A Rapidly Emerging WTE Technology: Circulating Fluid Bed Combustion

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Abstract

The management of solid waste has become a major problem and budget item of municipalities, especially in rapidly developing cities. The only alternatives for post-recycling waste are sanitary landfills, which require large tracts of land, and waste-to-energy (WTE) plants which are costly to build; an additional problem in the developing world is the high (>50%) organic and moisture content of the municipal solid waste (MSW). This paper examines the emergence of the circulating fluidized bed (CFB) in China. This technology is less capital intensive than the dominant moving grate combustion and, also, can efficiently process feedstock of heating value as low as 5 MJ/kg, with continuously dry discharge of bottom ash.

Since the beginning of the 21\(^{st}\) century, 47 CFB plants, of total capacity of over 14.6 million ton per year of MSW, have been built in China. The case study to be examined in this paper is the new 800 ton per day WTE unit, one of four units of total capacity of 2,300 tons per day serving the city of Cixi. The technology used was developed and tested extensively by Zhejiang University in the city of Hangzhou.
Introduction

Waste treatment has become a big problem in many developing countries especially those with large population and limited land resources, like China. A 2012 World Bank report estimated that by 2025, more than 40% of the world’s municipal solid waste (MSW) would be generated in East Asia and Pacific region [1]; in China, more than 180 million tons of MSW are collected from urban cities [2]. Similarly to most low to medium income countries, the common practice of MSW disposal in China is by landfilling, either in sanitary landfills or open dumping sites.

Combustion on a moving grate with energy recovery is the most commonly used waste-to-energy (WTE) technology for reducing the volume of waste by nearly 90% and the need of land for landfilling. Moreover, incineration plants equipped with boilers and steam turbines recover the hydrocarbon energy as electricity or steam for district heating. Ferrous or non-ferrous material recovery from incineration solid residue is also proven to be feasible.

Although, the moving grate combustion technology (as shown in Figure 1) has been used over one century and more than 1,000 plants are in operation globally [3], currently most of these plants are built in developed countries or in relatively affluent municipalities because waste-to-energy plants are still capital-intensive and costly to operate. Most of these plants are equipped with hydraulic feeders to feed as-received MSW to the combustion chamber, a moving grate to burn all combustible materials, a boiler to recover heat, air pollution control system to clean toxic species in the flue gas, and discharge units for the bottom and fly ash. The air or water-cooled moving grate is the central piece of the process and is made of special alloys to resist the high temperature and to avoid erosion and corrosion. Currently, only a few manufacturers around the world can provide high quality moving grates, the most costly single piece of equipment of the WTE plant.

Apart from the high investment and operating cost, another problem encountered in implementing WTE in developing countries is the high organic and moisture content of the MSW. The “Decision Makers’ Guide to Municipal Solid Waste Incineration” provided by World Bank [4] suggests that incineration is
applicable only when the lower calorific value (LHV) of the feedstock is on the average over 7 MJ/kg and should never fall below 6 MJ/kg in any season. This prerequisite prevents many developing countries from adopting traditional moving grate WTE systems for treating their MSW [5].

This paper describes a new and rapidly growing WTE technology: The circulating fluidized bed (CFB, as shown in Figure 2) combustion process that has been developed and is widely used in China. This technology is capable of treating mixed MSW with high moisture content and extremely low heating value and can be adopted by developing countries with limited budgets and low quality waste.

**Figure 1 Moving Grate MSW incineration system, Hitachi Zosen INOVA, Japan**
The development background of CFB in China

As a fast developing country with about 19% of the world’s population, China is likely to become the largest contributor to global waste generation. Due to the domestic cooking methods and the lack of waste classification and source separation, the Chinese MSW is very high in food waste and moisture, which makes the direct use of moving grate combustion technically difficult.

