Waste Gasification Technology with Direct Melting for Energy and Material Recovery

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Gasification of municipal solid waste has been widely researched all over the world and is recognized as an alternative thermal technology for waste treatment. The Direct Melting System is shaft-furnace type gasification and melting technology for various kinds of wastes. It has more than forty references and has been operated for 35 years. This gasification technology is employed to treat municipal solid waste with various kinds of wastes such as sewage sludge, clinical waste or incineration bottom ash and can achieve both the energy and material recovery from waste in one process.

Waste flexibility is one of the advantages of the gasification technology with direct melting. Waste is charged into the gasifier without any pre-treatment. The reference plants in Japan process not only municipal solid waste but also other waste such as sewage sludge, clinical waste, bottom ash from other incineration plants, reclamation waste from landfill site, and automobile shredder residues.

Emissions from this system are low. Especially, hydrogen chloride and sulphur dioxide are significantly low due to desulphurization reaction of limestone in the gasifier. Emissions at the stack are significantly lower than those of European regulations.

Due to the high-temperature gasification, toxic heavy metals such as lead and zinc are volatilized from the gasifier and distributed in fly ash. Therefore, the slag and metal produced contain few toxic heavy metals, which can be recycled completely as interlocking block aggregate, concrete aggregate, or civil engineering material with no additional treatment.

1. Introduction

Gasification is the conversion of any carbonaceous fuel to a gaseous product with a useable heating value [9] and is widely used for energy conversion from coal and biomass. Gasification as an energy recovery method has been widely researched all over the world. There are many research papers especially on gasification of biomass [1, 3, 13].

Gasification of municipal solid waste (MSW) has been well-researched in Japan. The development of MSW gasification technology was started in the 1970s in Japan. Because of oil crisis in the 1970s, MSW into energy and recycling of MSW generated became a great interest. The Direct Melting System (DMS), which is the gasification and melting technology developed by Nippon Steel & Sumikin Engineering Co., Ltd., was introduced for commercial use in Kamaishi City, Japan in 1979. There were other gasification technologies developed for commercial use. Andco-Torrax system and Purox system were also employed as a gasification and melting technology for MSW. They were introduced in Hamamatsu City in 1980, and in Chichibu City in 1981, respectively. Dual fluidized bed gasifiers, was introduced in Funabashi City in 1979. However, only the DMS is still under operation.

The waste gasification technology with direct melting is a shaft-furnace type gasification and melting process and is classified as an atmospheric fixed bed gasifier. The gasification technology is in commercial operation at more than forty plants in Japan and South Korea [12, 18, 19, 21]. One of the commercial plants is shown in Figure 1.

Waste to Energy (WtE), which indicates a power generation during waste processing, is a major interest especially in Europe. On the other hand, material recovery from wastes such as MSW and bottom ash is also becoming a major interest. Particularly, material recovery from MSW bottom ash is concerned [5] as well as reclamation waste from a landfill site, because it contains some valuable material and heavy metals such as gold, copper and ferrous and non-ferrous materials. Sewage sludge contains a lot of phosphorus which can be utilized as a fertilizer of agriculture. From the viewpoint of material recovery, energy recovery and final landfill amount reduction, co-treatment of many kinds of wastes with MSW could be one of the possibilities to solve these issues simultaneously. The gasification technology with direct melting can achieve these issues together. Bottom ash from incineration plants, reclamation waste from landfill site, and sewage sludge can be processed together with MSW in the gasification technology. Combustibles in these wastes are converted into energy via a steam boiler system and incombustibles are converted into recyclables such as slag and metal, which can facilitate minimizing the final landfill amount. This indicates that waste gasification with direct melting has a possibility to achieve both the energy and material recovery simultaneously.

In this study, waste gasification with direct melting for energy and material recovery via co-gasification were reported. The process scheme, waste flexibility, criteria of gasification evaluation, flue gas components and slag quality produced are also reported.

Figure 1:   Waste gasification plant in Japan (Photo courtesy of Kitakyushu-City)

2. Materials and methods

2.1. Waste gasification with direct melting

The typical process flow diagram of the waste gasification plant is shown in Figure 2. The plant mainly consists of a MSW charging system, a gasifier, a combustion chamber, a boiler and a flue gas cleaning system. Subsystems such as a material handling system and a fly ash treatment system are also developed.

