and will be put into operation, and another three plants (Liulitun, Nangong, and Asuwei) are set for construction. In Tianjin, the Shuanggang MSW–to-energy plant has been built and two plants (Guanzhuang, Qingguang) are under construction. Shanghai has two MSW-to-energy plants (Jiangqiao and Yuqiao), and is constructing another plant in Jiangqiao.

Currently, there are 15 MSW-to-energy plants distributed in the cities of Suzhou, Wuxi, Changzhou, and Nanjing in the south of Jiangsu province. Besides these, some plants have also been constructed or are to be constructed in the cities of Yangcheng, Lianyungang, and Suqian in the north of Jiangsu province. In Zhejiang province, more than 30 MSW-to-energy plants have been built up or are under construction in the cities of Hangzhou, Jiaxing, Shaoxing, Wenzhou, Ningbo, Jinhua, and Taizhou. While in Guangdong province, about 20 MSW-to-energy plants are in the cities of Guangzhou, Shenzhen, Dongguan, Zhongshan, Foshan, Huizhou, and Zhuhai.

Besides MSW-to-energy plants, there are also some small, batch-type or intermittently operated facilities in the MSW integrated treatment plants.

2.2 Status of application of MSW incineration technologies

Among MSW incineration plants in China, there are four major types of MSW incineration technologies, i.e., stoker, fluidized bed, rotary kiln, and paralysis, as shown in Table 1.

2.2.1 Stoker technology

Because of the complexity and high technology of the stoker incineration system, the construction of the large-scale grate furnace is mainly dependent on the importation of foreign technology and equipment. As shown in Table 2, almost all kinds of stoker technologies in the world could be found in China, including Japan Mitsubishi-Martin grate, Japan Takuma SN grate, Belgium Seghers SHA multi-grade grate, Japan Hitachi VonRoll grate, France Alston grate, German Noerkeerchi grate, German Sitanmile grate, and Swiss VonRoll R-10540 type grate. However, the widely used grates are the Japan Mitsubishi-Martin grate, Japan Takuma SN grate, and Belgium Seghers SHA multi-grade grate. Recently, a mechanical shuttle conveyer grate furnace was developed in China. The Weiming Group and the Hangzhou New Century Environmental Technology Co. Ltd developed a two-stage grate with the capacity of 150 and 225 t/d, respectively. Chongqing Sanfeng Environment Industrial Co., Ltd introduced Germany's SITY2000 type stoker technology (with the key facilities made in China), which has been used in the Chongqing Tongxing Incineration Plant with the capacity of 600 t/d. In the ''11th Five-Year Plan'' (2006–2010), furnaces with the capacity of 350 t/d will be the focus. Until now, more than 10 plants are using home-made technologies.

In China, most stoker systems have an average (approximately 500 t/d) or high capacity (approximately 1,000 t/d) in addition to a few furnaces with a very small

Table 1 Statistic results of MSWI technologies in China

incineration technologies	plant No.	incinerator No.	treatment capacity/t·d^{-1}	power capacity (MW)
stoker	25	69	20400	355
fluidized bed	24	50	16080	420
rotary kiln + paralysis	14	32	3540	25
total	63	151	40020	800

Table 2 Major stoker incinerator technologies in China

countries	technologies	MSW incineration plants
Japan	mitsubishi-Martin reverse acting stoker	Likeng (Guangdong), Huanwei (Guangdong), Binjiang (Zhejiang), Zhongshan (Guangdong)
	hitachi-Von Roll	Guanzhuang (Tianjin), Chengdu (Sichuan)
	takuma step-reciprocating grate	Shuanggang (Tianjin), Gaoantun (Beijing), Zhangjiagang (Jiangsu)
	JFE	N/A
	ebara	N/A
German	noer-keerchi grate	Fenglin (Zhejiang)
	sitanmile grate	Puxi (Shanghai)
	SITY 2000	Tongxing (Chongqing)
France	alston grate	Pudong (Shanghai)
Belgium	seghers SHA multi-grade grate	Nanshan (Guangdong), Suzhou (Jiangsu) Jinjia (Jiangsu), Changshu (Jiangsu)
USA	detroit grate	Zhuhai (Guangdong)
	basic grave	Nanhai (Guangdong), Shunde (Guangdong)
China	new central reciprocating and reverse acting grate	Jinjiang (Fujian), Pinghu (Guangdong), Taicang (Jiangsu)
	Sanfeng-SITY 2000	Hongmiaoling (Fujian)
	Shennengyuan-Seghers	Bao'an (Guangdong), Yantian (Guangdong), Laohukeng (Guangdong)