Table 1 shows that the concentration of food wastes in the MSW of three cities in China are all higher than 60% while other combustible components with high heat calorific value, like paper, plastic and textiles are very low because these valuable materials are usually segregated by formal recycling programs of the community or informal recycled by material scavengers.
Table 1. MSW components of different cities

<table>
<thead>
<tr>
<th>City</th>
<th>Food</th>
<th>Paper</th>
<th>Plastic</th>
<th>Textile</th>
<th>Wood</th>
<th>Glass</th>
<th>Metal</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>64.48</td>
<td>6.71</td>
<td>8.12</td>
<td>1.22</td>
<td>0.05</td>
<td>2.02</td>
<td>0.31</td>
<td>17.09</td>
</tr>
<tr>
<td>Shanghai</td>
<td>62.83</td>
<td>8.57</td>
<td>10.83</td>
<td>4.17</td>
<td>0.96</td>
<td>2.17</td>
<td>0.00</td>
<td>10.47</td>
</tr>
<tr>
<td>Hangzhou</td>
<td>67.10</td>
<td>7.81</td>
<td>9.61</td>
<td>1.05</td>
<td>3.45</td>
<td>0.97</td>
<td>0.33</td>
<td>9.68</td>
</tr>
<tr>
<td>New York</td>
<td>23</td>
<td>27.00</td>
<td>17.00</td>
<td>6.00</td>
<td>4.00</td>
<td>3.00</td>
<td>6.00</td>
<td>14.00</td>
</tr>
<tr>
<td>Singapore</td>
<td>25.4</td>
<td>26.20</td>
<td>25.40</td>
<td>3.22</td>
<td>3.20</td>
<td>2.01</td>
<td>2.40</td>
<td>12.17</td>
</tr>
<tr>
<td>Japan ave.</td>
<td>19.10</td>
<td>36.00</td>
<td>18.30</td>
<td>9.50</td>
<td>4.50</td>
<td>0.30</td>
<td>0.00</td>
<td>12.30</td>
</tr>
</tbody>
</table>

Figure 3. Moisture content and heating value of Shenzhen city at 2011
A 2011 survey of seasonal moisture content and lower heating value (LHV) was carried out by the Shenzhen department of environmental protection. Figure 3 shows that the moisture concentration increased from 52% at winter to a high 72% at summer, caused by the high ratio of fruit waste, especially watermelon peels.

The first large scale MSW incineration plant of China was built in 1984 in the Shenzhen city of Guangdong province with a capacity of 300 t/d. The plant was equipped with two incinerator lines and the reverse-acting moving grate of Martin Company. In 1996, this plant was expanded to a waste treatment capacity of 750 tons/day, supplying 22.7 million kWh of electricity to the local grid and 49170 MJ of heat to local industry. After the first two years of operation, a lot of problems emerged and several conclusions were drawn [6]:

(a) The existing moving grate system was not capable of burning high moisture and low heat value MSW directly and should be modified to improve combustion performance.

(b) High moisture waste should be stored in the bunker for at least five days for de-watering, before being burned, and the liquid effluent should be treated separately instead of re-injecting into the furnace.

(c) High quality chemical agents, including active carbon and limestone are essential for reducing dioxin and heavy metal emission.

In addition to the above technical conclusions, it was also determined that the purchase of moving grate equipment from abroad was too expensive and not affordable to developing cities.

On the basis of these findings, the Chinese government realized that the development of domestic incineration technology was essential for solving the MSW treatment problem with relatively limited budgets. Since the 1990s, academic research groups at Zhejiang University, Tsinghua University and the Chinese Academy of Science have focused on developing the CFB incineration technology [7].
CFB MSW combustion in China

Fluidized bed reactors have been used in the chemical and metallurgical industries for catalytic reactions, drying and metal production for a long time. After being introduced by Fritz Winkler in Germany in the 1920s for coal gasification, fluidized bed combustion has been widely adopted for the combustion of coal and other solid fuels under different equivalence ratios [8].

Increasing the velocity of gas flow and mounting a cyclone separator at the top of the fluid bed reactor results in a “circulating fluid bed” reactor, because the largest particles carried out by gas flow of the reactor are separated from the flue gas and returned back to the reactor. When the CFB process is applied to solid waste combustion, it has several inherent merits including a uniform temperature gradient throughout the bed and intensive turbulence. Moreover, the fraction of high temperature “bubbling” bed material in the reactor provides thermal inertia and can accommodate a large variation in waste moisture content and heating value of the feedstock to the WTE plant. Previous studies have also shown that the uniform temperature gradient, and cumulatively long residence time of CFB combustion can effectively decrease the emission of gaseous pollutants, such as NOx, HCl and SO2 [9-10].