This technology has been in commercial operation at more than 40 references and has been operated for more than 35 years. The capacity ranges from 10,000 Mg per year to 230,000 Mg per year.

2.2. Process description

One of the advantages of this waste gasification technology with direct melting is that no pretreatment of MSW is required, which differs from other gasification technologies such as a fluidized bed gasifier. MSW is directly charged into a gasification and melting furnace from the top with coke and limestone which function as a reducing agent and a viscosity regulator, respectively. Due to the limestone addition, the viscosity of the molten materials is adjusted properly and the molten materials are discharged smoothly from the bottom of the furnace without any clogging. Oxygen-enriched air is blown at the bottom of the gasifier via tuyere. The gasifier consists of three main parts: a drying and preheating zone, a thermal decomposition zone and a combustion and melting zone. MSW is gradually dried and preheated in the upper section (the drying

and preheating zone). Combustible waste is thermally decomposed in the second zone and syngas is discharged from the top of the gasifier. The syngas, which mainly contains carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4), hydrocarbons and nitrogen, is transferred to the combustion chamber in the downstream of the gasifier and then completely burned. Incombustible waste descends to the combustion and melting zone (1,000 – 1,800 ºC) at the bottom and is melted with the heat generated by coke burning. Gasification reactions such as water-gas-shift, water-gas and boudouard reactions, shown in Eq. (1) – (3), mainly take place in this zone. Molten materials are intermittently discharged from a tap hole, quenched with water, and magnetically separated into slag and metal. Slag and metal are completely recycled because they contain few toxic heavy metals such as lead (Pb) and zinc.

$$CO_2 + C \rightarrow 2\,CO \qquad \Delta H^0_{298K} = +173\,kJ/kmol \qquad (Boudouard\ Reaction) \qquad (1)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298K} = -41kJ/kmol \qquad (Water\text{-}Gas\text{-}Shift\ Reaction) \quad (2)$$

$$C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H^0_{298K} = +131\,kJ/kmol \qquad (Water\text{-}Gas\ Reaction) \qquad (3)$$
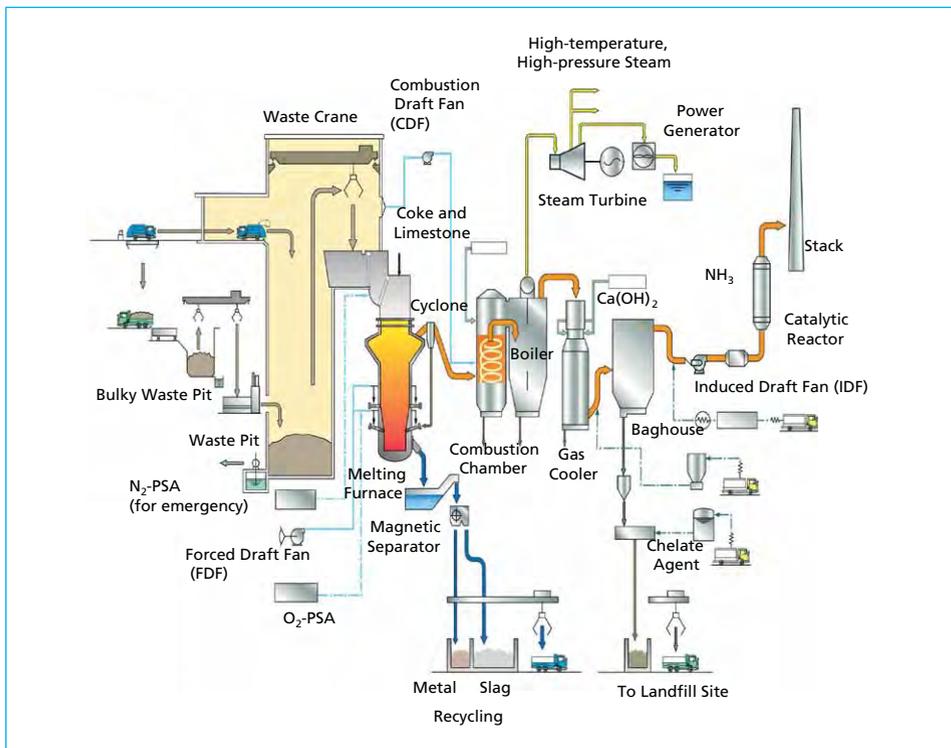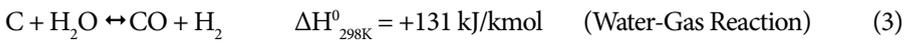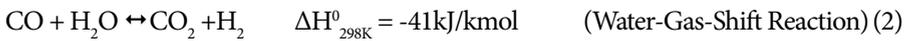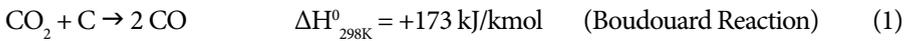