capacity (<100 t/d). The incineration capacity of the MSW-to-energy plant is increasing. The average incineration was only 181 t/d in 2001 but was 493 t/d in 2005. A 1500 t/d plant with the largest waste-to-energy facility is in Shanghai.

Because the investment is relatively high, and a minimum calorific value of 6000 to 6500 kJ/kg is necessary for incineration without support firing, the stoker systems are usually adopted by large and coastal areas. Some MSW-to-energy plants that have been constructed and put into operation are shown in Table 3.

Table 3 Some selected stoker systems in operation from 2003 to 2006

No	name	capacity/t·d^{-1}	year in operation
1	Pudong Yuqiao (Shanghai)	400 × 3	2003
2	Linjiang (Zhejiang)	250 × 3	2003
3	Puxi Jiangqiao (Shanghai)	500 × 3	2004
4	Tongxing (Chongqing)	600 × 2	2004
5	Nanshan (Guangdong)	400 × 3	2004
6	Yantian (Guangdong)	225 × 2	2004
7	Yongqiang (Zhejiang)	250 × 3 + 350 × 1	2004
8	Binjiang (Zhejiang)	150 × 3	2005
9	Changshu (Jiangsu)	350 × 3	2005
10	Fenglin (Zhejiang)	350 × 3	2005
11	Jinjiang (Fujian)	250 × 3	2005
12	Pinghu (Guangdong)	250 × 3 (Phase 1)	2005
		250 × 4 (Phase 1)	2006
13	Taicang (Jiangsu)	250 × 3	2006
14	Bao'an (Guangdong)	400 × 3	2005
15	Zhongshan Union (Guangdong)	350 × 3	2005

2.2.2 Circulating fluidized bed (CFB) technology

The CFB incinerator, based on the co-firing of MSW with coal, is another widely used incineration technology in China.

The first CFB incineration plant, the Qiaoshi MSW-to-energy plant at Hangzhou, was constructed and put into operation in 2000 by Jinjiang Co. Ltd. Because the addition of coals into a CFB incinerator is allowed and the produced electricity can be purchased at a good price, this incineration technology has much lower capital and operating costs. Thus, the small and mid-sized cities, as well as the larger cities in the middle and western parts of China appear to prefer having a CFB incinerator combusting their non-sorted MSW with high moisture contents and low calorific values. This is the reason for the rapid development of the CFB incinerator and its wide-spread use across China in the past five years.

Currently, more than 30 MSW–to-energy plants adopting a CFB incinerator have been built up or are under construction. These plants are located in mid-sized cities such as Qiaosi (Zhejiang province), Yuhang (Zhejiang province), Jiaxing (Zhejiang province), Zhenhai (Zhejiang province), Dongguan (Guangdong province), Heze (Shandong province), Pengzhou (Sichuan province), and the larger cities in the middle, western and the northeastern of China, including the cities of Changchun (Jilin province), Dalian (Liaoning province), Harbin (Heilongjiang province), Kunming (Yunnan province), and Zhengzhou (Henan province).

