



Process and technological aspects of municipal solid waste gasification. A review

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ABSTRACT

The paper proposes a critical assessment of municipal solid waste gasification today, starting from basic aspects of the process (process types and steps, operating and performance parameters) and arriving to a comparative analysis of the reactors (fixed bed, fluidized bed, entrained bed, vertical shaft, moving grate furnace, rotary kiln, plasma reactor) as well as of the possible plant configurations (heat gasifier and power gasifier) and the environmental performances of the main commercially available gasifiers for municipal solid wastes. The analysis indicates that gasification is a technically viable option for the solid waste conversion, including residual waste from separate collection of municipal solid waste. It is able to meet existing emission limits and can have a remarkable effect on reduction of landfill disposal option.

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1. Possible routes for energy production from waste

Thermochemical treatment processes are an essential component of a sustainable integrated municipal solid waste (MSW) management system, as confirmed by several analyses and studies (Brunner et al., 2004; Porteous, 2005; Psomopoulos et al., 2009) and, above all, by waste management systems that are operating successfully worldwide. They are characterized by higher temperatures and conversion rates than most other, biochemical and physicochemical, processes, so allowing an efficient treatment of different types of solid waste, in particular of unsorted residual waste (i.e. the waste left downstream of separate collection, which cannot be conveniently recycled from an environmental and economic point of view). Their main advantages are: (i) strong reduction of the waste in mass (about 70–80%) and in volume (about 80–90%), therefore preserving landfill space (Consonni et al., 2005); (ii) drastic saving of land, since that required is significantly smaller than that needed for landfilling the same quantity of MSW (it has been estimated that a waste-to-energy (WtE) plant processing 1 Mt/y for about 30 years requires less than 100,000 m² of land, which should be compared with the about 3000,000 m² that would be necessary for landfilling of 30 Mt of MSW) (Psomopoulos et al., 2009); (iii) destruction of organic contaminants, such as halogenated hydrocarbons (McKay, 2002; Buekens and Cen, 2011); (iv) concentration and immobilization of inorganic contaminants, so that they can be usefully and safely utilized or disposed (ISWA, 2008; Samaras et al., 2010); (v) utilization of recyclables from the thermal residues, such as ferrous and non-ferrous metals from bottom ash and slag (ISWA, 2006; CEWEP, 2011); (vi) reduction of greenhouse gas emissions from anaerobic decomposition of the or-

ganic wastes (independent studies estimated that about 1 ton of equivalent CO₂ is saved per each ton of waste combusted rather than landfilled (Psomopoulos et al., 2009)); (vii) avoided environmental burdens, that life cycle assessment studies (Arena et al., 2003; Azapagic et al., 2004) have quantified as a consequence of the better environmental performances and more severe emission regulations with respect to other energy sources (it has been publicly recognized WtE as a source of power “with less environmental impact than almost any other source of electricity” (US EPA, 2003; Rechberger and Schöller, 2006)); (viii) environmentally compatible exploitation of the renewable energy of the waste, particularly when the plant is designed and operated for cogeneration of heat and power (Rechberger and Schöller, 2006; EC-IPPC, 2006). Thermal treatment plants can in fact convert the energy value of MSW into different energy forms, such as electricity and process heat for both utilization in industrial facilities or district heating. They utilize one or more of the three main thermochemical conversion processes of combustion, pyrolysis and gasification, which are schematically compared in Table 1.

Gasification, or “indirect combustion”, in particular, is the conversion of solid waste to fuel- or synthesis-gases through gas-forming reactions: it can be defined as a partial oxidation of the waste in presence of an oxidant amount lower than that required for the stoichiometric combustion. Basically, part of the fuel is combusted to provide the heat needed to gasify the rest (auto-thermal gasification), as in the case of air gasification, or heat energy is provided by an external supply (allo-thermal gasification), as in the case of plasma torch utilization. The result is not a hot *flue gas* as in the conventional direct combustion of wastes but a hot *fuel gas* (“producer gas” or “syngas”), containing large amounts of not completely oxidized products that have a calorific value, which can be utilized in a separate process equipment, even at different times or sites. The organic content of the waste is converted mainly

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Table 1

Main characteristics of the chemical processes for thermal treatment of solid waste. Adapted from Arena and Mastellone (2009).

	Combustion	Gasification	Pyrolysis
Aim of the process	To maximize waste conversion to high temperature flue gases, mainly CO ₂ and H ₂ O	To maximize waste conversion to high heating value fuel gases, mainly CO, H ₂ and CH ₄	To maximize thermal decomposition of solid waste to gases and condensed phases
<i>Operating conditions</i>			
Reaction environment	Oxidizing (oxidant amount larger than that required by stoichiometric combustion)	Reducing (oxidant amount lower than that required by stoichiometric combustion)	Total absence of any oxidant
Reactant gas	Air	Air, pure oxygen, oxygen-enriched air, steam	None
Temperature	Between 850 °C and 1200 °C	Between 550–900 °C (in air gasification) and 1000–1600 °C	Between 500 °C and 800 °C
Pressure	Generally atmospheric	Generally atmospheric	Slight over-pressure
<i>Process output</i>			
Produced gases	CO ₂ , H ₂ O	CO, H ₂ , CO ₂ , H ₂ O, CH ₄	CO, H ₂ , CH ₄ and other hydrocarbons
Pollutants	SO ₂ , NO _x , HCl, PCDD/F, particulate	H ₂ S, HCl, COS, NH ₃ , HCN, tar, alkali, particulate	H ₂ S, HCl, NH ₃ , HCN, tar, particulate
Ash	Bottom ash can be treated to recover ferrous (iron, steel) and non-ferrous metals (such as aluminium, copper and zinc) and inert materials (to be utilized as a sustainable building material). Air Pollution Control residues are generally treated and disposed as industrial waste	As for combustion process. Bottom ash are often produced as vitreous slag that can be utilized as backfilling material for road construction	Often having a not negligible carbon content. Treated and disposed as industrial special waste
<i>Gas cleaning</i>			
	Treated in air pollution control units to meet the emission limits and then sent to the stack	It is possible to clean the syngas to meet the standards of chemicals production processes or those of high efficiency energy conversion devices	It is possible to clean the syngas to meet the standards of chemicals production processes or those of high efficiency energy conversion devices

to carbon monoxide, hydrogen and lower amounts of methane, although the syngas is generally contaminated by undesired products such as particulate, tar, alkali metals, chloride and sulphide (Heermann et al., 2001; Knoef, 2005). Diminishing landfill volume and high costs associated with traditional incineration technologies strongly increase the interest on the application of the gasification process to MSW: the evidence that gas is easier to handle (and to burn) than a solid waste makes it a candidate to become the advanced thermal treatment of the near future, for both the unsorted residual dry fraction left downstream of separate collection and that produced from mechanical treatment of MSW (Heermann et al., 2001; Malkow, 2004; DEFRA, 2007a).