Figure 2: Typical process flow diagram of the Direct Melting System (DMS)

The high-temperature and reducing atmosphere at the bottom of the gasifier helps the volatilization of toxic heavy metals. Because of the high-temperature reducing atmosphere, CO is generated by boudouard reaction and water-gas reaction shown in

Eq. (1) and (3). In boudouard reaction, CO_2 generated by combustion reaction reacts with fixed carbon in injected coke or char and is converted to CO. These reactions take place in the high temperature of approximately 1,200 K. The generated CO can help avoid the formation of lead oxide (PbO) and zinc oxide. Nakata et al. [15] reported that PbO is reduced to metallic Pb under this reducing atmosphere, which is generated by the reactions in (1) and (3), and the metallic Pb is easily volatilized. As a consequence, few toxic heavy metals remain in molten materials and high-quality slag and metal are produced.

A combustible dust collection and injection system is applied. As shown in Figure 3, this system consists of a cyclone and a dust feeder. The combustible dust discharged from the gasification and melting furnace is captured by the cyclone installed in the downstream of the furnace. The captured char is injected into the furnace via tuyere. This system has three major advantages [12]. Firstly, the coke amount is reduced because the injected combustible dust reacts with oxygen-rich blown air as a coke substitute. Secondly, the combustion condition in the combustion chamber is improved because of gas combustion with little dust. Lastly, dust is captured by the cyclone and this reduces fly ash amount in the downstream.

The sensible heat in the flue gas discharged from the combustion chamber is recovered by a boiler and power is generated by a steam turbine system. A typical steam pressure and temperature are 40 bar and 400 °C, respectively. Power generated is used for power supply in the plant and surplus power is sold outwards. Flue gas after exhaust heat recovering is transferred to the flue gas treatment system (FGT) to remove hydrogen chloride (HCl), sulfur dioxide (SO_2), nitrogen oxides (NO_x) and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/DFs).
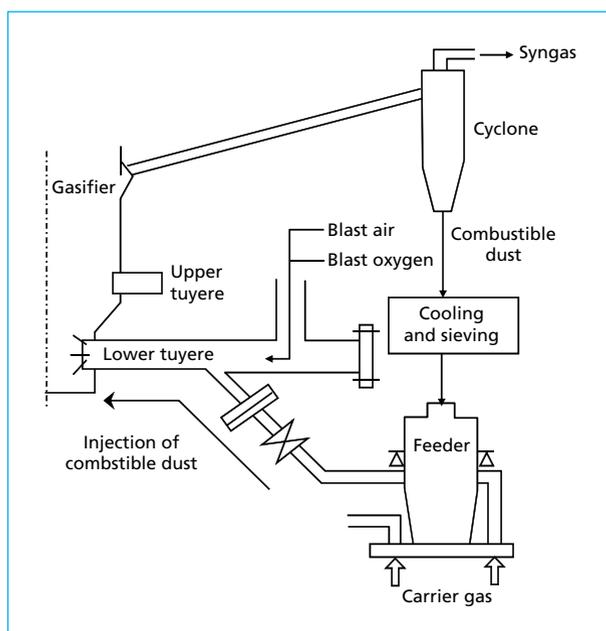

Figure 3:

Combustible dust collection and injection unit

2.3. Gasification criteria

Several different criteria are frequently quoted for gasification processes. The two most commonly encountered are cold gas efficiency (CGE) and the equivalence ratio [9]. CGE and the equivalence ratio (ER) are generally defined as shown in Equation (4) and (5):

$$\text{CGE \%} = \frac{\text{Heating value in product gas [MW]}}{\text{Heating value in feedstock [MW]}} \cdot 100 \qquad (4)$$

$$\text{ER \%} = \frac{\text{Total injected oxygen amount}}{\text{Stoichiometric oxygen amount of the feedstock}} \cdot 100 \qquad (5)$$