In contrast with the stoker incinerator, most CFB incinerators mainly use domestic technologies, provided by Zhejiang University, Tsinghua Univeisity, and Beijing Zonked General Energy-Envier. Co. Ltd. The treatment capacity of these CFB incinerators ranges from 100 to 500 t/d. Most MSW-to-energy plants employ both the CFB incineration technologies provided by Zhejiang University and the Beijing China Sciences General Energy-Envier. Co. Ltd, which requires the addition of more than 20% of coals based on MSW mass. Japan Ebara Co. Ltd also has three CFB incineration projects in China. One is in operation in Harbin, and the other

Table 4 Pollutants emission limit of Chinese MSW incinerator

pollutants	unit	determined value	air emission limit	
			national standards	Beijing standards
particles	mg/m^3	hourly average	80	30
gas darkness	Lingleman, grade	hourly average	1	1
SO_2	mg/m^3	hourly average	260	100
NO_x	mg/m^3	hourly average	400	200
CO	mg/m^3	hourly average	150	55
HCl	mg/m^3	hourly average	75	60
Hg	mg/m^3	measured average	0.2	0.2
Cd	mg/m^3	measured average	0.1	0.1
Pb	mg/m^3	measured average	1.6	1.6
Dioxins	TEQ ng/m^3	measured average	1.0	0.1

Note: Reference oxygen concentration is 11%.

two are in construction in Dalian and Taiyuan, respectively. These two CFB incinerators, provided by Ebara and Tsinghua University, require the addition of less than 20% of coals as auxiliary fuels.

2.2.3 Other technologies

China now has some small scale furnaces, which are mainly used as supporting parts of integrated treatment technologies. These furnaces are usually built in the incineration plant, including the sieving center, composting facilities, incineration facilities, and landfill plant. The treatment capacity of such furnaces is usually 100–200 t/d, and they do not have the ability of electricity generation.

2.3 Secondary pollution control of MSW incineration

2.3.1 Leachate treatment

In the beginning of incineration development in China, there had been many problems with imported stoker incinerators because of the high moisture and the low calorific value of the wastes. Diesel is often added as a supplementary fuel to support combustion of the low energy content MSW, which substantially increases the incinerator's operating cost.

However, the above problems have been solved through improving the stoker design and prolonging the storage period to increase the lower heating value. After 5–6 days of storage before MSW is fed into the incinerator, the lower heating value could be increased by 10–15%. However, a larger amount of leachate is generated and has to be treated to comply with the discharge standard.

2.3.2 Air pollution control

It is widely known that the thermal process in MSW incineration has the potential of emitting diverse types of air pollutants to the environment. These potential emissions may arise from compounds (for example, heavy metals) present in the waste stream, or may be formed as part of the normal combustion process (e.g., particulate and acid gases) or of incomplete combustion (such as carbon monoxide). Therefore, the State Environmental Protection Administration of China promulgated the Pollution Control Standards for Municipal Solid Waste Incineration in 1999 to guide the development of technology for MSW incineration. Usually, the MSWI air pollutants emission limit demanded by the local Environmental Protection Bureau (EPB) is much stricter than the national emission standard limit. For example, the dioxin emission standard of MSWI, with an emission standard limit of 1.0 ng TEQ/Nm^3, is not very stringent. However, the dioxin level of the incinerator stack is required to comply with an emission limit of 0.1 ng TEQ/Nm^3 for imported foreign incinerators and incinerators located in the larger cities and in eastern and southern China by the local EPB. Table 4 shows the emission limits for MSWI in the National Standard and in the local standard.

The first and most important method of emission control is to operate only international standard high temperature incinerators that have a secondary high temperature afterburner. Remaining emissions are then reduced through air pollution control equipment at the back-end of the incinerator, such as devices for particulate bughouse filtration, flue gas cleaning, and activated carbon filtration. In China, MSW incinerators are usually equipped with semi-scrub in addition to lime, activated carbon and bughouse filtration devices without denitrogenization installations.

According to the current dioxin monitoring data for some MSW incinerators under operation in China, all of the dioxin emission concentrations are below the national standard limit of 1.0 ng TEQ/Nm^3. Adopting the best available air pollution control technologies, dioxin emission concentrations from large-scale MSW incinerators can comply with the European Standard of 0.1 ng TEQ/Nm^3, as shown in Table 5.