Gasification has several potential benefits over traditional combustion of solid wastes, mainly related to the possibility of combining the operating conditions (in particular, temperature and equivalence ratio) and the features of the specific reactor (fixed bed, fluidized bed, entrained bed, vertical shaft, moving grate furnace, rotary kiln, plasma reactor) to obtain a syngas suited for use in different applications. It can be utilized as a fuel gas that can be combusted in a conventional burner, connected to a boiler and a steam turbine, or in a more efficient energy conversion device, such as gas reciprocating engines or gas turbines. Its main components, carbon monoxide and hydrogen, can also offer the basic building blocks for producing valuable products as chemicals and fuels (Heermann et al., 2001; E4tech, 2009; Young, 2010; Stantec, 2010).

2. Gasification process basic features

2.1. Process types

The solid waste gasification is a complex process that includes a number of physical and chemical interactions that occur at temperatures generally higher than 600 °C, the exact temperature

depending on the reactor type and the waste characteristics, in particular the ash softening and melting temperatures (Arena and Mastellone, 2009; Higman and van der Burgt, 2003; E4tech, 2009). The different types of waste gasification processes are generally classified on the basis of oxidation medium: the process can be carried out by partial oxidation with air, oxygen-enriched air or pure oxygen; by steam gasification; by plasma gasification. The *partial oxidation with air* generates a producer gas diluted by the atmospheric nitrogen (up to about 60%) that has a calorific value ranging between 4 and 7 MJ/m³_N. This value was considered too low to be utilized in a gas turbine (since it is remarkably lower than that of natural gas that is close to 38 MJ/m³_N) but in the last years the market makes available new generation gas turbines that are able to efficiently burn low heating value syngas (provided that it is partially cooled and adequately cleaned to protect turbine blades). Some processes are operated with oxygen-enriched air, i.e. a mixture of nitrogen and oxygen having an oxygen content larger than 21% and up to 50%. The goal is to obtain a higher heating value gas as a consequence of the reduced nitrogen content, that makes possible to carry out auto-thermal processes at higher temperature, without expensive consumption of oxygen (Mastellone et al., 2010a). The *partial oxidation with pure oxygen* generates a syngas free (or almost free) of atmospheric nitrogen and then with a higher calorific value, ranging between 10 and 15 MJ/m³_N. The additional investment and operating costs for oxygen production in an air separation units (ASU) are remarkable and appear justified only for large scale units (larger than 100kt/y), on the basis of the obtained higher syngas heating value, reduced volumetric flow rate, low tar content and, in particular, vitreous ash production (that allows easier disposal options). The *steam gasification* generates a high hydrogen concentration, medium heating value (15–20 MJ/m³_N), nitrogen-free syngas. In this case, steam is the only gasifying agent, the process does not include exothermic

reactions and then it needs an external source of energy for the endothermic gasification reactions. In case of (thermal) plasma gasification (Moustakas et al., 2005; Lemmens et al., 2007), the heat source of the gasifier is one or more plasma arc torches that create an electric arc and produce a very high temperature plasma gas (up to 15,000 °C), which in turn allows control of temperature independently from fluctuations in the feed quality and supply of a gasification agent (air, oxygen or steam). This allows variations in the feeding rate, moisture content and elemental composition of the waste material: plasma gasifiers can therefore accept feedstocks of variable particle size, containing coarse lumps and fine powders, with minimal feed preparation (Gomez et al., 2009).

2.2. Process steps

The gasification of a solid waste includes a sequence of successive, endothermic and exothermic, steps (Knoef, 2005; de Souza-Santos, 2004), schematically described in Fig. 1 with reference to main reactants and products:

- *Heating and drying*, that occurs at temperatures up to about 160 °C: it is a combination of events that involve liquid water, steam and porous solid phase through which liquid and steam migrate.
- *Devolatilization* (or pyrolysis or thermal decomposition), that occurs at temperatures up to about 700 °C, involving thermal cracking reactions and heat and mass transfers and determining the release of light permanent gases (such as H₂, CO, CO₂, CH₄, H₂O, NH₃), tar (condensable hydrocarbon vapours, that release from solid matrix as gas and liquid in form of mist) and char (the remaining devolatilized solid waste residue). Part of the produced vapours undergoes thermal cracking to gas and char. For MSW, volatiles represent a significant portion of the carbonaceous fuel that provides an easily ignitable atmosphere of fuel gases around the solid waste as well as part of the produced gases of the gasification process, as schematically described in Fig. 1. The composition, quantities and characteristics of chemical species released from devolatilization (not necessarily in a

single stage) depend on several factors, mainly original composition and structure of the waste (Kawaguchi et al. 2002), temperature, pressure and composition of waste-involving atmosphere and heating rate imposed by the particular reactor type (de Souza-Santos, 2004). It should be emphasized that devolatilization releases many components, and hydrogen is required for molecular links in several of them: then devolatilization depletes hydrogen from the original carbonaceous matrix of the waste.

- A number of *chemical reactions*, that occurs in a reducing environment, i.e. under a presence of oxygen remarkably lower (from 25 to 50%) than that required for a stoichiometric oxidation. As indicated in Table 2, in an auto-thermal gasification process the partial oxidation of combustible gas, vapours and char with a controlled amount of air, oxygen or oxygen-enriched air provide the heat necessary to the thermal cracking of tars and hydrocarbons and to the gasification of char by steam or carbon dioxide, and then to keep fixed the operating temperature of the gasifier. Looking at the enthalpy of reactions No. 1, 2 and 3 in Table 2, it can be deduced that in auto-thermal gasification processes, about 28% of the heating value of carbon is “invested” in the CO production to obtain that the remaining 72% of the carbon heating value is conserved in the gas. Since the fuel contains also some hydrogen, the percentage of the heat in the original fuel, which becomes available in the gas is generally between 75 and 88%: were this value only 50% or lower, gasification would probably never have become such an interesting process for coal, biomass and waste (Higman and van der Burgt, 2003). On the contrary, in an allo-thermal gasification process, the heat required by endothermic process is provided from external sources by using heated bed materials, by burning some of the chars or gases separately or by utilizing a plasma torch. The specific gasification reactions are those taking place between the devolatilized solid waste (char) and gases excluding oxygen.