The carbon conversion ratio is defined as:

$$\text{Carbon conversion ratio [\%]} = \left(1 - \frac{\text{Carbon in gasification residue [kmol/h]}}{\text{Carbon in feedstock [kmol/h]}}\right) \cdot 100 \qquad (6)$$

This equation indicates the ratio between carbon in feedstock and carbon converted into gases. Carbon in gasification residue indicates the char discharged from the gasifier and combusted in the combustion chamber. Slag and metal discharged from the bottom have no ignition loss, which means no carbon loss in molten materials.

3. Results and discussion

3.1. Operating data

Typical operation data of two commercial plants is shown in Table 1. MSW throughputs in plant A and B are 251.8 Mg per day and 251.6 Mg per day, respectively. Slag, metal produced and fly ash discharged in plant A are 173 kg/t-MSW, 27 kg/t-MSW and 33 kg/t-MSW, respectively. Fly ash yields are almost the same in both plants. The syngas temperature of the furnace in plant A is 517 °C, which is lower than that of plant B.

The equivalence ratio (ER) in plant A, which is 0.34, is higher than that in plant B due to ash content. In this system, ash is melted by coke and char burning heat at the bottom of the furnace. This indicates that higher ash content requires higher energy, which is generated by the partial oxidation reaction of coke and char. In plant A, bottom ash is treated with MSW and ash content of processing waste is as high as 18.5 %$_{\text{a.r.}}$. Therefore, the ER in plant A is much higher than that in plant B.

The net calorific values (NCVs) of syngas in plant A and B are 4.4 MJ/m$^3_{\text{N, d.b.}}$ and 5.9 MJ/m$^3_{\text{N, d.b.}}$, respectively. A NCV of the syngas is decreased by using an air-blown gasification process. The waste gasification technology is a so called moving bed air-blown gasifier. Syngas is diluted by nitrogen and has a lower LHV than that in an oxygen-blown gasifier and a steam gasification process. The LHVs in this study are in the range of other reports results, even though these experiments are conducted by air-blown fluidized bed gasifiers. Furthermore, the moisture content in feedstock could also affect the value of an NCV [11] or gross calorific values [7]. Doherty et al. [7] reported that CO and CH$_4$ were shifted and reformed respectively and produced CO$_2$, with rise in the moisture content in feedstock. These factors lead to low NCV in this study.

	Units	Plant A	Plant B
MSW throughput	t/day	251.8	251.6
Coke	kg/t-MSW	44.9	49.0
Natural gas injection	m^3_N/t-MSW	4.31	-
Syngas Temperature	°C	517	602
Slag produced	kg/t-MSW	173	97
Metal produced	kg/t-MSW	27	18
Fly ash	kg/t-MSW	33	32
LHV of syngas	$MJ/m^3_{N, d.b.}$	4.4	5.9
Carbon conversion ratio	%	91.7	95.3
CGE	% LHV	54.6	49.2
ER	-	0.34	0.26
Power generation	kWh/t-MSW	408	673
Gross power generation efficiency	%	18.9	23.0

Table 1:

Typical operating data

The CGEs of the gasifier in plant A and B are 54.6 %$_{LHV}$ and 49.2 %$_{LHV}$, respectively. Compared with previous biomass gasification results [3, 6, 7, 10, 13], CGEs in this study are moderate. This is caused mainly by two factors: An air-blown gasification process and the moisture content of MSW. As explained above, in an air-blown gasifier, syngas is diluted by nitrogen and a NCV is decreased. In addition, moisture content in MSW to be treated is an important factor. Doherty et al. [7] has simulated that CGE is decreased with the biomass moisture content increasing. The moisture content of MSW in plant A and B is 42.8 %$_{a.r.}$ and 44.0 %$_{a.r.}$, respectively, which is much higher than the biomass in previous reports. Thus, these factors affect a CGE in the gasifier.