Table 5 Monitoring data of dioxin concentrations of MSW incineration facilities in China

locations	Dioxin concentration/ng TEQ/Nm^{3*}	examination date
Ningbo MSWI Plant	0. 13–0.085	November, 2003
Taicang MSWI Plant	0.096–0.041	February, 2007
Binjiang MSWI Plant (Hangzhou)	0.11–0.015	September, 2002
Linjiang MSWI Plant (Wenzhou)	0.84–0.3	May, 2005
Jiangqiao MSWI Plant (Shanghai)	0,045–0.005	June, 2006

Note: Emission standards in China is 1.0 ng TEQ/Nm^3.

2.3.3 Fly-ash control

MSWI fly-ash is a hazardous waste due to its dioxin and heavy metal content. Approximately 200,000 t/a of fly-ash is generated by MSW incineration. The fly-ash rates of the stoker incinerator and the CFB incinerator are 3–5% and 10–20% of treated MSW, respectively. As a requirement, the fly-ash should be stabilized firstly by cement solidification or other pretreatment technologies, and then be disposed of in a special landfill. A few cities have hazardous waste landfills in service or under construction, most of which do not consider receiving MSW incineration fly-ash. A common hazardous waste landfill would be filled up and closed in 2 years if it received MSW incineration fly-ash due to the huge quantity and volume of fly-ash. In fact, only a few MSW incineration plants dispose of their fly-ash according to the requirement, and most MSW incineration plants dump or sell the fly-ash privately. Therefore, it is very necessary to develop suitable technologies for MSWI fly-ash disposal.

Sintering technology has been developed by Tsinghua University to convert the MSWI fly-ash into non-toxic material and make the decontaminated products safely reusable in construction materials. The results obtained from a pilot plant with a treatment capacity of 5 t/d of fly-ash show that the decomposition rate of dioxin-like compounds during the sintering process was about 99.3%. The remained rate of the heavy metal in the sintered product depended on pretreatment of the fly-ash. The water-extraction pretreatment could remove at least 90% of chlorides from the MSWI fly ash, which are considered as the main factors controlling vaporization during the heating process. Another beneficial result of water-extraction is the significant increase in the content of SiO_2 in pretreated fly ash, contributing to strength forming in the sintering process.

3 Energy policy and the promotion of MSW–to–energy conversion

China is now the world's second largest consumer of energy and third largest importer of oil. With the high demand for energy during rapid economic expansion, government policies have been put in place to encourage the development of alternative domestic energy sources. On February 28, 2005, the Renewable Energy Law of the People's Republic of China was passed by the Standing Committee of the National People's 14th Congress. MSW-to-energy was singled out as an important renewable energy. A series of preferential policies for the exploitation and development of renewable energy are set forth in the Law, including:

- The enterprises operating electricity networks shall be required to enter interconnection agreements with qualified energy producers that use renewable resources and to purchase all electricity generated by them.
- A special national foundation will be established to support activities regarding the development of the renewable resources.
- The financial institutions shall provide loans to renewable resource projects so long as the projects fall into the Instructional Catalogue regarding Development of Renewable Resources and satisfy the credit conditions of the institution.''

As for the purchasing price of electricity generated by a MSW-to-energy plant, a clear prescript is given in the recent regulation and policies. Following the Renewable Energy Law, the State Development and Reform Commission (SDRC) issued the ''Regulation of the Price of Electricity from Renewable Energy and Fee Sharing'' on January 4, 2006, and the ''Management Regulation for Electricity from Renewable Energy'' on January 5, 2006. According to these two regulations, two approaches could be used to calculate the purchasing price of electricity from MSW-to-energy plants. One is the government-decided price, and the other is the government-suggested price. For the purchasing price decided by the State Council, the price is calculated using the purchasing price of electricity in 2005 from a coal-burning power plant with desulphurization and the subsidized electricity price of 0.25 RMB/(kW·h). Obviously, the beneficial electricity price will promote the development of MSW-to-energy. For example, since 2000 the price of electricity from MSW-to-energy has been 0.54 RMB/(kW h) in Zhejiang province and 0.55 RMB/(kW h) in Guangdong province. Based on the ''Regulation of the Price of Electricity from Renewable Energy and Fee Sharing'', the prices of electricity from waste-to-energy in Zhejiang and Guangdong provinces after 2006 are 0.666 and 0.69 RMB/(kW·h), respectively.