There is a very large number of gasification reactions but it is possible to individuate just three independent gasification reactions (Table 2): the water–gas reaction, the Boudouard reaction

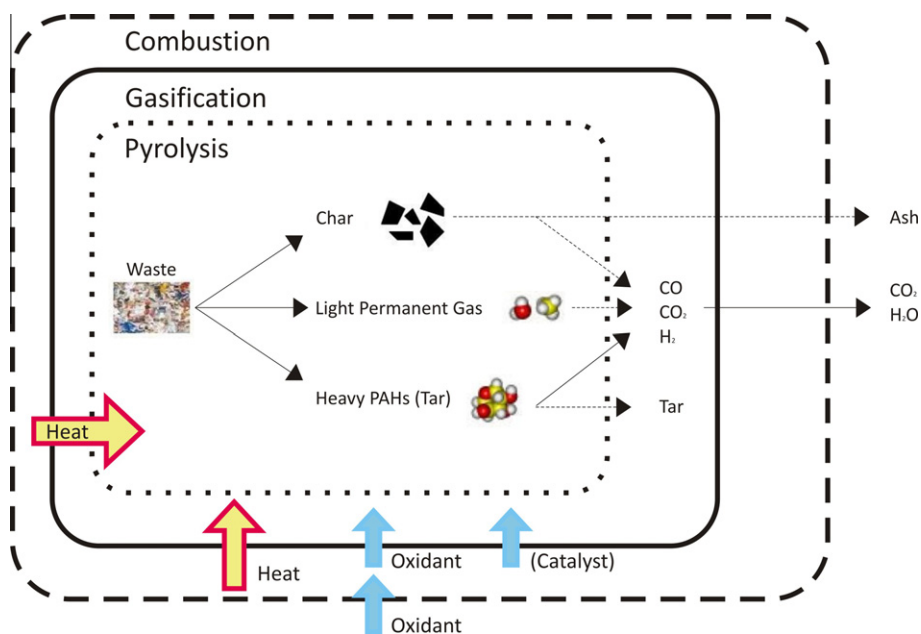


Fig. 1. Schematic representation of pyrolysis, gasification and combustion stages (redrawn from Knoef, 2005).

Table 2
Main reactions in heterogeneous and homogeneous phase during the solid waste gasification process.

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

and that of hydrogasification. In the sections of gasifier where there is no more solid carbon, these reduce to only two: water-gas shift reaction, which is the combination of water-gas and Boudouard reactions, and methanation, which is the combination of water-gas and hydrogasification reactions. This necessarily is a simplified framework, since other components (H, N, O, S, etc.) could be involved as reactants and products (de Souza-Santos, 2004). It is evident that most of the species from gasification reactions are their reduced or less-oxidized forms, such as CO 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 or other oxides. Moreover, the absence of an oxidizing atmosphere eliminates one of the steps of the dioxins synthesis mechanism (Stieglitz and Vogg, 1987; McKay, 2002; Vehlow, 2005) and strongly reduces their formation.

All these gasification reactions, with the exception of the oxidation ones, are equilibrium reactions. In practice, the final composition is determined by reaction rates and by the presence of catalytic effects (particularly important for tar decomposition reactions) rather than by the chemical equilibrium after an infinite time (Heermann et al., 2001; C-Tech, 2003; Arena et al., 2010). Anyway, modeling on the basis of the thermodynamic equilibrium of the main gaseous components and carbon gives important tendencies for a number of the commercially available gasifiers. In particular (C-Tech, 2003):

- At low temperatures (i.e. around 600 °C), carbon and oxygen prefer to exist as carbon dioxide and carbon char, i.e. the char conversion is lower.
- At high temperatures, if there is an excess of carbon, the carbon dioxide breaks down to form carbon monoxide; moreover oxygen prefers to react with carbon (to form CO and CO_2) rather than with hydrogen to form water (so hydrogen content increases at higher temperatures).
- Methane and other hydrocarbons tend to decompose at temperatures above 600 °C: this can also imply a remarkable decrease of tar content but only for temperature higher than 1000 °C. Anyway, a tar-free gasifier does not exist and tar removal and/or conversion is required in most cases (Devi et al., 2003; Arena et al., 2010).
- Char is present even at high temperatures, and it is in part discharged as unconverted carbon in the rejected ash, so determining loss of conversion efficiency.

2.3. Operating and performance process parameters

There are some operating parameters that always play a key role in waste gasification process, whatever the specific reactor technology is used. They are:

- **Equivalence ratio (ER)**, i.e. the ratio between the oxygen content in the oxidant supply and that required for complete stoichiometric combustion. It is likely the most important operating parameter in gasification-based WtE units, since it strongly affects the gas composition (including tar content) and its chemical energy. Values close to zero correspond to pyrolysis conditions while values equal or greater than one indicate combustion conditions. As it is shown in Fig. 2, values around

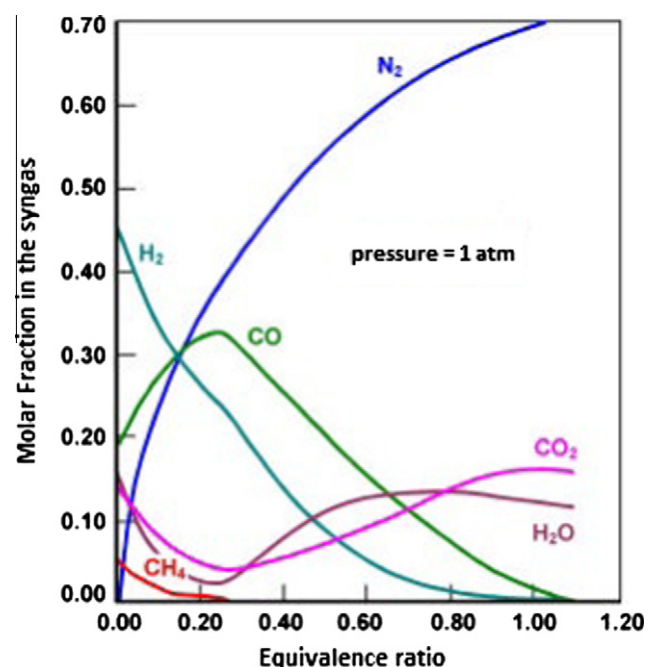


Fig. 2. Syngas composition at the chemical equilibrium as a function of equivalence ratio, for the gasification of wood at 1 atm (redrawn from Kaupp and Goss, 1981).