Carbon conversion ratio is as high as 91.7 percent and 95.3 percent, respectively. The rest of carbon is discharged from the gasifier and is burned in the combustion chamber. High carbon conversion ratios are achieved in both results [4, 11]. This high carbon conversion ratio is also improved by the application of a combustible dust injection system (Figure 2). In this system, most of the char discharged from the gasifier is captured by a cyclone and is injection into the gasifier. The injected char is converted into gases, which improves the carbon conversion ratio.

Table 1 also shows the gross power generations and gross power generation efficiency. The gross power generations in both plants are 403 kWh/t-MSW and 673 kWh/t-MSW, respectively. The gross power generation efficiencies are 18.9 percent and 23.0 percent, respectively. Compared with the average gross power generation efficiency (11.2 percent) of MSW incinerators in Japan [14], the gross power generation efficiencies in this study are significantly high. However, these efficiencies are lower than those in the EU. This could be caused by three main reasons: The priority of waste management (the first priority is not energy recovery but volume reduction), smaller scaled facilities and the moisture contents in waste to be processed (approximately between 40 %$_{a.r.}$ and 50 %$_{a.r.}$). However, nowadays, Waste-to-Energy is becoming a great interest even in Japan and the power generation efficiency has been improved.

Today, new technologies for the waste gasification technology with direct melting have been developed and reported [23]. As a consequence, the coke consumption is reduced to 2 %$_{wt}$ or 3 %$_{wt.}$

3.2. Waste flexibility

Waste flexibility is one of the advantages of the waste gasification with direct melting. Because of high-temperature gasification, various kinds of waste can be processed without any pre-treatment. Sewage sludge, clinical waste, bottom ash from incineration plants, reclamation waste from landfill site, disaster refuse, incombustibles from recycling centers, chlorofluorocarbon (CFC), and automobile shredder residues (ASR) can be processed with MSW in the reference commercial plants. Combustibles in these wastes are converted into energy via a steam boiler system and incombustibles are converted into recyclables such as slag and metal, which can facilitate minimizing the final landfill amount. This co-processing of waste and recycling material as slag and metal are defined as a co-gasification. This indicates that co-gasification has a potential to achieve both the energy and material recovery simultaneously.

Figure 4: Relationship between net calorific values and CO concentrations

Source: Tanigaki N, Fukinaka N, Ishida Y and Osada M., 2012. Proceedings 7th international conference on *combustion, incineration/pyrolysis and emission control (i-CIPEC 2012)*, Seoul/Ilsan, Korea 4–7, September 2012, pp. 129–135

Waste compositions, especially the NCVs of waste, affect the syngas compositions. Figure 4 shows the relationship between CO concentrations and NCVs of processed feedstock. Plant A, C and D process bottom ash from other incineration plants, reclamation waste from landfill site and sewage sludge with MSW, respectively. The higher NCVs of waste to be processed lead higher CO concentrations in the syngas. This indicates that the NCVs of feedstock affect the CO concentrations in the syngas in the co-gasification of MSW with other wastes.

3.3. Emissions

Table 2 shows the flue gas components in two commercial plants, which developed a wet scrubber system and a dry flue gas cleaning system, respectively. No activated carbon injections are applied in both plants. Air pollutants were measured at the inlet of baghouse (BF), at the outlet of BF and at the stack. As shown in Table 2, all components at the stacks are within the regulation values and EU directive.

Low HCl and SO_2 emissions are assumed to be caused by the gasifier operating conditions. The gasification technology with direct melting employs the limestone injection to the gasifier in order to adjust the viscosity and fluidity of molten materials. Calcium oxide (CaO) generated from limestone reacts with chlorine and sulfur and assumed to reduced gas-phase chlorine (HCl) and sulfur (SO_2).

