Chapter 7

Gasification of Municipal Solid Waste

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Additional information is available at the end of the chapter

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Abstract

Gasification of municipal solid waste (MSW) is an attractive alternative fuel production process for the treatment of solid waste as it has several potential benefits over traditional combustion of MSW. Syngas produced from the gasification of MSW can be utilized as a gas fuel being combusted in a conventional burner or in a gas engine to utilize the heat or produce electricity. Also, it can be used as a building block for producing valuable products such as chemicals and other forms of fuel energy. This book chapter covers the properties of MSW, gasification mechanism, chemistry, operating conditions, gasification technologies, processes, recovery system, and most importantly by reviewing the environmental impacts of MSW gasification. As one of recent advanced technologies, a case study of pilot-scale MSW gasification is introduced, which could be one of the most efficient pathways to utilize the technology to produce electricity with a newly developed gasification process by reducing tar and pollutant emission.

Keywords: municipal solid waste, gasification, waste to energy

1. Introduction

Gasification of municipal solid waste (MSW) is an attractive alternative fuel production process for the treatment of solid waste as it has several potential benefits over traditional combustion of MSW. The so-called "syngas" obtained by gasification has several applications. It can be utilized as a gas fuel being combusted in a conventional burner or in a gas engine and then connected to a boiler and a steam turbine or gas turbine to utilize the heat or produce electricity. Also, it can be used as a building block for producing valuable products such as chemicals and other forms of fuel energy, as discussed in the following literature review [1]. This reference, called *Waste to Energy Conversion Technology*, introduces the theory behind gasification and pyrolysis and outlines the key differences between them and conventional combustion in Chapter 9, "Gasification and pyrolysis of MSW." This chapter also provides an overview of the types of products that can be made from gasification, and the applications of these products are presented. In addition, different types of gasification processes are addressed. However, it fails to discuss the properties of MSW, also gasification principles were not described in details into the chapter. Most importantly, environmental impacts of MSW gasification were not addressed in the chapter. Therefore, an up-to-date book chapter on gasification of MSW was much needed. To address this issue, an initiative was taken to write a book chapter on MSW gasification by assessing the present contents of MSW gasification by covering the properties of MSW, gasification mechanism, chemistry, operating conditions, gasification technologies, processes, recovery system, and most importantly by reviewing the environmental impacts of MSW gasification. The properties of MSW are discussed in Section 2. In Section 3, we discuss gasification principles such as the mechanism, chemistry (reactions), and operating parameters (equivalent ratio, temperature, residence time, cold gas efficiency, carbon conversion efficiency, tar content, etc.). Section 4 shows the MSW gasification technologies and processes, including plasma gasification, fixed-bed gasification, fluidized gasification, and worldwide plants of various types. Sections 5 and 6 describe energy recovery systems and environmental impacts of MSW gasification by reviewing available literatures and some case studies in recent practices and developments. Finally, a case study of a pilot-scale MSW gasification is introduced, which could be one of the most efficient pathways to utilize the technology to produce electricity with a newly developed gasification process with reducing tar and pollutant emission in Korea.

2. MSW properties

The design of a process for the management of MSW and the results for the economic evaluation and development of a feasible business plan require an introduction of the properties of MSW. Therefore, these are presented to support those who are performing such design and economic evaluations [2]. **Table 1** shows the density of various components such as some typical properties of the MSW of interest. **Table 1** also illustrates the typical moisture content with range for some specific properties of the MSW of interest. The typical values of elemental analysis and proximate analysis for some material of interest in MSW are also shown in **Table 1**. In the case of elemental analysis values for carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and ash; and in the case of proximate analysis values for moisture, volatiles, fixed carbon, and ash are shown on a percentage of weight basis [3].

Another important factor for evaluating and designing the process of MSW is calorific value of the appeared materials. **Table 2** shows some standard calorific value of various materials generally found in MSW [5].

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Typical properties of uncompacted wastes (USA Data)-density						
	Density (kg/m³)					
Food wastes	288					
Paper	81.7					
Plastics	64					
Garden trimmings	104					
Glass	194					
Ferrous metal	320					
Typical moisture contents of wastes						
	Moisture content (wt.%)					
Residential	**Range**	**Typical**				
Food wastes (mixed)	50–80	70				
Paper	4–10	6				
Plastics	1–4	2				
Yard wastes	30–80	60				
Glass	1–4	2				
Typical proximate analysis values (% by weight)						
Type of waste	**Moisture**	**Volatiles**	**Carbon**	**Ash**		
Mixed food	70.0	21.4	3.6	5.0		
Mixed paper	10.2	75.9	8.4	5.4		
Mixed plastics	0.2	95.8	2.0	2.0		
Yard wastes	60.0	30.0	9.5	0.5		
Glass	2.0	—	—	96–99		
Residential MSW	21.0	52.0	7.0	20.0		
Typical elemental analysis (% by weight):						
Type of waste	**C**	**H**	**O**	**N**	**S**	**Ash**
Mixed food	73.0	11.5	14.8	0.4	0.1	0.2
Mixed paper	43.3	5.8	44.3	0.3	0.2	6.0
Mixed plastics	60.0	7.2	22.8	—	—	10.0
Yard wastes	46.0	6.0	38.0	3.4	0.3	6.3
Refuse derived fuel	44.7	6.2	38.4	0.7	<0.1	9.9

Table 1. Physical properties of MSW [4].

Material	Calorific value (BTU/lb)	Ash content (wt.%)	Moisture content (wt.%)
Soft wood	6330	0.1	19
Fiberboard, 90% paper	7600	4.6	7.5
Damp wood	5690	1.2	27.5
Leather trimmings	7670	5.2	10.4
Cotton seed hulls	10,600	2.47	8.9
Sludge material (steel mill)	9150	24.5	1.9
Nitrile rubber	15,240	3.4	
Cardboard, granulated	8592	12.3	6.4
Carbon residue	13,681	8.7	0.0
Wood waste, sawdust	7500	0.8	14
Nut shells	7980	1.75	11.85

Table 2. Calorific values of various materials [4].

3. Basics of gasification

3.1. Mechanism

Combustion, gasification, and pyrolysis are thermal energy conversion processes available for the thermal treatment of solid wastes. **Figure 1** introduces all the potential pathways to convert MSW or biomass into different energy forms using thermal, mechanical, and biological processes. **Figure 2** shows the schematic diagram of syngas production and how to utilize the gas for various purposes such as power generation, creating chemicals by upgrading steps, and further biochemical processing before producing fuels or chemicals. As shown in these figures, different products are obtained from the application of these processes, and different energy and residual material recovery systems can be used in various types of technologies.

Gasification is a thermochemical conversion process of carbonaceous materials into gaseous product at high temperatures with the aid of gasification agent. The gasification agent (another gaseous compound) allows the feedstock to be quickly converted into gas by means of different heterogeneous reactions [6–9]. The gaseous product obtained during this process is called synthetic gas (syngas) or producer gas, and it mainly contains hydrogen, carbon monoxide, carbon dioxide, and methane. Also, a small amount of inert gases, hydrocarbons, tar, and gas pollutants can be found [10]. Based on the effect of gasification agent, gasification can be divided into two categories. If the gasification agent partially oxidizes the feed material it is called direct gasification. During direct gasification, to maintain the temperature of the process, oxidation reaction supplies the required energy. If the gasification process takes place without the aid of gasification agent it is called indirect gasification [7, 11]. Usually steam is used for indirect gasification as it is easily available. Moreover, it increases the hydrogen content in the producer gas [7].