Table 3

Typical ranges of variations of some operating and process performance parameters in air- or oxygen-enriched air-gasification of municipal solid waste.

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 _N ³	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_N³ in oxygen gasification process.

0.25–0.35 appear to maximize char conversion and then are those typically used in large-scale commercial plants, as reported in Table 3 even though values as high as 0.5 can be used, in particular with moving grate gasifiers (Grimshaw and Lago, 2010) and fluidized bed gasifiers operated with wet fuels (Hankalin et al., 2011). Lower values of ER leave unconverted char and higher tar content while higher values of ER determine the oxidation of part of syngas and the consequent reduction of syngas heating value: this could cause incomplete combustion in the combustion chamber that is usually downstream of the gasifier (Devi et al., 2003; Li et al., 2004; Arena et al., 2010).

- **Reactor temperature** or, better, the temperature profile along the different reactor sections. It is another important operating parameter for both allo-thermal (indirectly heated) gasifiers, where the external supply of heat provided to the gasifier can adequately be adjusted, and auto-thermal (directly heated) gasifiers, where the reactor temperature profile is a state variable of the process, i.e. the system answer to different parameters, such as the equivalence ratio, residence time, waste chemical energy, composition and inlet temperature of the gasifying medium, quality of reactor insulation, etc. The temperature profile along the reactor can also determine the state of bottom ash (i.e. the possibility to obtain a vitrified slag) and to a certain extent the content of tar in the syngas (Devi et al., 2003; Arena et al., 2010).
- **Residence time of gases and waste** inside the reactor, which is largely defined by reactor type and design, and for a fixed gasifier design can be varied to a limited extent: for instance, in a fluidized bed, by varying the superficial gas velocity and, in a moving grate, by increasing the velocity of the grate elements (Arena and Mastellone, 2005; Grimshaw and Lago, 2010; Suzuki and Nagayama, 2011).
- **Waste composition and physical properties.** The performances of a waste-to-energy gasification-based process are necessarily affected by the specific properties of the municipal solid waste. The most important properties for gasification are: elemental composition, lower heating value (LHV), ash content (and composition), moisture content, volatile matter content, other contaminants (like N, S, Cl, alkalies, heavy metals, etc.), bulk density and size (Zevenhoven et al., 2001; Hermann et al., 2001; C-Tech, 2003). Some of these properties are so crucial that most of current gasification technologies generally utilize pre-processed waste or refuse-derived fuel (RDF) rather than the waste as it is. The pre-treatment is mainly oriented to adequately limit the highly heterogeneous nature of the waste and reduce its size as well as its ash and moisture content. Moreover, the composition of waste (in particular its heating value) and that of its ash (that in some cases could provide a catalytic action) could suggest to investigate the possibility to utilize a co-gasification process, i.e. to feed into the gasifier a mixture of different fuels since the possible synergy between their products and interme-

diates could lead to maximize the process performance, to reduce the carbon losses (in both particulate and tar fractions) and to increase the energy content of syngas (Pinto et al., 2007; Pinto et al., 2008; Mastellone et al., 2010b).

- **Composition and inlet temperature of the gasifying medium**, that necessarily affect mass and energy balances of the reactor. For a fixed oxidant, the inlet temperature is related both to the temperature profile that must be established along the gasifier and to the possibility/necessity of heat recovery from the hot syngas, for instance to meet the requirements of an internal combustion engine or another specific end-use device (Arena et al., 2011).

The high number of these parameters reflects the higher complexity of the gasification process with respect to the conventional direct combustion. It also suggests the potential to define adequate combinations of the operating conditions to obtain an efficient treatment of different kind of wastes. Similarly, the process performance is not indicated by one parameter as in the combustion process, where the combustion efficiency (defined as the amount of heat available in the waste that is released and utilized) gives a substantially exhaustive indication of the quality of the waste thermal treatment. For a gasification process different performance parameters are used. The most important are:

- **Cold gas efficiency (CGE)**, defined as the ratio between the chemical energy of the produced syngas (obtained as syngas flow rate multiplied by its net heating value) and the chemical energy of the waste fed to the plant (obtained as waste flow rate multiplied by its net heating value), i.e. $CGE = (Q_{\text{syngas}} \text{LHV}_{\text{gas}}) / (Q_{\text{waste}} \text{LHV}_{\text{waste}})$. It is called “cold” efficiency since it does not take into account the gas sensible heat but only its potential chemical energy, i.e. that related to the combustion heats of obtained syngas and fed waste.
- **Hot gas efficiency (HGE)**, defined as the ratio between the sum of chemical energy and sensible heat of the produced syngas (H_{out}) and the sum of chemical energy and sensible heat (H_{in}) of the waste fed to the plant, i.e. $HGE = (H_{\text{out}} + Q_{\text{syngas}} \text{LHV}_{\text{gas}}) / (H_{\text{in}} + Q_{\text{waste}} \text{LHV}_{\text{waste}})$.
- **Carbon conversion efficiency (CCE)**, that is defined as the ratio between the carbon flow rate converted to gaseous products and that fed to the reactor with the solid waste, i.e. $CCE = (Q_{\text{syngas}} C_{\text{carbon_syngas}}) / (Q_{\text{waste}} C_{\text{carbon_waste}})$, where $C_{\text{carbon_waste}}$ is the carbon fraction in the waste and $C_{\text{carbon_syngas}}$ is that of carbon in gaseous component of the syngas (i.e. dust and tar excluded). It gives an indication of the amount of unconverted material that must be treated with other technique or sent to disposal, and then provides a measure of chemical efficiency of the process.
- **Tar content** and, when it is possible, **tar composition**. This is a crucial parameter since tars (a complex mixture of condensable hydrocarbons, which includes single ring to 5-ring aromatic compounds along with other oxygen-containing hydrocarbons and polyaromatic hydrocarbons) causes problems in the process equipments as well as in the devices for end-use application (Milne et al., 1998). They increase the occurrence of slagging in boilers and on other metal and refractory surfaces, can ruin reforming catalysts, sulphur removal systems, ceramic filters; can cause blockages and corrosion and also reduces the overall efficiency of the process. Moreover, if tar content of the syngas is reduced by means of a wet physical method, tars are just moved from the gas to wastewater, with the consequent dual drawback of losing their chemical energy and generating a hazardous wastewater. Therefore, tar content and composition indicate the energy conversion device that can be reasonably utilized, taking into account the technical and

Table 4
Comparison between the main energy generation devices that can be used in a gasification-based waste-to-energy plant. Adapted from Arena and Mastellone (2009) and Arena et al. (2011).