Table 2:   Flue gas components in the plant A and E

	Units	Plant A			Plant E		
		Inlet of BF	Outlet of BF	Stack	Inlet of BF	Outlet of BF	Stack
SO_2	mg/m^3_N	12.7	–	<3	4.8	–	<3.3
NO_x	mg/m^3_N	264	–	8.9	188	–	20.9
HCl	mg/m^3_N	180	1.7	<0.6	171	–	3.7
CO	mg/m^3_N	<4.0	<4.0	<4.0	5.6	–	6.2
PCDD/DFs	$ng\text{-}TEQ/m^3_N$	0.79	0.74	0.0066	1.4	1.2	0.00087

*1 Concentrations are based on 11%-O_2
*2 HCl, SO2, NOx: n=4, CO: 4 hrs continuous measuring, PCDD/DFs: n=2

Source: Tanigaki, N., Fujinaga, Y., Kajiyama H., Ishida, Y., 2013a. Waste Management & Research 31, 11, 1118-1124

PCDD/DFs concentrations in the flue gas are significantly low. It is explained by the high carbon conversion ratio. Because of this, less char is discharged from the gasifier. This leads to a gas-gas combustion (homogeneous combustion) in the combustion chamber and improves the combustion conditions in the temperature range between 950 and 1,050 °C. As a result, stable and complete syngas combustion is achieved. A combustion dust injection system also contributes to the combustion condition in the combustion chamber by achieving a high carbon conversion ratio [12].

3.4. Slag, metal and fly ash compositions

Table 3 shows the concentration of heavy metals in slag, metal and fly ash in two commercial plants in Japan. The major contents in slag were Si, Ca and Al in both plants. Lead and zinc concentrations in slag are significantly low. Especially lead concentrations in slag were less than 0.001 %$_{d.b.}$ in both plants. Iron is a main component in metal, which are 85.0 %$_{d.b.}$ and 84.0 %$_{d.b.}$. Copper is also highly distributed in metal.

Table 3:   Typical components of slag, metal and fly ash

	Unit	Plant A			Plant E		
		Slag	Metal	Fly ash	Slag	Metal	Fly ash
Si	%$_{db}$	16	2.0	3.1	16	5.1	4.7
Ca	%$_{db}$	23	0.18	22	26	0.23	22
Al	%$_{db}$	8.3	0.096	2.3	6.6	0.08	2.3
Mg	%$_{db}$	1.20	0.029	0.7	0.82	0.016	0.8
Pb	%$_{db}$	<0.001	0.018	1.1	<0.001	0.013	0.3
Zn	%$_{db}$	0.027	0.054	5.6	0.008	0.024	2.2
Na	%$_{db}$	1.9	0.084	4.4	1.3	0.077	4.2
K	%$_{db}$	0.73	0.010	4.9	0.67	0.019	5.7
Cl	%$_{db}$	0.01	<0.01	15	<0.01	<0.01	17
S	%$_{db}$	0.22	0.035	1.4	0.17	0.031	1.5
Cu	%$_{db}$	0.018	8.9	0.29	0.014	7.5	0.17
Fe	%$_{db}$	1.5	85.0	0.52	1.1	84.0	0.79
Hg	mg kg-1	<0.01	<0.01	1.00	<0.01	<0.01	1.10
Cr	%$_{db}$	0.036	1.1	0.0098	0.018	0.95	0.011

Source: Tanigaki, N., Fujinaga, Y., Kajiyama H., Ishida, Y., 2013a. Waste Management & Research 31, 11, 1118-1124

In fly ash, heavy metal concentrations were different between both the plants. Lead concentration in plant A was 1.1 %$_{d.b.}$, which was approximately four times higher than that in plant B. Zinc in plant A were also higher than that in plant B. Co-gasification of MSW with incineration bottom ash was applied in plant A, which indicates higher heavy metals are charged into the process. Even though the processing waste is different, heavy concentrations in slag and metal are almost the same and the difference can be appeared only in the concentration of the fly ash.

These results indicate that the heavy metal concentration in the slag and metal are almost stable regardless of the processing waste.