In China, the first commercial CFB MSW incinerator was successfully put into operation in 1998 in Hangzhou City. It was constructed by the Jin Jiang group of companies using the differential density CFB technology developed by Zhejiang University (Figure 4a). The reactor’s nominal capacity was 150 t/d and, to compensate for the high moisture MSW and maintain furnace temperature, coal was used as auxiliary fuel. The air pollution control system included an active carbon adsorption system, semi-dry scrubber, and fabric filter bag house. In 2002, a second plant with three CFB furnaces (1 × 200 t/d and 2 × 300 t/d) was built in the Qiaosi district of Hangzhou, using the same technology. This plant was a high technology demonstration project supported by Chinese National Program Committee and the capital investment was approximately $40,000 (250,000 RMB) per daily ton of capacity.
The CFB technology developed by Chinese Academy of Sciences is shown in Figure 4b. A compact external supercritical heat exchanger was employed to solve the problem of corrosion at high temperature and improve adaptability to waste seasonal variation. Auxiliary coal fuel is not needed when the lower heating value of waste is higher than 4 MJ/kg and moisture content lower than 50%.

A third CFB incineration technology has been developed in China by Tsinghua University (Figure 4c). A small internal moving conveyer was used for drying the raw MSW.

By 2012, the CFB technology had been adopted in 47 WTE plants, accounting for about 46% of all such plants in China. Each day, more than 40,000 tons of MSW are combusted in the CFB WTE plants of China (Table 2). Twenty-eight of these plants use the CFB technology developed by Zhejiang University.
Table 2. Incineration technology used in China [11]

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>Total MSW treatment capacity (t/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving Grate</td>
<td>49</td>
<td>42395</td>
</tr>
<tr>
<td>CFB</td>
<td>47</td>
<td>40170</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>2850</td>
</tr>
<tr>
<td>Total</td>
<td>101</td>
<td>85415</td>
</tr>
</tbody>
</table>

After 20 years of development and industrial application, it has been found that CFB has the following main features:

(a) High adaptability to different MSW: After shredding, almost all kinds of solid waste can be burned in CFB with high combustion efficiency. The high turbulence in the CFB reactor significantly improves the mixing of incoming cold material with the high temperature bed.

(b) Effective control of pollutants: The temperature within the entire combustion chamber can be well controlled in the range of 800~950 °C and thus destroy toxic species in the MSW and reduce the formation of pollutants, such as CO, NOx, PAH and dioxin. Moreover, de-acidification agents (e.g., limestone) can be directly injected into the incinerator during combustion to remove acid gases, like SO2 and HCl and reduce corrosion in the boiler after the CFB reactor.

(c) Compact size: Table 2 shows a comparison of the parameters of several MSW plants using different technologies. It can be seen that the heat releasing rate per square meter of furnace cross section (i.e., the heat flux) is commonly 4-6 MW/m², which is approximately four to five times higher than that per square meter of moving grate area. The waste treatment capacity of the CFB reactor, with respect to cross-section size, is correspondingly greater than that of moving grate furnaces.

(d) Outstanding load adjusting capability: The waste treatment load of a CFB incinerator can be adjusted from 50% to 110% with stable combustion.
(e) Excellent capability of co-combustion: When the moisture of the waste is too high or the heating value is too low, other waste or solid fuels with higher heating value can be used to maintain combustion temperature.