Energy conversion device	Net electrical efficiency of gasification plant	Main advantages	Main disadvantages	Required level of syngas cleaning ^a
Steam turbine	15–24%	High electrical efficiency. Turbine components are isolated from combustion products. Long maintenance intervals, high availability. High specific work (kJ/kg yielded for working fluid)	Expensive. Partial load decreases efficiency significantly. Plants is extremely large due to space requirements for the condenser and the heat recovery steam generator (HRSG)	Tar: not limited Dust: not limited. Alkalies: not limited. Heavy metals: not limited H ₂ S: not limited
Gas turbine	20–30%	High electrical efficiency. Compact assembly. Long maintenance intervals, high availability. Ideal for cogeneration plants (CHP) due to high exhaust temperatures	Turbine components are exposed to combustion products. Partial load decreases efficiency significantly. Moderately expensive	Tar: 10 mg//m ³ Dust: 5 mg//m ³ Alkalies: 0.1 ppm,wb Heavy metals: 0.1 ppm,wb H ₂ S: 20 ppm, vb
Gas engine	14–26%	High electrical efficiency. Relatively inexpensive. Durable and reliable. Partial load effects efficiency only marginally	Engine components are exposed to combustion products. Short and expensive maintenance intervals, low availability	Tar: 100 mg//m ³ Dust: 50 mg//m ³ Alkalies: 0.1 ppm,wb Heavy metals: 0.1 ppm,wb H ₂ S: 20 ppm, vb

^a wb = weight basis; vb = volume basis.

economical performance of the cleaning techniques that can be applied inside the reactor (primary measures) and/or downstream of it (secondary measures) (Devi et al., 2003; Arena et al., 2010).

- Other parameters, such as *syngas heating value* (kJ/m³_N), *specific syngas flow rate* (m³_N/kg_{waste}), *specific energy production* (i.e. the chemical energy of the syngas obtained by the mass unit of solid waste fed to the gasifier, kJ/kg_{waste}).

Anyway, the parameters reported above not necessarily provide an exhaustive assessment of the quality of the obtained syngas, since it can have different possible utilization. For instance, a syngas with an elevated CGE can be adequate for a WtE unit but less for an application focused to a conversion to liquid fuels or to chemicals. Even in the present market of MSW gasifier, where the energy production appears to be the main goal of the treatment, CGE and the specific energy production could be both crucial but not sufficient for a definitive assessment of a process. This could prefer to maximize the stability of solid residues instead of the overall energy recovery, these two objectives being often in conflict (Heermann et al., 2001). Table 3 reports the range of variations of the main parameters of process performances, as collected by different sources (Knoef, 2005; Grimshaw and Lago, 2010; Tanigaki et al., 2011; Suzuki and Nagayama, 2011; Hankalin et al., 2011).

3. Possible configurations of gasification-based waste-to-energy units

The gasification-based WtE technologies can work as stand-alone applications or as part of integrated or modular systems combining pyrolysis, gasification and/or combustion processes. Their configurations can be sketched as a combination of three sections (Arena et al., 2011): syngas production, syngas utilization and syngas/flue gas cleaning. The first defines the syngas that can be produced and then, for fixed solid waste and gasification technology, the quantity and quality of this syngas. The utilization section indicates the syngas that can be fed in a specific energy conversion device and then, for a given machinery (steam turbine, gas engine, gas turbine), its temperature, heating value and cleaning level (i.e. tar and dust content but also that of alkali metals and inorganic contaminants). Table 4 lists main advantages and disadvantages of the energy generation devices available for large- or medium-scale gasification-based WtE plant, together with the related required levels of syngas cleaning.

The relative succession of the utilization and cleaning sections depends on two possible configurations of the waste-to-energy gasification system that can be adopted: the *power gasifier*, where the producer gas is first cleaned then burned, and the *heat gasifier*, where the producer gas is first burned then cleaned (Fig. 3). Then, for a power gasifier the cleaning section is the interface between the characteristics of the producer gas and those required by the specific end-use device whereas for a heat gasifier it consists of a possible pre-treatment of the syngas to remove contaminants (such as hydrogen chloride) before it goes into a combustor (where the part of waste chemical energy contained within the tars is also recovered) and then to air-pollution control (APC) system for flue gas cleaning. The heat gasifier – where the raw syngas is combusted into a boiler to feed an externally-fired cycle (that in practice is almost always a Rankine steam cycle) – is the most used configuration in the WtE gasification-based plant that is today in operation. It is less energy efficient but has a number of advantages over conventional incineration of wastes: (i) combustion of low molecular fuel gases from gasification processes can be more efficient and cleaner than direct combustion of raw wastes, mainly because the exact required amount of oxidant can be well mixed with the fuel gases to obtain an optimized reaction; (ii) the lower excess of air implies lower thermal losses at the stack; (iii) the homogeneous-phase combustion allows an easier control and a more continuous operation; (iv) the volume of output fuel gas from a gasifier is much smaller per ton of waste processed than that from an incinerator; (v) even if this output gas is eventually combusted, gasification process offers an intermediate step where gas clean-up can occur. The heat gasifier can be seen as a staged combustion process, and, in some cases, it is not possible to discern a distinction between the gasification and combustion stages. On the contrary, the power gasifier configuration – where the syngas is properly treated to meet the specifications of an internally-fired cycle or a synthesis process – presents a clear distinction of the gas production stage from those of gas cleaning and better utilizes the potential of the gasification plant.