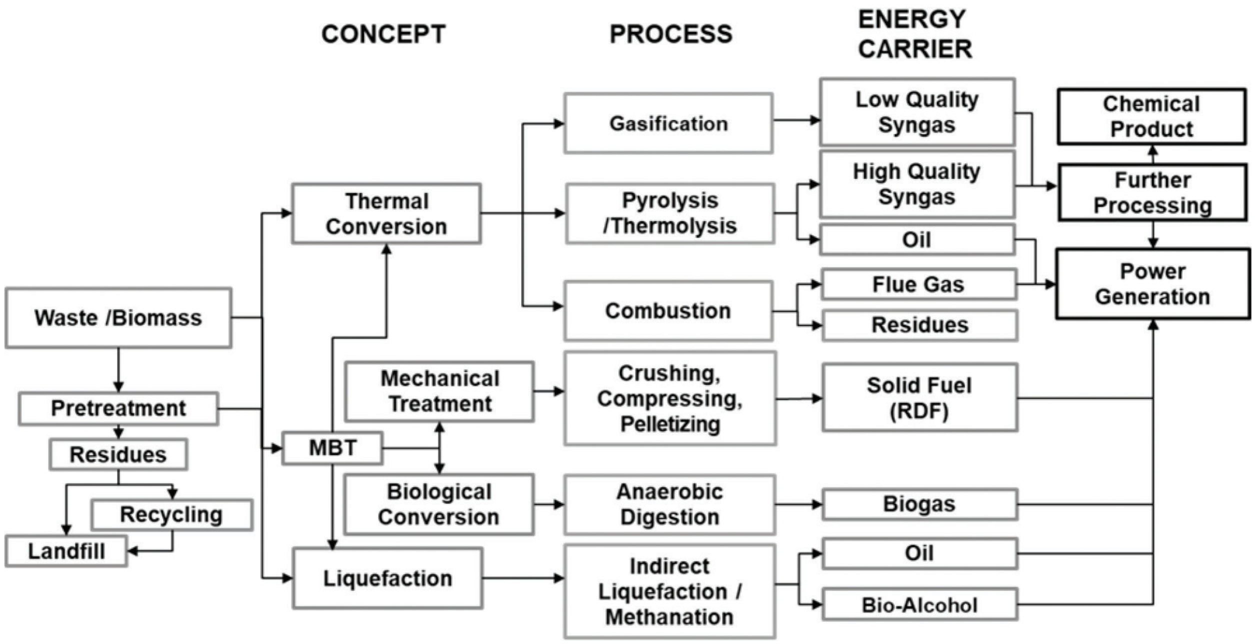

Figure 1. Pathways to convert MSW to different types of energy forms or chemicals through various conversion processes.

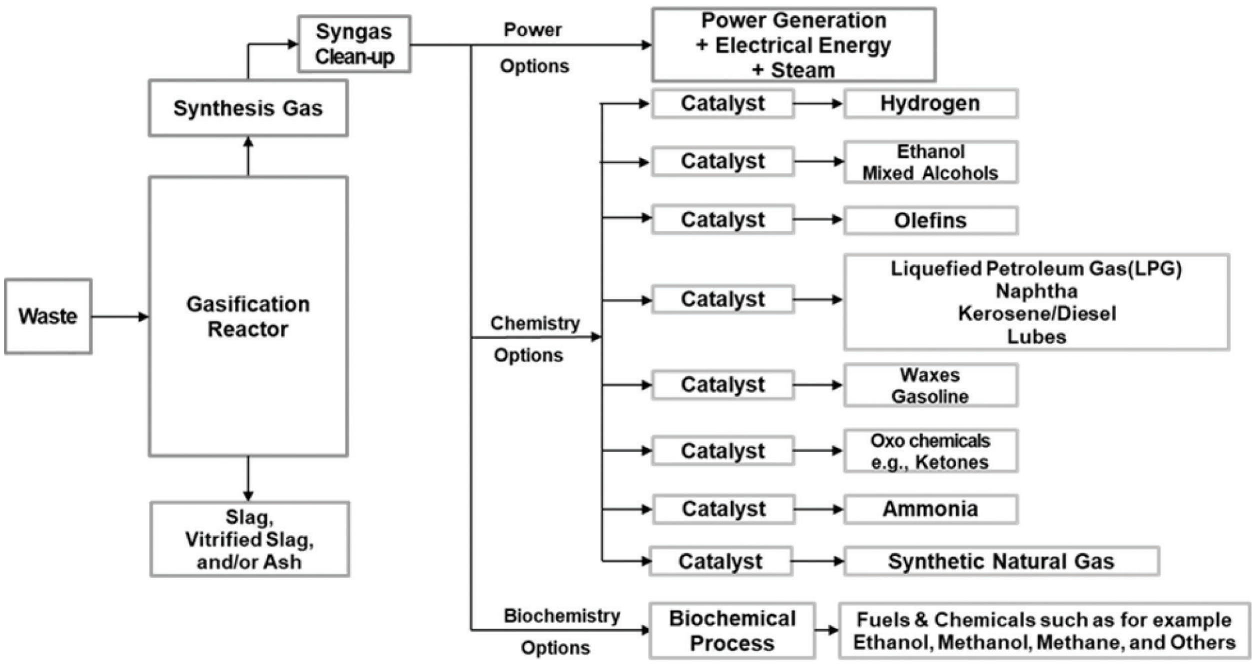

Figure 2. Pathway of waste to energy (gases, fuels, chemicals) by gasification.

As shown in **Figure 3**, two main gasification processes can be classified into direct and indirect gasification processes. Indirect gasification processes are conducted without air or oxygen injection. The heating value of the syngas is significantly affected by the presence of nitrogen. In the absence of nitrogen in indirect gasification process, the volumetric efficiency and higher heating value of producer gas both increases [12, 13]. Also, indirect gasification

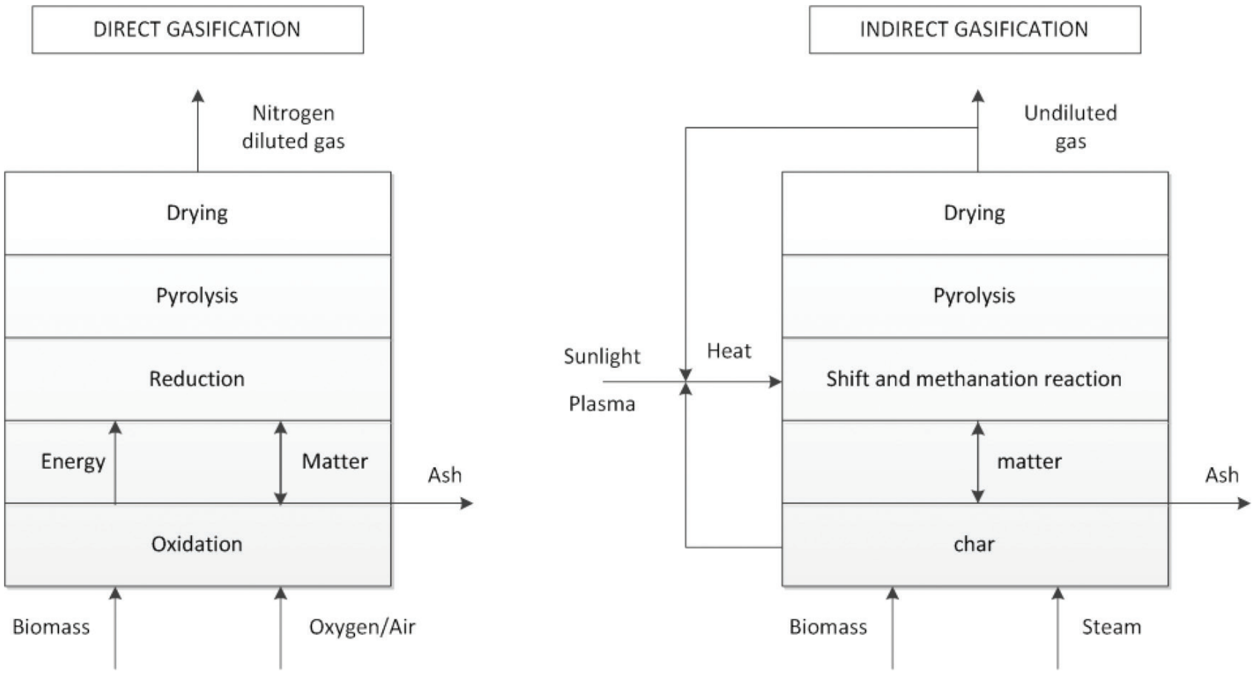

Figure 3. Direct and indirect gasification processes.

process decreases the cost of gas clean up and energy recovery by lowering the gas production rate. However, the process is quite complex and the investment cost is higher [7].

Pure oxygen gasification as direct gasification has same advantages over indirect gasification. However, the cost of producing pure oxygen is expected to account for more than 20% of the total cost of electricity production [14].

Generally, a gasification system is composed of three stages: (1) gasifier for useful producing syngas; (2) the syngas cleaning system for removal of pollutants and harmful compounds; (3) an energy recovery system such as a gas engine. Additionally, sub-systems are included to prevent environmental impacts such as air pollution, solid wastes, and wastewater.