Table 3. Comparison of moving grate incinerators and CFB

<table>
<thead>
<tr>
<th>Plants</th>
<th>Ningbo Fenglin</th>
<th>Shanghai Pudong</th>
<th>Shanghai Hongqiao</th>
<th>Tianjin Shuanggang</th>
<th>Zhejiang Cixi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology Type</strong></td>
<td>Multistage moving grate</td>
<td>Reverse moving grate</td>
<td>Reverse moving grate</td>
<td>SN grate</td>
<td>CFB</td>
</tr>
<tr>
<td><strong>Treatment capacity</strong></td>
<td>350</td>
<td>364.8</td>
<td>500</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td><strong>Grate/Plate size (m²)</strong></td>
<td>73.90</td>
<td>61.47</td>
<td>86.00</td>
<td>94.74</td>
<td>10.60</td>
</tr>
<tr>
<td><strong>Grate/Plate mechanical load (kg/m²/h)</strong></td>
<td>197.34</td>
<td>237.24</td>
<td>242.25</td>
<td>175.92</td>
<td>3144.65</td>
</tr>
<tr>
<td><strong>Heat releasing rate (kW/m²)</strong></td>
<td>372.75</td>
<td>498.21</td>
<td>508.72</td>
<td>369.43</td>
<td>3485.32</td>
</tr>
</tbody>
</table>
The largest CFB MSW incinerator in China

In 2012, a new CFB WTE furnace, designed by Zhejiang University, with a capacity of 800 t/d was put into operation in the city of Cixi (Figure 7).

Figure 5. Layout of 800 t/d CFB incinerator at Cixi city, Zhejiang province, China

1) MSW feeder; 2) Air distributor; 3) Bottom ash discharger; 4) CFB combustion chamber; 5) Cyclone separator; 6) Super heater 7) Economizer;

It is considered to be as the largest CFB WTE furnace in China. It is designed to burn very low quality MSW with a heating value of less than 4.2 MJ/kg and without any auxiliary fuel. To help the waste to ignite and to enhance the combustion performance, this plant includes the following features:

a) Two shredders, located at the end walls of the bunker are used to improve the homogeneity of the feedstock to the older three 500-tpd lines and the
new 800-tpd line. The length of the shredded particles is less than 15 cm.

b) The combustion chamber is provided with water walls that are fully covered with refractory material to form a semi-adiabatic combustion environment.

c) A high temperature air preheater is placed before the economizer units to increase the primary air temperature to 300 °C and improve combustion in the CFB unit.

d) The recirculating flow of solid particles is maintained in the ratio of about 10 to the feed rate of MSW to the CFB reactor, in order to achieve uniform temperature gradient inside the combustion chamber.

e) A particle settling chamber was installed before the heat recovery units to reduce the particle concentration in the flue gas.

**Conclusions**

Waste-to-energy (WTE) processes are the only alternative to landfilling and are used throughout the world. However, the dominant WTE technology, combustion on a moving grate, is capital intensive and possibly out of reach of cities in the developing world. This paper presents the circulating fluid bed reactor process, a technology that in the last fifteen years has been applied successfully in forty-seven WTE plants in China. Environmentally, it is as efficient as the moving grate process, can easily process MSW of very low heating value, and is less costly to build than the moving grate process. After more than ten years of development and industrial application, about one half of the WTE plants in China are based on the CFB combustion technology. Currently, the largest CFB WTE plant, developed by Zhejiang University, combats 800 tons/day of low heating value MSW (5 MJ/kg) without using any auxiliary fuel. The capital cost of this addition, including furnace, boiler, air pollution control system and steam turbine was about $26 million (160 million RMB).
Acknowledgments

The authors gratefully acknowledge support of the development of the Zhejiang University CFB technology by the national China 973 Program (Grant No. 2011CB201500), National Science & Technology Pillar Program (No. 2012BAB09B03), National High Technology Research and Development Program (No. 2012AA063505) and Creative Team Project of Solid Waste Treatment of Zhejiang Province (A2009R50049) for their financial support.

The authors also acknowledge the contribution of the Global WTERT Council (www.wtert.org or global.wtert.org) in disseminating information on sustainable waste management worldwide and its support of WTERT-China at Zhejiang University (wtert.zju.edu.cn).

References


[7] Li Xiaodong, Yan Jianhua, Chi Yong, Ni Mingjiang,Cen Kefa, Development of Municipal Solid Waste Incineration Technologies, Better Air Quality in Asian and Pacific Rim Cities (BAQ 2002), 16 Dec 2002, Hong Kong SAR

[8] E.J. Anthony, fluidized bed combustion of alternative solid fuels: status,
success and problems of the technology, Prog. Energy Combust. 21, 239-268, 1995