4. Waste gasification vs waste combustion

The considerations reported above indicate that solid waste gasification presents several, effective or potential, benefits over traditional direct combustion of solid wastes. They can be schematically reported as in the following:

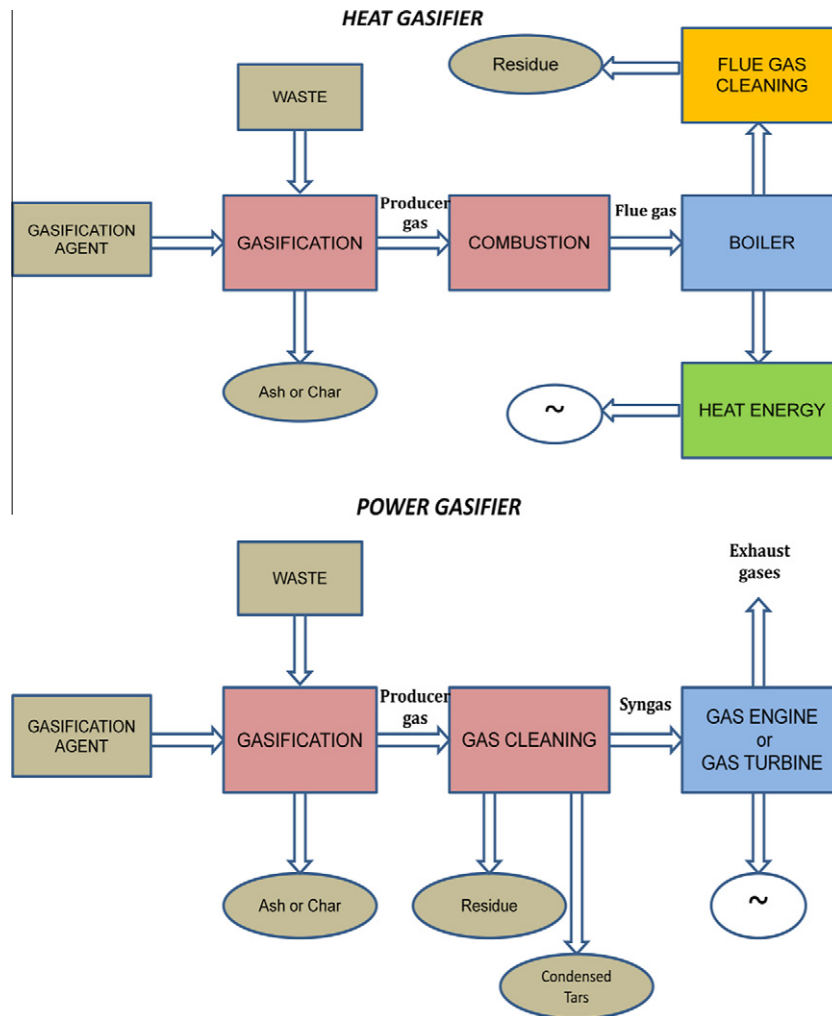


Fig. 3. Schematic representation of the WtE gasification-based configurations of a heat and a power gasifier (Arena et al., 2011).

- Gasification produces an intermediate product, which is suitable for use in a wide range of applications, such as energy generation or liquid fuels and chemicals manufacturing processes. On the contrary, conventional WtE units directly combust waste feedstock.
- There is a potential for higher efficiency conversion when the fuel gas is burned in gas reciprocating engines or gas turbines or, better, integrated gasifier combined cycles, compared with conventional Rankine steam cycle power systems.
- Operating temperatures typically lower than those of direct combustion reduce potential for alkali volatilization, fouling, slagging, heavy metal volatilization and (for fluidized bed reactors) bed agglomeration.
- Application for power generation at a smaller scale (typically lower than 120 kt/y), for which the conventional direct combustion system could be not convenient, since gas cleaning (that is primary concern and expense) could be less relevant.
- Gasification plants are often modular (and this allows the possibility to modify the capacity of solid waste treatment) and are also quicker to build.
- Except for fly ash and some volatile components, most of the inert, non-combustible material is collected at the bottom of the reactor, with metals mainly in a non-oxidized form.
- Due to the reducing atmosphere, emission of dioxins and furans are strongly limited.
- Pre-mixed flames can yield substantial reduction of NO_x emissions.
- In the case of heat gasifier configuration, between the gasifier and the combustor, raw syngas may undergo cooling and some sort of treatment. Cleaning of the product gas from gasification prior, for instance, to firing the gas in a boiler means that high temperature corrosion of the metal of the superheater is so reduced that higher steam temperatures can be tolerated and thus higher electric efficiencies can be achieved. However, syngas treatment is generally mild (typically, removal of coarse particular matter) because the homogeneous combustion process downstream can easily handle high contents of acid gas, impurities, tar, etc. In fact, the homogeneous gas–gas oxidation is much easier to control than the heterogeneous solid–gas oxidation taking place in a conventional WtE plant: this allows reducing excess air and possibly realize pre-mixed flames.
- The deficit of air (instead of an excess) reduces heat losses at the stack and thus increases energy recovery efficiency.

Some of these potential advantages are schematically listed in Table 5 and compared with the corresponding potential drawbacks.

5. Gasification technologies for thermochemical conversion of solid waste

There are several gasification technologies that in the last two decades have been developed and are now commercially available

Table 5

Schematic analysis of main potential advantages of solid waste gasification with respect to solid waste combustion. Adapted from Consonni and Viganò (2010).

Potential advantage/benefit of gasification vs. combustion	Related drawbacks/issues that hinder the benefit of gasification
Fuel syngas generated by gasification is easier to handle, meter, control and burn than solid MSW	<ul style="list-style-type: none"> • Syngas is toxic and potentially explosive, its presence raises major security concerns and requires a reliable control equipment • Plants tend to be more complex and more difficult to operate and maintain since feedstock is converted in two steps (gasification + syngas combustion/conversion)
Gasification plants can be designed for a small-medium scale (up to about 120kt/y) at which the direct combustion plants appear too expensive	At the smallest scale of waste treatment plants, efficiency of internally-fired systems is low (especially if gas turbine-based) so that the heat configuration becomes an unescapable choice
The reducing environment of the gasifier: (i) improves the quality of solid residues, particularly metals; (ii) strongly reduces the generation of some pollutants (dioxins, furans and NO _x)	The actual production of pollutants depends on how syngas is processed downstream of the gasifier: if syngas is eventually oxidized, dioxins, furans and NO _x potentially may still be an issue
Syngas can be used, after proper treatment, in highly efficient internally-fired cycles (gas turbines and combined cycles, Otto engines)	<ul style="list-style-type: none"> • The required syngas conditioning and cleaning is today costly • The consumptions and losses of gasification and syngas clean-up imply that the overall energy conversion efficiency is close to that of combustion plants
Syngas could be used, after proper treatment, to generate high-quality fuels (diesel fuel, gasoline or hydrogen) or chemicals	The required syngas treatment is very costly, so that synthesizing quality fuels or chemicals could entail prohibitive costs