3.2. Chemistry

3.2.1. Process steps

The gasification process of solid waste has endothermic and exothermic reactions, which are successive and repetitive [15, 16]. **Figure 4** describes the main reactants and steps of the gasification process.

• Heating and drying at about 160°C: In this stage, the moisture and steam from the feedstock are removed by the porous solid phase.

• Devolatilization (or pyrolysis or thermal decomposition) at about 700°C: This stage determines the thermal cracking reactions and conversion of heat and mass, including light permanent gases (such as H_2, CO, CO_2, CH_4, H_2O, and NH_3), tar (condensable hydrocarbon vapors), and char (residue emitted after devolatilization). Vapors produced in this stage undergo thermal cracking to gas and char. In the case of MSW, as described in **Figure 4**, high contents

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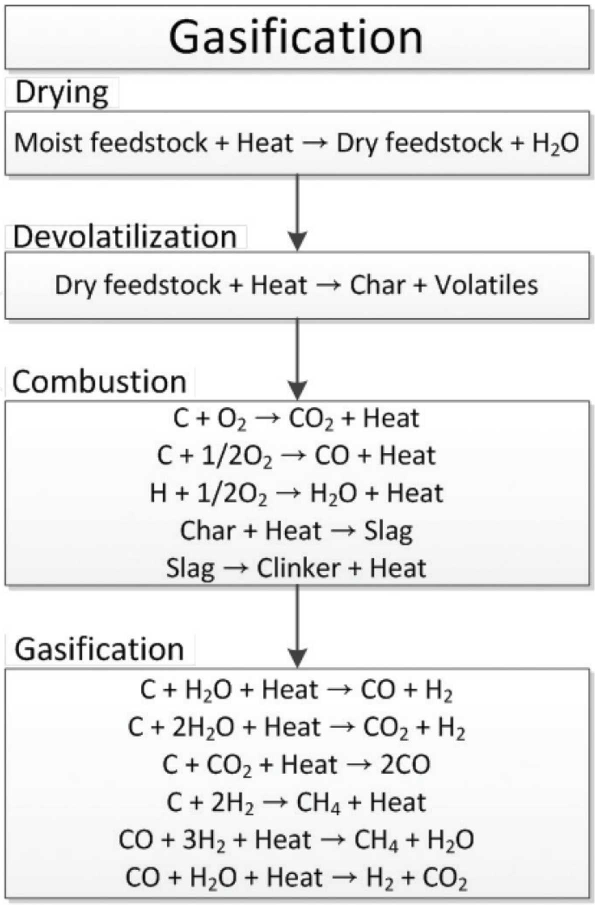

Figure 4. Main reactions and steps of gasification process.

of carbon and hydrogen, which are easily converted to combustible gases in volatiles, are included in the feedstock. The quantities, composition, and characteristics of chemical species released due to devolatilization are dependent on several factors such as original composition and structure of the waste, temperature, pressure, and heating rate imposed by particular reactor types. In devolatilization, various gas compositions are produced, and these gases are generated by the hydrogen and carbon in the waste [16, 17].

• Many chemical reactions occur in a reducing environment that is in remarkably lower oxidation (25–50%) than stoichiometric oxidation. Following **Table 3**, in an auto-thermal gasification process, the partial oxidation of combustible gas, vapors, and char are controlled by the amount of air, oxygen, or oxygen-enriched air. Also, this heat is necessary for the thermal cracking of tar hydrocarbons and char gasification by steam, and carbon dioxide maintains the operation temperature of the gasifier. Following the enthalpy of reactions 1, 2, and 3 in **Table 3**, in auto-thermal gasification processes, about 28% of the carbon heating value is invested in CO production, and the remaining 72% of the carbon heating value is conserved in the gas. The heating value of gas is generally between 75 and 88% of the original fuel because it also contains some hydrogen. If this value were 50% or lower, gasification using coal, biomass, and waste would probably never have become such an interesting process [18]. On the other hand, in an allo-thermal gasification process, the heat is supplied by external sources that are using heated bed materials, burning chars or gases, and utilizing plasma touch. The specific

Oxidation reactions			
1	$C + ½O_2 \rightarrow CO$	−111 MJ/kmol	Carbon partial oxidation
2	$CO + ½O_2 \rightarrow CO_2$	−283 MJ/kmol	Carbon monoxide oxidation
3	$C + O_2 \rightarrow CO_2$	−394 MJ/kmol	Carbon oxidation
4	$H_2 + ½O_2 \rightarrow H_2O$	−242 MJ/kmol	Hydrogen oxidation
5	$C_nH_m + {}^n/_2O_2 \rightarrow nCO + {}^m/_2H_2$	Exothermic	C_nH_m partial oxidation
Gasification reactions involving steam			
6	$C + H_2O \rightarrow CO + H_2$	+131 MJ/kmol	Waster-gas reaction
7	$CO + H_2O \rightarrow CO_2 + H_2$	−41 MJ/kmol	Water-gas shift reaction
8	$CH_4 + H_2O \rightarrow CO + 3H_2$	+206 MJ/kmol	Steam methane reforming
9	$C_nH_m + nH_2O \rightarrow nCO + (n + {}^m/_2)H_2$	Endothermic	Steam reforming
Gasification reactions involving hydrogen			
10	$C + 2H_2 \rightarrow CH_4$	−75 MJ/kmol	Hydrogasification
11	$CO + 3H_2 \rightarrow CH_4 + H_2O$	−227 MJ/kmol	Methanation
Gasification reactions involving carbon dioxide			
12	$C + CO_2 \rightarrow 2CO$	+172 MJ/kmol	Boudard reaction
13	$C_nH_m + nCO_2 \rightarrow 2nCO + {}^m/_2H_2$	Endothermic	Dry reforming
Decomposition reactions of tars and hydrocarbons[a]			
14	$pC_xH_y \rightarrow qC_nO_m + rH_2$	Endothermic	Dehydrogenation
15	$C_nH_m \rightarrow nC + {}^m/_2H_2$	Endothermic	Carbonization

[a]Note that C_xH_y represents tars and, in general, the heavier fuel fragments produced by thermal cracking, and C_nH_m represents hydrocarbons with a smaller number of carbon atoms and/or a larger degree of unsaturation than CxHy.

Table 3. Main reactions in the heterogeneous and homogeneous phases during the solid waste gasification process.

gasification reactions are those taking place between the devolatilized solid waste (char) and gases excluding oxygen.

3.2.2. Gasification reactions

The gasification reactions have various reactions, but **Table 3** shows just three independent gasification reactions: the water-gas reaction, the Boudard reaction, and hydrogasification. In the gasifier, where there is no more carbon in the feedstock, only two reactions are produced: the water-gas shift reaction, which is the combination of the water-gas and Boudard reactions, and methanation, which is the combination of the water-gas and hydrogasification reactions. These reactions are a simple framework related to reactants and products of H, N, O, S, etc. in the feedstock [16]. Also, CO is produced instead of CO_2, H_2 instead of H_2O, and for other elements, H_2S instead of SO_2, and NH_3 or HCN instead of NO. Moreover, the formation of dioxin strongly declines because of the oxidation reactions of the dioxin synthesis mechanism [19–21]. All gasification reactions except oxidation reactions create equilibrium. In fact, the final gas composition is determined by reaction rates and catalytic effects, rather than by the chemical equilibrium after an infinite period of time [22–24].