With regard to the MSW-to-energy plant using a mixed-fuel of MSW and conventional fuels (for example, coal), 20% (weight ratio) of raw coal is allowed to be fed into fluidized-bed combustion furnaces in the "Cognizance and Management Measures for the National Encouragement of the Comprehensive Utilization of Natural Resources", issued by the SDRC on September 7, 2006. However, if the added conventional energy exceeds 20% in heat consumption for power production, the plant shall be regarded as a conventional energy power generation project and as such the yardstick tariff of local thermal power plants shall apply without the subsidy price according to the "Regulation of the Price of Electricity from Renewable Energy and Fee Sharing" and the "Management Regulation for Electricity from Renewable Energy".

Besides the energy policy, a series of actions has been taken to promote MSW disposal by waste-to-energy incineration and other approaches. The Chinese government is encouraging support from the private sector in the development of the environmental protection industry. In July 2004, the State Department issued the "State Department Issuance on the Reformation of the Investment System", which aims to "encourage investment, enlarge the investment fields of social capital, and allow capital into basic facilities and public utilities within the law." The Chinese government also provides tax incentives to the waste-to-energy industry. Waste-to-energy incineration facilities are exempted from corporate income tax for the first 5 years of operation and are eligible for the immediate refund of value-added tax.

4 Discussion and prospect

MSW incineration has recently emerged as the method of choice for the primary treatment of MSW in many Chinese cities due to the advantages it offers, such as volume reduction, harmlessness, and energy recycling. Under this framework, the MSW-to-energy industry is experiencing rapid growth in China. According to the construction plans for MSW treatment in the "11th Five-Year Plan", China will build 82 MSW-to-energy plants from 2006 to 2010, as shown in Table 6.

Table 6 Distribution of MSW-to-energy plants to be constructed in the 11th Five-Year Plan

area of China	incineration plant	capacity/t·d^{-1}
East part	56	45100
South-west part	6	6100
North-west part	4	3300
Middle part	9	7200
South-east part	7	4900
Total	82	66600

In existing MSW incinerators, the subsidy for the CFB incinerator is lower than that of the stocker incinerator. This is because too much coal may be used in the CFB incinerator to produce more electricity, the purchased price of the electricity is high, and the MSWI fly-ash is not disposed of in an environmentally sound manner.

Before 2006, CFB technology was highly competitive for MSW incineration in China because there was no policy to limit it. From 2006, its competitiveness was diminished by the increase in coal prices, the large amount of fly-ash, the need for pre-treatment, and the change in government policy.

The most notable change is the requirement that the proportion of coals added into the CFB incinerator should be less than that equivalent to 20% in heat consumption for power production. If the added coal exceeds that percentage, the plant shall be regarded as a conventional energy power generation project and the yardstick tariff of local thermal power plants shall apply without the subsidy price. Up to now, there is no fluidized-bed MSW incinerator that achieves the standard of adding only 20% extra combustion-supporting coal; the fluidized-bed MSW incinerator may not get the electricity price subsidy.

Compared with the stoker incinerator, the CFB incinerator generates more fly-ash (about 3 to 5 times more than the stoker fly-ash). Without considering the fly-ash treatment, the subsidy for the incinerator is 0–40 RMB/t (MSW), which is much lower than the subsidy of 50–70 RMB/t (MSW) for the stocker incinerator. When considering the MSW incineration fly-ash, the CFB incineration comes out much more expensive than the stoker incineration.

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