for WtE plants (Heermann et al., 2001; Malkow, 2004; Arena and Mastellone, 2005; Juniper, 2009). A possible taxonomy is proposed in Table 6. It highlights that the main differences are related to the direct or indirect way of heat supply, to whether the gasifier is operated at above atmospheric pressure (so obtaining higher throughputs, larger hydrogen contents and smaller clean-up units but entailing higher investment and operating costs, that are likely prohibitive for a WtE unit), to the operating temperature range (that can determine the possibility to obtain bottom ash under form of an easy-to-handle molten or vitreous slags), to the way by means of the waste is fed into the gasifier (into the top or into the side) and is moved around within it (by gravity, air flows or mechanical devices); to whether air or oxygen or O₂-enriched air is used as oxidant (steam is utilized mainly for coal or biomass gasification). Most of these technologies have been developed and commercialized for the cogeneration of heat and power from the syngas, on the basis of the above mentioned “heat gasifier” configuration. Only a few, particularly in Japan, utilizes a “power gasifier” configuration or are operated to produce chemicals (in particular, ammonia) (Steiner et al., 2002). Table 7 proposes a list of some selected companies (among more than 20) that in total have in operation more than 100 gasifiers and are able to offer a proven gasification process for different kinds of solid wastes. With reference to their range of capacity, it is interesting to note that the main reason of the relatively low values of the maximum capacity of the MSW gasifiers is likely related to the guidelines of the government of Japan, where the gasification technology was first largely utilized. Japanese municipal governments are in principle required to treat wastes inside their own territories so that WtE plants have a reduced average capacity (about 70 kt/y), much smaller than that of Europeans plants (Suzuki and Nagayama, 2011).

A brief description of the types of gasification reactors that are today utilized for solid waste gasification is reported in the following, while their peculiar characteristics are compared in detail in Table 8.

5.1. Fixed bed gasifiers (updraft and downdraft)

In a fixed (or moving) bed gasifier a deep bed of waste is present in almost all the volume of the reactor and different zones can be distinguished, with a sequence that depends on the flow direction of the waste and gasification medium. These zones are not physically fixed and move up- and downwards depending on operating conditions, so that they can be to some extent in overlapping. In the *updraft reactors* the waste is fed in at the top of the gasifier, and the oxidant intake is at the bottom, so that the waste moves

counter-currently to the gases, and passes through different zones (drying, pyrolysis, reduction and oxidation) successively. The fuel is dried in the top of the gasifier, so that waste with high moisture content can be used. Some of the resulting char falls and burns to provide heat. The methane and tar-rich gas leave at the top of the gasifier, and the ash falls from the grate for collection at the bottom. In the *downdraft reactors*, the waste is fed in at the top of the gasifier while the oxidant from the top or the sides: then the waste and gases move in the same direction. It is possible to distinguish the same zones of updraft gasifiers but in a different order. Some of the waste is burnt, falling through the gasifier throat to form a bed of hot char which the gases have to pass through. This ensures a fairly high quality syngas (with a relatively low tar content), which leaves at the base of the gasifier, with ash collected under the grate. A sort of atmospheric moving bed downdraft gasifier is the vertical shaft-furnace proposed by Nippon Steel as “Direct Melting System”. It is a high temperature gasification and melting process, with O₂-enriched air injection in the melting section (at 36% of O₂ concentration), which directly evolved from metallurgical processing technology (Williams et al., 2003; Shibaiki et al., 2005). MSW is charged from the top of the furnace, together with coke, used as reducing agent, and limestone, used as viscosity regulator. A coke bed layer is formed in the lower part of direct melting furnace (about 50 kg of coke is added for each ton of MSW) and it is burned and kept at high temperatures in order to melt ash stably, to prevent cool-down of slag and accelerating waste thermal devolatilization and gasification. Limestone is also added for about 5% by weight, to provide some pH buffering of the melt and to form fluid slag that can be easily discharged from the furnace bottom. From the top to the bottom of the gasifier it is possible to individuate a pre-heating and drying region (which operates at about 300 °C), a gasification region (which operates between 300 and 1000 °C), a combustion region (between 1000 and 1700 °C) and a fusion region (between 1700 and 1800 °C). The produced syngas is transferred to a swirling combustor that transfers the generated thermal energy to a boiler, which in turn powers a steam turbine that produces electricity. Nippon Steel claims power generation from about 400 kWh/t_{MSW} (when MSW is co-gasified with bottom ash discharged from other MSW incinerators and with combustible and incombustible residues from recycling centers) to about 670 kWh/t_{MSW} (when only MSW is gasified), depending on the feedstock properties (LHV and ash content, which causes higher sensible heat of melt) and boiler system (Tanigaki et al., 2011). There are more than 30 plants constructed by Nippon Steel in Japan and in Korea, with a capacity range from 100 to 450 tons/day (UCR, 2009). Another high-temperature gasification, again carried out in a sort of moving bed downdraft gasifier coupled with a

Table 6
Taxonomy of solid waste gasifiers.

Criteria	Types (Acronym)
Heat supply	<ul style="list-style-type: none"> • Directly heated (auto-thermal) gasifiers • Indirectly heated (allo-thermal) gasifiers
Pressure	<ul style="list-style-type: none"> • Atmospheric gasifiers (<i>A</i>) • Pressurized gasifiers (<i>P</i>)
Gasification agent	<ul style="list-style-type: none"> • Air gasifiers (<i>AG</i>) • Oxygen enriched-air gasifiers (<i>EAG</i>) • Oxygen gasifiers (<i>OG</i>) • Steam gasifiers (<i>SG</i>) • Plasma gasifiers (<i>PG</i>)
Reactor design	<ul style="list-style-type: none"> • Fixed bed gasifiers: <ul style="list-style-type: none"> – Up-draft (<i>UD</i>) – Down-draft (<i>DD</i>) • Fluidized bed gasifiers: <ul style="list-style-type: none"> – Bubbling fluidized bed (<i>BFB</i>) – Circulating fluidized bed (<i>CFB</i>) – Internally circulating fluidized bed (<i>ICFB</i>) • Entrained flow gasifiers (<i>EF</i>) • Rotary kiln gasifiers (<i>RK</i>) • Moving grate gasifiers (<i>MG</i>) • Plasma gasifiers (<i>PG</i>)
Temperature	<ul style="list-style-type: none"> • Low-temperature gasifiers (typically below 900 °C) (<i>LT</i>) • High-temperature gasifiers (typically above 1200 °C) (<i>HT</i>)
Bottom ash status	<ul style="list-style-type: none"> • Dry bottom ash gasifiers (<i>BA</i>) • Vitrified slag gasifiers (<i>VS</i>)
Energy recovery	<ul style="list-style-type: none"> • Heat gasifiers (dirty syngas is post-combusted in a recovery boiler with heat/electricity production via steam turbine cycle) (<i>HEG</i>) • Power gasifiers (syngas is first cooled and cleaned and clean syngas is then burned in an internal combustion engine or a gas turbine) (<i>PWG</i>)