3.3. Operating and performance parameter

3.3.1. Equivalent ratio

Equivalent ratio (ER) is defined as the ratio of the actual amount of oxidant to stoichiometric oxidant for complete combustion. This parameter is the most important operating parameter in gasification process because it affects syngas composition, tar content, gas yield, and its chemical energy. The pyrolysis process is operated at close to ER zero, and the combustion process is operated at more than ER one for complete combustion. In **Figure 5**, the conversion of char in the gasification process at ER 0.25 to 0.35 appears to maximize even though these gasifiers and those that are used in large-scale commercial plants (following **Table 4**), namely, moving grate gasifiers [25] and fluidized bed gasifiers [26] operated with wet fuels, are operated at about ER 0.5. With a lower ER, the gas yield from char is reduced, and the tar in syngas increases while with a higher ER, the oxidation reactions in the gasification process improve

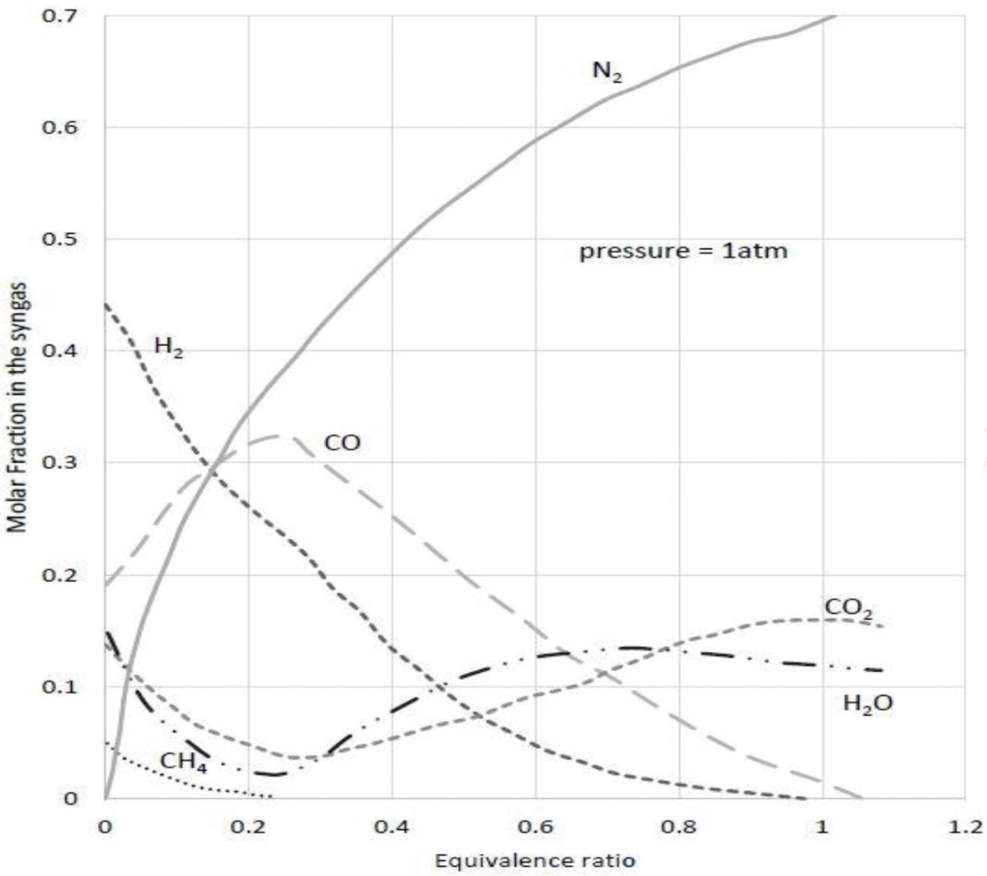

Figure 5. Syngas composition at chemical equilibrium as a function of ER for the gasification of wood at 1 atm [29].

Operating parameters	
Equivalence ratio, −	0.25–0.35[a]
Waste low heating value, MJ/kg_{waste}	7–18
Process performance parameters	
Carbon conversion efficiency, %	90–99
Cold gas efficiency, %	50–80
Syngas low heating value, MJ/m^3_N	4–7[b]
Net electrical efficiency, %	15–24
Specific net energy, kWh/t_{waste}	400–700

[a]This value is typically equal to 0.50 in moving grate gasifiers.

[b]This value can increase to about 10 MJ/m^3_N in oxygen gasification processes.

Table 4. Typical ranges of operating and process performance parameters in air/ oxygen-enriched gasification of MSW [30].

and the heating value of syngas is reduced; this could cause incomplete combustion in a flare or syngas combustor, which is generally downstream from the gasifier [24, 27, 28].

3.3.2. Reactor temperature

Temperature profile along the reactor is another important characteristic of both allo-thermal (indirectly heated) gasifier and auto-thermal (directly heated) gasifier. The reactor temperature profile is considered as a state variable of the process, and it is affected by different parameters, such as ER, residence time, waste chemical energy, composition, inlet temperature of the gasifying medium, quality of the reactor insulation, etc. Moreover, the state of the bottom ash and the content of tar in the syngas can also be determined by the temperature profile of the reactor [24, 27].

3.3.3. Residence time

Generally, the residence time of gases and waste in the reactor is determined by the reactor type and design. Also, a fixed reactor type and design have limitations in terms of varied residence times: for example, the superficial gas velocity is varied in a fluidized bed and the velocity of grate elements is varied in the moving grate reactor [25, 31, 32].

3.3.4. Cold gas efficiency

Cold gas efficiency (CGE) is defined as the ratio between the heating value of the syngas produced and the heating value of the feedstock fed into the gasification process, that is, $CGE = (Q_{syngas}\ LHV_{syngas})/(Q_{waste}\ LHV_{waste})$. This is called "cold gas efficiency" since it does not take into account the gas sensible heat but only its potential chemical energy, that is, those related to the combustion heats of obtained syngas and fed waste.

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3.3.5. Carbon conversion efficiency

Carbon conversion efficiency (CCE) is defined as how many carbons in the waste gets converted to carbon in the syngas such as CO, CO_2, CH_4, C_2H_6, C_3H_8, etc., that is, CCE = $(Q_{syngas} C_{carbon\_syngas})/(Q_{waste} C_{carbon\_waste})$; C_{carbon_waste} is the carbon fraction in the waste and C_{carbon_syngas} is the carbon fraction in the syngas with no dust or tar. This parameter shows the amount of the unconverted portion, which has to be treated by other processes or sent for disposal (such as in a landfill) as well as the chemical efficiency of the process.

3.3.6. Tar content

In the case of tar, if possible, the content and composition of the tar is analyzed. These tars, which are condensable heavy hydrocarbon materials, including oxygen-containing hydrocarbons and polyaromatic hydrocarbons, are an important parameter because they cause problems in all gasification processes, including the end of process [33]. The occurrence of excessive slag in boilers can cause blockages, corrosion, and also reduces the overall efficiency of the process. The amount of other metals and refractory surfaces increase and can also causes of ruin reforming catalysts, sulfur removal system, ceramic filters, etc. Also, if these tars are removed by a wet system using water, the tar is just moved from the gas to the water, and this water changes to wastewater with a loss of chemical energy of the gas and the generation of hazardous wastewater. Therefore, the content and composition of tar in syngas is an important factor in determining the energy conversion device that can be utilized, taking into consideration the cleaning system, and the technical and economic performance. These cleaning systems can be applied inside the reactor (primary measures) and/or downstream from it (secondary measures) [24, 27].

3.3.7. Other parameters

Other parameters are the heating value of the syngas (kJ/Nm^3), the flow rate of the specific syngas (Nm^3/kg waste), and the specific energy production, that is, the chemical energy of the syngas produced by the mass unit of waste fed to the gasification process (kJ/kg waste).

4. MSW gasification technologies

4.1. Overview of existing gasification technologies

Gasification can be considered as a process between pyrolysis and combustion in that it involves the partial oxidation of the material. This means that oxygen is injected but not enough to cause complete combustion. The temperatures are typically above 650–800°C. Although this process is mostly exothermic, it may be required to initialize and maintain the gasification process.

Raw MSW is not appropriate for the gasification process, so generally a separation is needed, including mechanical homogenization and the separation of glass, metals, and inert materials before the treatment of residual waste. The main gasification syngas product contains carbon monoxide, hydrogen, and methane. Generally, the gas generated from gasification has a net calorific value (NCV) of 4–10 MJ/Nm^3. The calorific value of syngas from pyrolysis and gasification is lower than that of natural gas, which has a NCV of approximately 38 MJ/Nm^3 [34]. As mentioned earlier, an important issue in using syngas in alternative thermal treatment facilities is a problem related to tar. The tar can cause blockages and other operational problems, and it is associated with plant failures and inefficiencies in many pilot and commercial-scale facilities. The application of the high-temperature secondary processing phase can be used to "crack" the tars and purify the syngas before applying the energy recovery systems. This process is referred to as "gas clean up" or "polishing," and can enable higher efficiency energy recovery than can be applied through other waste heat treatment processes.