3.5. Heavy metal distributions

Figure 5 shows the heavy metal distribution in a commercial gasification plant. According to our previous research [18], the concentrations of heavy metals in flue gas after dust removal by BF are significantly low and could be neglectable. Takaoka et al. [22] also reported that most of heavy metals were removed by BF and the removal efficiencies were more than 99.9 percent. Therefore, in this study, it is assumed that heavy metals are removed totally by BF and the concentrations of heavy metals in the flue gas are assumed to be 0 mg/m^3$_N$. Furthermore, for the calculation of the distribution factor, it is assumed that fifty percent of the substances below the limit of determination are to be output.
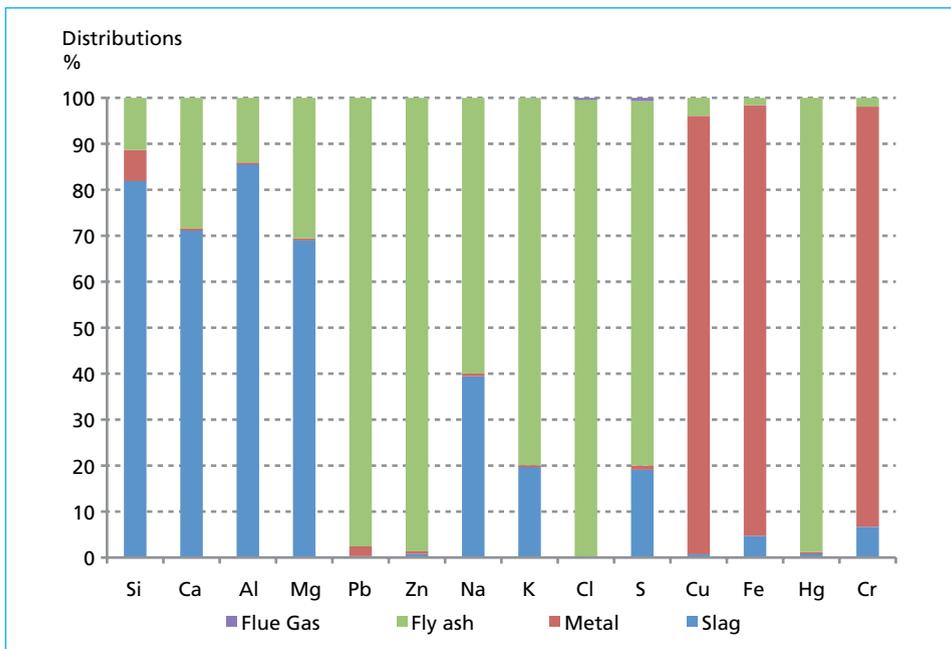

Figure 5:   Distributions of heavy metals and other elements

Source: Tanigaki, N., Fujinaga, Y., Kajiyama H., Ishida, Y., 2013a. Waste Management & Research 31, 11, 1118-1124

Most of the low-boiling-point heavy metals such as lead, zinc and mercury were distributed in fly ash: the distribution rate of lead in fly ash in plant B was 97.6 percent. That of zinc was 96.9 percent. Most high-boiling-point heavy metals such as iron and copper are distributed in metal, at the respective distribution rates 93.7 percent and 95.4 percent in plant B. Most of Si, Ca, Al and Mg were distributed to slag. The distribution ratios of K and total sulfur (T-S) were mainly distributed to fly ash and were fluctuated. These distribution tendencies are same as those in our previous researches [18, 21].

According to European commission [8], lead and zinc are distributed to fly ash with the values of 28 percent (+/-5 percent) and 54 percent (+/-3 percent), respectively. On the other hand, 72 percent of lead and 46 percent of zinc are distributed to bottom ash. Similar results are reported by Arena and Di Gregorio [17]. Compared with incineration systems, some differences in heavy metals distributions can be seen. Especially, significant differences were found in the distribution ratios of lead and zinc to fly ash.

According to a thermodynamics calculation, lead and zinc in the form of sulfide or oxide are moved to slag and Osada et al. [17] showed that a high temperature reducing atmosphere is effective in preventing the formation of lead and zinc sulfide or oxide. Regardless of the processing waste composition, the same tendency is seen in the distribution of toxic heavy metals such as lead, zinc and mercury.

3.6. Slag leaching behavior and utilization

It is clarified that the slag produced in this study contains almost no harmful heavy metals such as lead. Table 4 shows the results of the slag leaching test (in compliance with JIS K0058) in plant A. The values of lead resulting from the slag leaching test are less than 0.005 mg/L, which is remarkably lower than the target reference (less than 0.01 mg/L). The value of lead in the acid-extractable test (in compliance with JIS K0058) is 21.7 mg/kg, which is far below the target reference (less than 150 mg/kg).