However, most commercial gasification facilities processing MSW-derived feedstock (SRF) utilize a secondary combustion chamber to burn the syngas and recover energy from a steam circuit, seeking to recover more energy. Other major products produced by gasification include solid residues of noncombustible materials (ash) that contain a small amount of carbon. Also, high-temperature plasma gasification technologies are being used at various stages of gasification process. Using this plasma technologies, tar-free clean syngas can be produced, as well as the ash can be fused into glassy or vitreous residue [35]. To recover high energy efficiency from hydrogen fuel cells attached with gasifiers and engines, different pathways are available. Waste to energy (WTE) processes are a combination of partial oxidation and volatilization of the contained organic compounds. The first gasification furnace is the combustion of the volatile gases and the steam generation of the second furnace. Japan is the world's largest producer of MSW gasification. However, the main technology used in Japan is the grate combustion of "as-received MSW," but there are more than 100 thermal treatment plants based on relatively novel processes such as direct smelting, the Ebara fluidization process, and melting process such as Thermoselect gasification [36, 37]. These processes produce glass fibers that are less hazardous than conventional WTE combustion processes and can be used advantageously in external landfills.

Transportation of as-collected MSW from one location to another is not permitted in Japan. Consequently, the grate combustion facilities are relatively small. In addition, the MSW is transported to a central WTE facility that serves as a SRF in local SRF facilities and in several communities. Additionally, all WTE facilities are used to vitrify their ash after combustion by means of electric furnaces, thermal plasma melting, or other means.

The following sections introduce several technologies available in worldwide.

4.2. Energos grate combustion and gasification process

The Energos grate combustion and gasification technology is currently operating one plant in Germany, six plants in Norway, and one in the UK. This technology was developed in Norway in the 1990s to provide an economical alternative to reducing greenhouse gas emissions such as those from gasoline. All operating plants handle MSW and commercial waste or industrial waste. The current operating plants range in capacity from 10,000 to 78,000 tons per year.

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Energos plant is using a mixture of post recycled MSW and industrial waste residue from material recovery facility as a feedstock. However, the amount of industrial waste is smaller compared with MSW. Before applying thermal treatment, using a low rpm and high torque shredder the feedstocks are shredded. After that ferrous metals are removed magnetically. Partial oxidation of the feedstock at sub-stoichiometric oxygen conditions (air to fuel ratio, k = 0.5–0.8), and combustion of the fixed carbon on the bed results in total organic carbon (TOC) of less than 3% from WTE ash in the first chamber of Energos process. In the adjoining chamber, the syngas generated during gasification are combusted completely, and the heat generated during combustion of the syngas is sent to the heat recovery system. During this process, temperatures climb up to 900 and 1000°C in the gasification chamber and oxidation chamber, respectively. All dioxins formed in this process are destroyed in combustion chamber and rapidly cooled in the heat recovery steam generator, which minimizes dioxin formation. NO_x formation was also kept comparatively low in this process (around 25% of the EU limit). A schematic diagram of the gasifier and the combustion chamber is shown in **Figure 6** [38].

After passing through the heat recovery steam generator, the flue gas enters into a dry flue gas cleaning system, which consists of a bag filter, an activated carbon injection, dry scrubbing with lime, and a filter dust silo. The lime absorbs the acidic compounds in the flue gas and the heavy metal molecules and activated carbon adsorb the dioxins. Emissions are continuously monitored. **Table 5** shows typical emission measurements at the Averoy Energos plant in Norway. These measurements were performed by TUV NORD Umweltschtz for the Norwegian Environmental Agency and reported an 11% oxygen concentration.

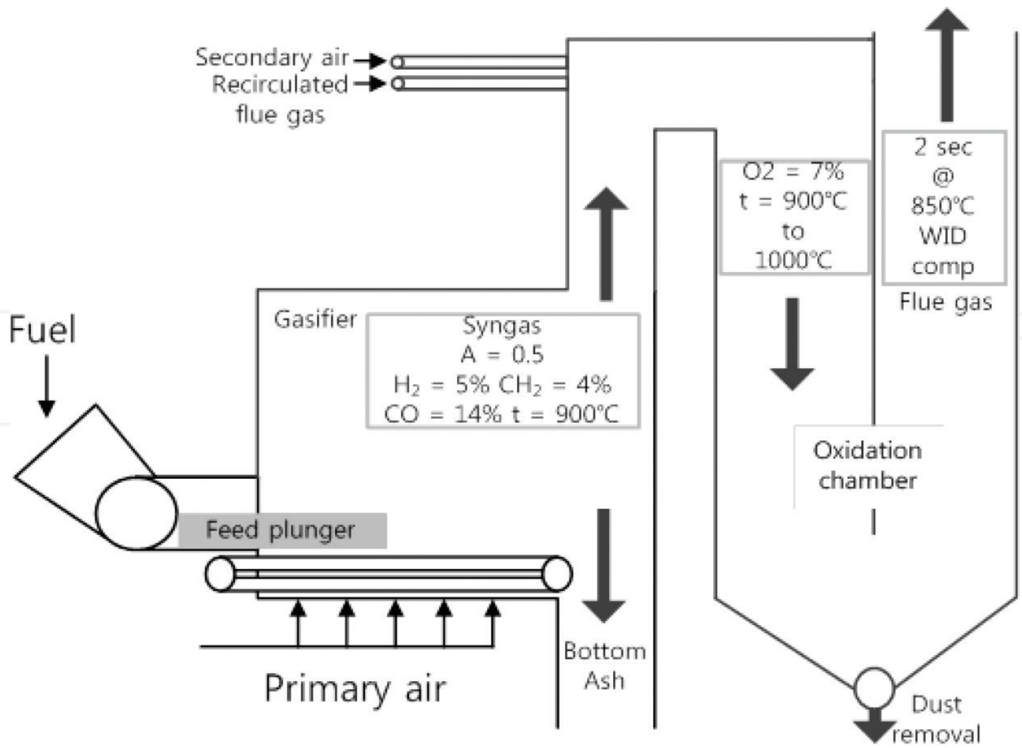

Figure 6. Flowchart of a model Energos plant.

Parameter	EU limits (mg/Nm^3)	Energos, Averoy
Particulate matter	10	0.24
Hg	0.05	0.00327
Cd + Ti	0.05	0.00002
Metals	0.5	0.00256
CO	50	2
HF	1	0.02
HCl	10	3.6
TOC	10	0.2
NO_x	200	42
NO_3	10	0.3
SO_2	50	19.8
Dioxins (ng/Nm^3 TEQ)	0.1	0.001

Table 5. Emissions from Energos plant (at 11% oxygen) [38].

The reported availability of the Energos plants is approximately 90% (8000 hours per year, similar to a typical combustion WTE plant).

4.3. Ebara fluidized bed process

The Ebara process (**Figure 7**) consists of partial combustion of shredded MSW in a fluidized bed reactor. The second furnace is where the gas produced in the fluidized bed reactor is combusted to generate temperatures up to 1350°C [36]. There is no oxygen enrichment. The largest application of the Ebara process is a three-line in Spain, with 900 tons per day.

In the reactor, the ash overflow from the fluidized bed is separated using a vibrating screen whose screen size is 3–4 mm. Metal particles are unable to pass it, however, sand particles can. The bottom ash produced during this process cannot be used for pavement construction purpose; it must be melted with slag, which is the final solid product used in construction areas. The Spanish plant using the Ebara process produces approximately 560 kWh per SRF ton.

4.4. Thermoselect gasification and melting process

Many plants, ranging from grate combustion to the Japan steel[Fe] engineering (JFE) direct smelting process and the seven JFE Thermoselect plants with a total capacity of 2000 tons per day, are operated by the JFE steel company of Japan [37]. In order to enter the gas turbines or engines, which generate electricity, the syngas produced in Thermoselect furnaces requires purification. Compared to conventional grate combustion, the amount of processed gas per ton of MSW is low. However, cleaning the reducing gas is more complicated than cleaning combustion processed gas. The Thermoselect process also produces industrial oxygen used for partial oxidation and gasification of MSW using part of the generated electricity. There is the possibility that the syngas product can be burned in a gas turbine to generate electricity

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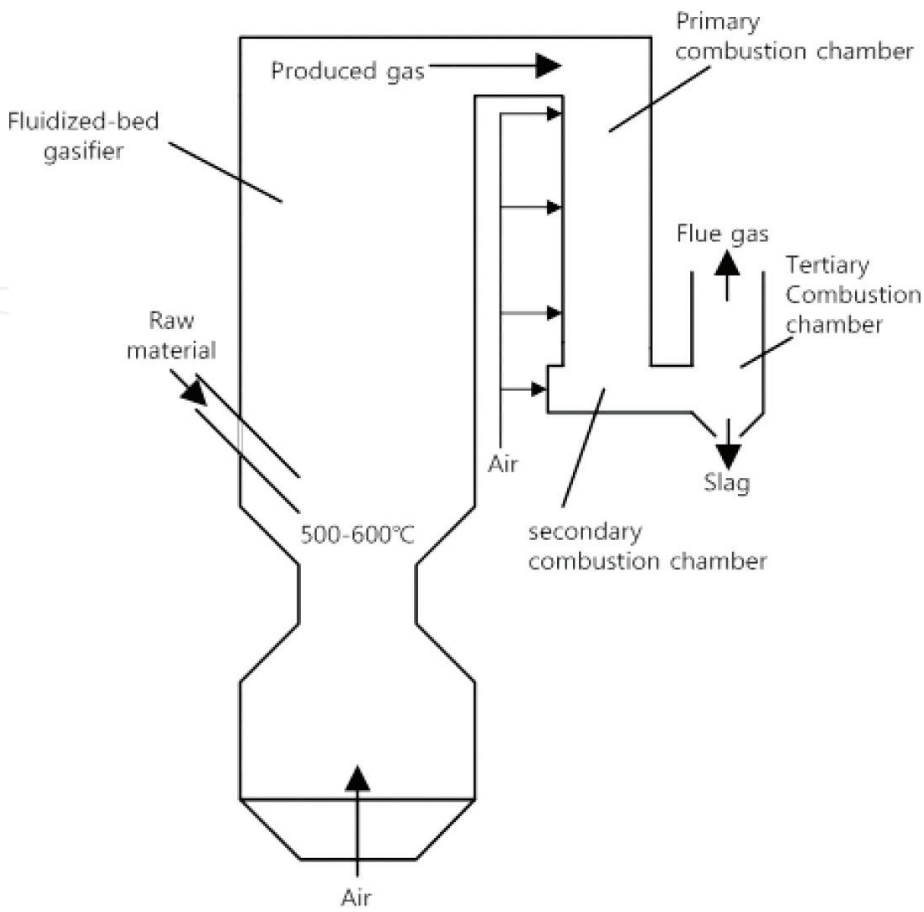

Figure 7. Ebara fluid bed gasification process.

at much higher heat efficiency than is possible in the conventional WTE plant using a steam turbine.

4.5. Plasma-assisted gasification WTE process

Recent research has shown there is a growing interest in plasma-assisted gasification of MSW. A plasma torch is a device that transforms electricity into heat by passing the current through a gas stream. Increased interest is focused on plasma-assisted gasification applied to the treatment of MSW. It might be a new way to increase WTE around the world. The Earth Engineering Center of Columbia University under the supervision of Professor Nickolas J. Themelis conducted a study of this technology. Plasma technology has long been used for the destruction of harmful materials such as asbestos, toxic wastes from hospitals, and surface coatings. Although plasma technology has been used for these purposes, its application in MSW has not yet been studied. Plasma-assisted gasification in the WTE process combines the partial oxidation of hydrocarbon in the MSW and the use of plasma. Using a relatively high voltage, high-current electricity is passed between two electrodes to create an electric arc. The inert gas is passed through the arc under pressure and is transferred to a closed container of waste, reaching a maximum temperature of 13,900°C in the arc heat. The temperature from the torch can reach 2760–4427°C. At this temperature, most types of waste are decomposed into gaseous elements, and complex molecules are separated into atoms. This arc decomposes the waste with a device known as a plasma converter to a molecular gas and solid waste (slag). This process is for net generators of electricity depending on the composition of the input waste, and the amount of waste sent to landfills is reduced.

For MSW processing, a plasma torch can be used to gasify the solids, dissolve volatile gases, and electrify ash into slag and metal globules. A syngas product can be used to produce synthetic fuels or electricity in a gas engine or turbine generator. As mentioned in the previously discussed earth engineering center (EEC) study, the technology is a Westinghouse plasma owned by Alter NRG, Plasco Energy Group, Europlasma, and the In EnTec Process [39]. A major benefit to grate combustion is a dramatic reduction in process gas flow (up to 75%). In addition, the reducing atmosphere in the gasification process should reduce NOx emissions more than in the grate combustion process. However, this study showed that the cost of capital per ton of capacity is the same as that of grate combustion. Since electricity is used for high-temperature gas, energy production per ton of raw material is not expected to be higher than that of combustion. In a system such as the Alter NRG gasification process, it is expected to generate approximately 0.6 MWh/ton of MSW. Finally, the availability of these plants is different from the combustion process WTE plants (8000 hours annually).

5. Energy recovery systems

5.1. Steam cycle

In terms of energy recovery, steam is the simplest option. No gas pre-treatment is required because the burner burns the tar [40] so the tar cannot harm the boiler. The gasification-steam cycle plant shows approximately 23% of the maximum net electrical efficiency [41]. It is similar to the efficiency of the typical solid waste incinerator. Due to HCl that may be present in flue gas, corrosion of the tube occurs at temperatures above 450°C. It is a problem of traditional waste incineration and the gasification-steam cycle boiler. These limits reduce the vapor temperature for steam turbines and therefore lower the overall electrical efficiency of the plant [42]. However, through gas pre-treatment or integration with a thermoelectric power plant, this restriction can be overcome in a gasification-steam plant [14]. Prior to putting the gas into the burner, the HCl can be removed by pre-treating the gas. Therefore, in modern boiler combinations, the firing of the clean gas enables a steam temperature of 520°C and electric efficiency is improved by 6% [42].

Co-firing refers to integration with conventional power plants; it utilizes the high-efficiency steam cycle of the thermoelectric power plant to improve performance. In general, a co-firing system is performed in two possible configurations [41, 43]. For co-firing, one configuration is using a gas burner in a separate boiler that is only in the water evaporation phase, and the other is to use a gas burner in the same boiler as the primary fuel.

5.2. Engine

Gasoline and kerosene are usually used as fuel in the spark ignition engine. However it can also be operated using gas. For that, we need to install a spark ignition system, as well as we need lower the compression ratio of diesel engine [40, 44]. Due to the lower heating value (LHV), untransformed engines show superior performance than engines converted to gas. Nevertheless, a correctly modified modern engine can allow more than 25% of the net power output [44]. The engine has the advantage of being stronger than gas turbines, and it is more resistant to pollutants [10]. Nevertheless, when the gas is compressed into a turbocharger, the same condition as in the gas turbine will occur [10, 44]. The main disadvantage of the gas engine is that the efficiency achieved using the combined cycle mode is low, and the economies of scale are poor [10].

5.3. Gas turbine

The power plants that build on advanced combined cycle gas turbines could enable an efficiency rate of approximately 60% [45]. Due to the consumption for gas pre-treatment, the effective net electrical output is below 40% [46, 47]. In fact, gas turbines allow extremely low levels of pollutants, mainly tar, alkali metals, sulfur, and chlorine compounds [10]. The chemical recovery cycle is an exciting and novel option. In this case, pre-treatment of the gas, which usually uses the tar or the catalytic cracking process of the steam reforming process, needs the energy content in the turbine exhaust gas [14, 48]. Typical gas turbines should be suitable for low LHV, for easy start-up, the burner must allow dual fuel operation, and a longer combustion chamber is needed to improve CO emissions control [49, 50].