Table 4:   Results of the slag leaching test

	Leaching test		Acid-extraction test	
	Target reference	Measured	Target reference	Measured
Cd	< 0.01 mg/l	< 0.001	< 150 mg/kg	< 5
Pb	< 0.01 mg/l	< 0.005	< 150 mg/kg	18
$Cr6^+$	< 0.05 mg/l	< 0.02	< 250 mg/kg	< 5
As	< 0.01 mg/l	< 0.001	< 150 mg/kg	< 5
T-Hg	< 0.0005 mg/l	< 0.0005	< 15 mg/kg	< 0.05
Se	< 0.01 mg/l	< 0.001	< 150 mg/kg	< 5
CN	–	–	< 50 mg/kg	< 1
F	–	–	< 4000 mg/kg	172
B	–	–	< 4000 mg/kg	260
Metal- Fe	–	–	< 1.0 %	0.18

*1 Both results are conducted six times.

Likewise, the values of Cd and other heavy metals in the slag leaching test and acid-extractable test are remarkably lower than the target reference. Based on the above findings, it is evident that the molten slag as a result of treatment by this gasification technology contains few harmful heavy metals such as lead, slag is stable, and the slag can be used as interlocking block aggregate, concrete aggregate, or civil engineering material with no additional treatment (Figure 6). Further application of slag has been developed such as agricultural utilization shown in Figure 6.
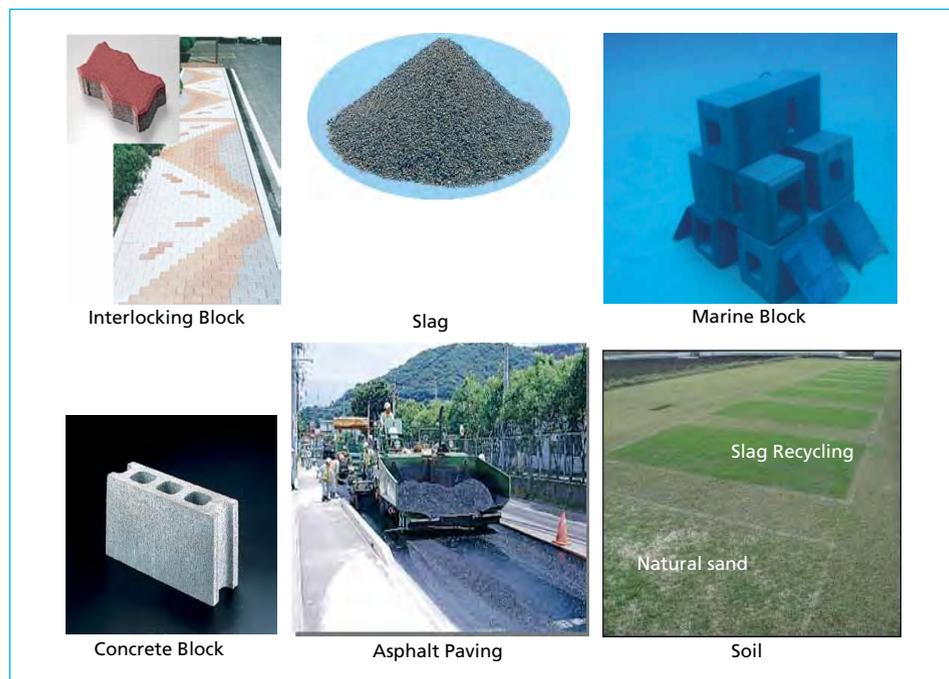
Figure 6:   Utilization of slag produced

4. Conclusions

This paper reported a waste gasification technology with direct melting, which has the world largest gasification references and achieve the energy and material recovery simultaneously. The first waste gasification technology has been operated since 1979.

Waste flexibility is one of the advantages of the gasification technology with direct melting. Waste is charged into the gasifier without any pre-treatment. The reference plants in Japan process not only municipal solid waste but also other waste such as sewage sludge, clinical waste, bottom ash from other incineration plants, reclamation waste from landfill site, and automobile shredder residues.

Emissions from this system are low. Especially, hydrogen chloride and sulphur dioxide are significantly low due to desulphurization reaction of limestone in the gasifier. Emissions at the stack are significantly lower than those of European regulations.

Due to the high-temperature gasification, toxic heavy metals such as lead and zinc are volatilized from the gasifier and distributed in fly ash. Therefore, the slag and metal produced contain few toxic heavy metals, which can be recycled completely as interlocking block aggregate, concrete aggregate, or civil engineering material with no additional treatment.

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