6. Environmental impacts

6.1. Air pollution

Environmental performance in a MSW thermal treatment technology is important for the feasibility of the whole process. Recent research [51, 52] has shown that the operation of thermochemical and biochemical solid waste conversion processes poses little risk to human health or the environment compared to other commercial processes. Biochemical processes and those of anaerobic digestion have gained a wider acceptance in recent years [53]. The strong opposition to gasification processes from environmental organizations is the result of misunderstanding that these processes are only minor variations of incineration. As mentioned above, an important difference is that gasification is an intermediate process for producing fuel gas that can be used for various purposes. The most common process these days is the use of syngas for the production of on-site electricity and/or thermal energy, but there is a potential for chemical and fuel production due to the gasification of MSW, and this is possibly a true goal in the near future. The type of indirect combustion process discussed above is already emphasized in several important aspects that make it different from conventional incineration. Moreover, it makes air pollution control easier and cheaper compared with the conventional combustion processes. Although exhaust gas cleanup of thermochemical conversion processes is easier compared with incineration process, still a proper process and emission control system design is required to satisfy the safety and health requirements. The producer gas obtained from gasification process includes various air pollutants that must be controlled before being discharged to outside. These include hydrocarbons, carbon monoxide, tars, nitrogen and sulfur oxides, dioxins and furans, and particle materials. Various strategies can be adopted to control exhaust gas in the gasification process, and, as mentioned above, they are rigorously dependent on the adopted plant configurations, especially regarding the particular requirements of the specific energy conversion device. In any case, an obvious advantage in that air pollution control is possible not only at the reactor outlet but also at the exhaust gas outlet through a variety of approaches. Furthermore, the low levels of oxygen (ER ranges between 0.25 and 0.50) in the gasification process strongly inhibit the formation of dioxins and furans even though hydrogen chloride in the syngas must be managed if combustion for heat or power follows gasification. Recently collected emissions data indicate that gasification technology meets emission standards [52]. A synthesis of these data is shown in **Table 6**, together with the limits of the European Community and Japanese standards.

6.2. Solid residue treatment

It is important to report some considerations regarding the management of solid residues such as bottom ash and air pollution control (APC) residues to define the environmental performance of gasification-based WTE facilities. Depending on the type of waste and on the specific gasification technology, the type and composition of these residues differ greatly [22, 51, 53, 58]. **Table 7** reports some leaching tests carried out on the slags of two large-scale, high-temperature gasification units. All values are significantly lower than the emission standard, and the low impurity content of the slag and its good homogeneity make it possible to sell for a variety of uses such as aggregates in asphalt pavement mixtures. The metals recovered from the melting section can be also recovered during the chemical treatment of fly ash and then landfilled.

Company, plant location	**Nippon Steel Kazusa, Japan**	**Thermoselect Nagasaki, Japan**	**Ebara TwinRec Kawaguchi, Japan**	**Mitsui R21 Toyohashi, Japan**	**Energos Averoy, Norway**	**Plasco En. Ottawa, Canada**	**EC/ Japanese Standard**	**Korea Standard**
Waste capacity	200 tons/day	300 tons/day	420 tons/day	400 tons/day	400 tons/day	100 tons/day		
Power production	2.3 MWe	8 MWe	5.5 MWe	8.7 MWe	10.2 MWe	—		
Emission, mg/m^3_N(at 11% O_2)								
Particulate	10.1	< 3.4	< 1	< 0.71	0.24	9.1	10/11	14.2
HCl	< 8.9	8.3	< 2	39.9	3.61	2.2	10/90	16.7
NOx	22.3	—	29	59.1	42	107	200/229	106.8
SOx	< 15.6	—	< 2.9	18.5	19.8	19	50/161	85.5
Hg	—	—	< 0.005	—	0.0026	0.0001	0.03/–	0.09
Dioxins/ furans, n-TEQ/m^3_N	0.032	0.018	0.000051	0.0032	0.0008	0.006	0.1/0.1	—

Table 6. Some certified emissions from waste gasification plants [30, 48, 52, 54–57].

Element (mg/L)	Regulation[a]	Measured[b]	Measured[c]	Korea standard[d]
Cd	< 0.01	< 0.001	< 0.001	< 0.03
Pb	< 0.01	< 0.005	< 0.005	< 0.1
Cr^{6+}	< 0.05	< 0.02	< 0.02	< 0.05
As	< 0.01	< 0.001	< 0.005	< 0.05
T-Hg	< 0.0005	< 0.0005	< 0.0005	< 0.001
Se	< 0.01	< 0.001	< 0.002	—
F	< 0.8	—	< 0.08	—
B	< 1.0	—	< 0.01	—

[a]Quality standard for soil (in agreement with Notification No. 46, Japanese Ministry of the Environment and the JIS-Japanese Industrial Standard K0058).
[b]Tests carried out in a Nippon Steel high-temperature shaft furnace with a capacity of 252 tons/day of MSW, bottom ash from other MSW incinerators, and residues from recycling centers [59].
[c]Tests carried out in a JFE high-temperature shaft furnace plant having a capacity of 314 tons/day of RDF from MSW [32].
[d]Recycling standard of waste (No. 5 of enforcement regulations in waste management law in Korea).

Table 7. Results of some slag leaching tests in two high-temperature MSW gasifiers [30].

Therefore, it can be deduced that the amount of solid residues generated in the MSW gasification process is reduced and the throughput at the landfill can be reduced.

6.3. Wastewater treatment

In the gasification process, wastewater produced by the gas cooler and the wet scrubber containing many soluble and insoluble pollutants such as acetic acid, sulfur, phenol, and other organic compounds [10]. The insoluble matter in this wastewater is mainly composed of tar. The amount of wastewater generated by removing tar through the scrubber is about 0.5 kg/Nm^3 of treated gas [60], and requires expensive treatment. There are also some minor problems such as high salt content and low pH associated with the wastewater generated in gasification process. However, these can be controlled easily by doing chemical precipitation and neutralization [61].

"In the gasification plant Thermie Energy Farm, one of the three IGCC projects selected for funding by the European Union, the sequence of treatment for tar-rich wastewater is: (a) precipitation of sulfur by iron sulfate addition; (b) recovery of sulfur and dust by filtering; (c) disposal of filter cake; (d) stripping off gases and the major part of the hydrocarbons dissolved in the water; (e) partial evaporation of water and usage of condensate as scrubber make-up; and (f) discharge of evaporator blowdown to conventional bio-treatment" [60, 62].

The recovered salts are treated through sanitary landfills because their potential for contamination is very low. The hydrocarbons and the recovered gas are decomposed and recovered as energy in the combustor [60, 62]. Recent trends due to difficulties in treatment and disposal are developing tar-free gasification technologies, but this is nonetheless possible only for wastes with low contaminant content [10].

7. Case study on the recent gasification technology for MSW to electricity

7.1. Introduction of MSW gasification pilot plant in Korea

The MSW gasification pilot plant in Korea, performed by the R&D project of the Korea Ministry of the Environment, was developed by the research team of the authors. This pilot gasification plant, installed in Y city of Korea, is composed of a fluff SRF manufacturing system and a fixed-bed gasification pilot system whose capacity is 8 tons/day. **Figure 8** shows the whole flow diagram of this plant. Generally, the economic efficiency of fluff SRF is higher than the economic efficiency of pelletized SRF due to skipping the pelletizing process. However, the fluff SRF created an issue for transporting and storage work because of its low density. In this process, manufactured fluff SRF was directly fed into the gasification process to overcome the transporting and storage problem.

7.2. Configuration of gasification system

This plant is divided into four sections, which are the feeding system, the gasifier, the cleaning system, and the gas engine generator. The feeding system is a two-step process of a conveyor for SRF transfer to the hopper and an input screw for continuous feeding into the gasifier. The gasifier is operated using a fixed-bed and downdraft concept. However, the gasifier can be converted to updraft depending on the operation conditions. The cleaning

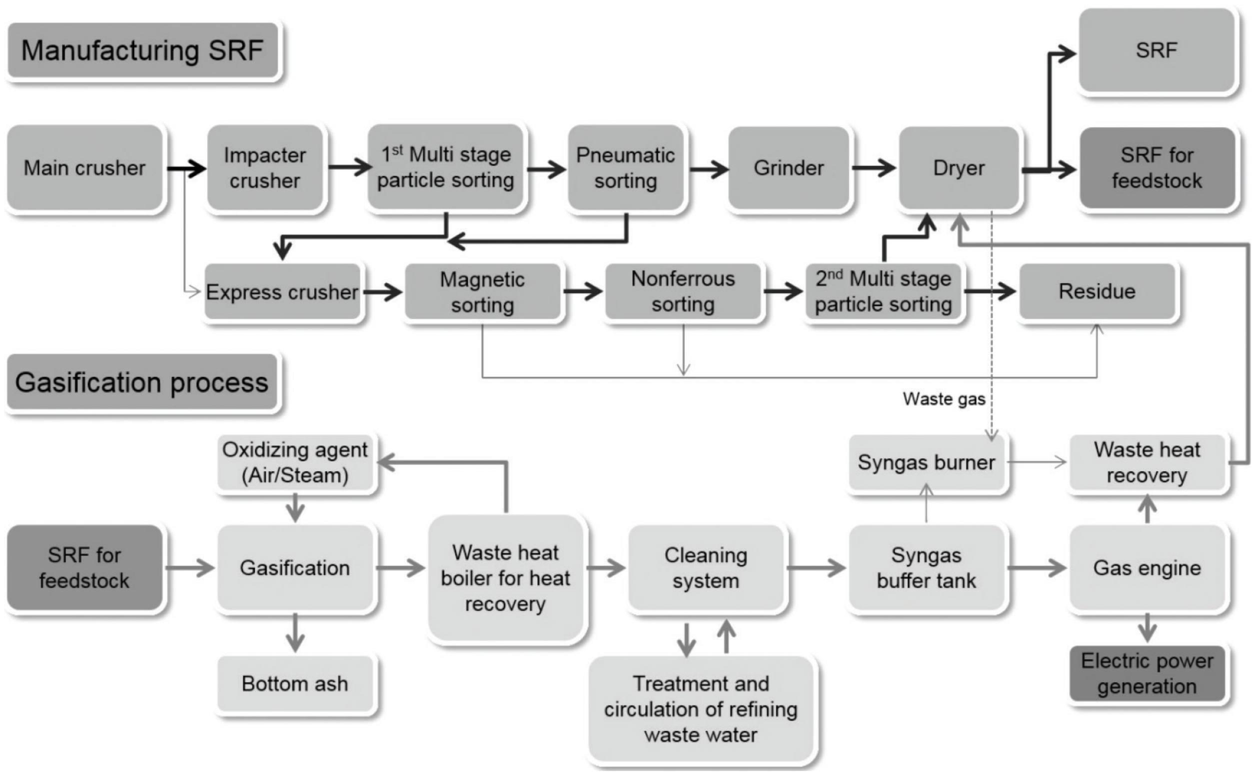

Figure 8. Overall diagram of pilot-scale SRF manufacturing system and gasification process.

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system is composed of a cyclone, various scrubbers based on a wet system, and wet electric precipitation. All of the cleaning units except for the water used in the cyclone, which is recirculated by the water tank, and tar removal system for cleaning the produced gas. Lastly, the gas engine generator is installed for electricity production. For stable operation, this gas engine generator uses a low-speed gas engine that has a high-tolerance to tar and pollutants. The maximum power production of the gas engine is 300 kW but for stable power production, this is used at 100–250 kW.

7.3. Performance of gasification system

For the stable operation of this gasification process, the process was controlled by various factors that affected operation. These conditions were selected so that the charging rate of the gasifier was 50–60% and ER was 0.17–0.36. **Figure 9** shows a representative performance test result of the gasification system. The gasification process was operated for 63 hours and shows stable operation trends for the production of syngas and electricity. Among these results, the heat-keeping and check on facility were included for continuous operation. Average syngas composition in the producer gas was about 20% and the heating value of the syngas was

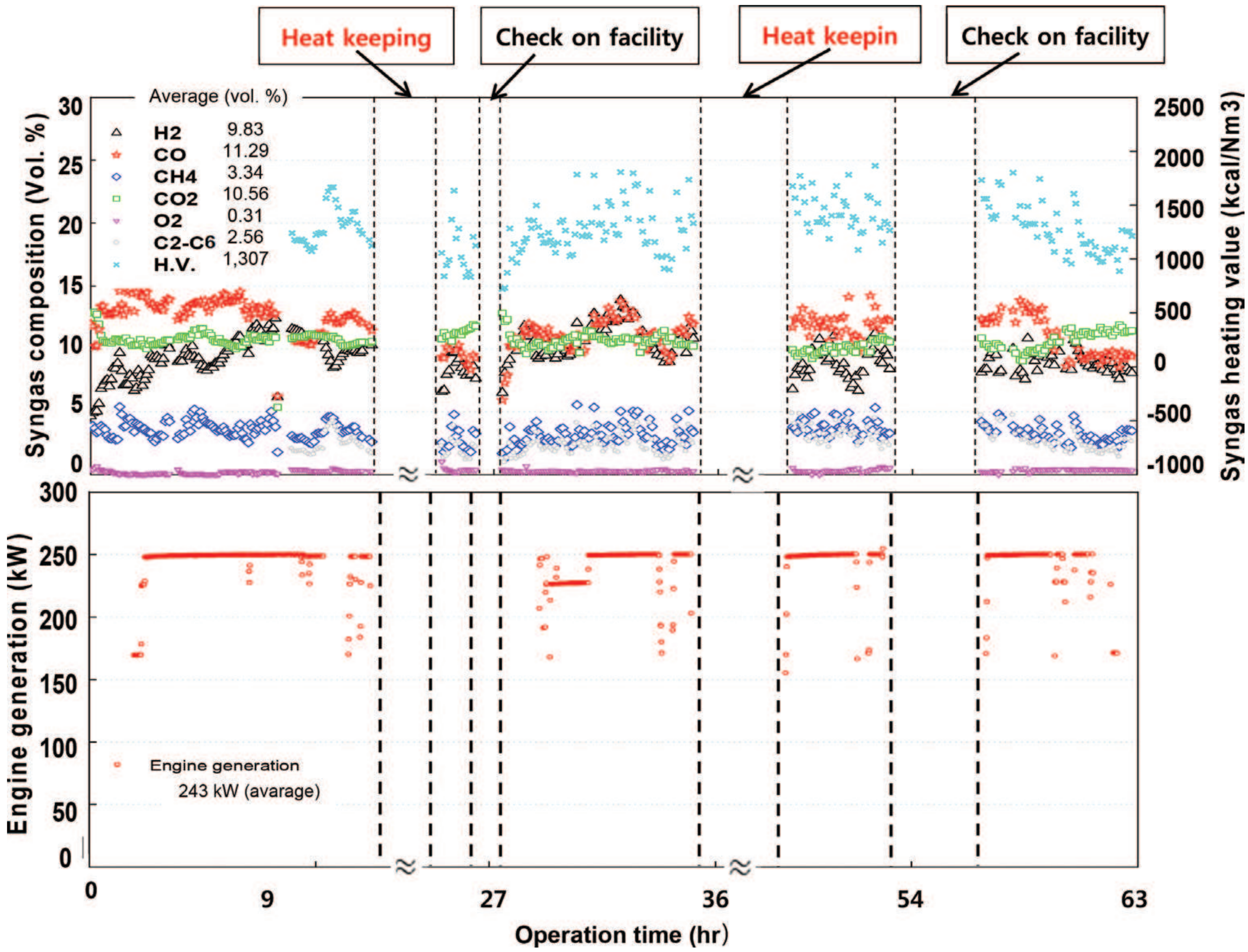

Figure 9. Reprehensive performance test results of the gasification system.

1307 kcal/Nm^3. Also, the average power generation by the gas engine was 243 kW. Following this result, the MSW gasification shows sufficient possibility and stable operation trends. Particularly in the case of power production, and even though this plant was on a pilot scale, the gas engine generator shows good performance using syngas from a gasification system.

8. Conclusion

In this book chapter, the properties of MSW have been discussed, which will help us to select the proper technology. Also, discussion on the gasification processes and technologies has been done to strengthen the basics on gasification. In addition, a review on energy recovery system has been made to guide and select the most viable option for energy recovery. The environmental benefits of MSW gasification has been also reported in this book chapter. Finally, a case study on pilot-scale MSW gasification to generate electricity has been presented to discuss one of the most efficient pathways to utilize it. Based on the above discussion, it is quite clear that gasification process offers considerable energy recovery and reduces the amount of potential pollutants emission. Moreover, gasification may be proposed as a viable alternative solution for waste treatment by converting waste into a gaseous energy form, syngas for further potential uses to energy production or chemicals. MSW gasification has some drawbacks due to the heterogeneous characteristics of MSW. However, a possible solution to address this issue could be production of solid refuse fuel (SRF) with homogeneous and controlled characteristics. The strongest point for gasifying MSW is its environmental performance. Several MSW gasification emission test results indicate that the gasification of MSW is able to meet the emission standard and can effectively reduce the environmental impacts, which can be considered as a sound response to the increasingly restrictive regulations applied around the world.

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