process integrated melting, is that proposed by JFE Engineering Co. that licensed two technologies: one from Thermosteel S.A. (“converter” reactor, which utilizes pure oxygen and, in some configuration, includes a degassing section before the gasifier) and another one, JFE “Gasifying and Melting System”, from NKK and Kawasaki Steel (“shaft” reactor, which utilizes oxygen-enriched air, with about 35% of oxygen content, as gasifying medium). There are several plants in operation, mostly in Japan but also in Germany and Italy: they process mixed MSW, industrial waste, incineration residues or refuse-derived fuel (RDF) (Heermann et al., 2001; Juniper, 2009; UCR, 2009; Suzuki and Nagayama, 2011).

5.2. Bubbling and circulating fluidized bed gasifiers

In a bubbling fluidized bed (BFB), the flow of gaseous oxidant (air, oxygen or oxygen-enriched air) is blown upwards through a distributor plate and permeates a bed of inert material (typically, silica sand or olivine) located at the gasifier bottom, which contains the waste to be treated (Arena and Mastellone, 2005). The superficial gas velocity (the ratio between gas volumetric flow rate and the cross section area) is usually about 1 m/s, i.e. several times larger than the value (called minimum fluidization velocity) that causes the drag forces on the particles to equal the weight of the particles in the bed and gives it a fluid-like behaviour (Kunii and Levenspiel, 1991). This fluid-like state produces an intense mixing and gas–solid contact that allow very high heat and mass transfers. All the main properties of the system are strongly related to the crucial role that hydrodynamics plays in the design and operations of a fluidized bed (Kunii and Levenspiel, 1991; Grace, 1986; Arena and Mastellone, 2005). There are not moving parts inside the reactor, and then the maintenance is simple and relatively cheap. The waste is generally fed overbed from one or more points along the side walls, is fast heated and devolatilized and reacts. Most of gasification reaction occur inside the bed and the splashing zone, i.e. the region just above the top of the bed, where there is the maximum turbulence induced by bubbles eruption (Mastellone and Arena, 2008; Arena et al., 2010). The produced syngas moves upwards along the freeboard (the vertical space above the bed height) and leaves the reactor. A BFB gasifier operates at temperatures below 900 °C to avoid ash melting and sintering that can determine a

worsening of the fluidization quality and in some cases the bed defluidization. Some companies, such as Hitachi Zosen Co. and Kobelco Eco-Solutions Co., propose BFB gasifiers coupled with a swirl-flow melting furnace, where the producer gas is burned at high temperatures (above 1200 °C) to fuse ash and produce vitrified slags. Steel and aluminum contained in the waste are extracted from the gasifier bottom in an unoxidized state (Hitachi Zosen, 2011; Kobelco-eco, 2011). A special version of BFB gasifiers is that called internally circulating bed (ICFB) that has a special fluidizing gas distributor, able to improve the radial mixing of gas and solids. This technology is offered by Ebara and, as in the solution mentioned above, is coupled with a melting furnace (cyclone combustor) operated at about 1400 °C (Selinger et al., 2003).

When the superficial gas velocity increases significantly more than the terminal velocity of the solids (typically to more than 3 m/s), there is a no more distinct upper surface of the bed and large amounts of particles are carried out of the bed with the gas: steady state operation is possible only if entrained particles are collected by a cyclone and then returned to the bed by means of a downcomer and a non-mechanical valve. This type of fluidized bed reactors are called circulating fluidized beds (CFB), where the term ‘circulating’ signifies that the particle separation and return systems are integral and essential components of the reactor: the regime is defined not only by the superficial gas velocity but also by the solid mass flux that recirculates in the system. In a CFB gasifier the waste is fed from the side, fast heated and devolatilized and then reacts with air or oxygen-enriched air. The suspension of syngas and particles (inert material and waste char) moves upwards along the riser and enters the cyclone. The temperatures are below 900 °C to avoid ash melting and sintering. CFB gasifiers of biomass and refuse-derived fuel are proposed for instance by Metso Power that is completing a 160 MW_{fuel} unit at Lahti, in Finland, fired with household waste (origin sorted), industrial waste, demolition wood and waste wood from industry, that will start in operation in April 2012 (Hankalin et al., 2011).

5.3. Entrained flow gasifiers

These reactors are commonly operated at high pressures, about 25 bar. Then they are used to treat coal, but also refinery residues

Table 7
Selected companies of WtE gasification-based plants, that offer a commercially proven process. Main sources data are: Heermann et al. (2001), Steiner et al. (2002), Williams et al. (2003), Selinger et al. (2003), Okuwaki (2004), Arena and Mastellone (2005), UCR (2009), Juniper (2009), Grimshaw and Lago (2010), Suzuki and Nagayama (2011), Tanigaki et al. (2011).

Company	Gasification process ^a	Type of solid waste ^b	No. of WtE gasifiers	Range of capacity, kt/y
AlterNRG (Canada), Westinghouse Plasma Corp., Hitachi Metals (Japan)	A-PG-HT-VS-PWG	MSW, RDF, ASR, TDF	2 (+1)	8–90
Ebara TIFG (Japan)	A-AG-ICFB-LT-(BA + VS)-HEG	MSW, ASR, MPW, IW	12	30–135
Ebara Co. and Ube Industries Ltd (Japan)	P-OG-ICFB-(LT + HT)-VS-NH ₃ production	MPW	3	10–60
Energos (Norway/UK)	A-AG-MG-BA-HEG	MSW, RDF	8 (+6)	10–80
Hitachi Zosen (Japan)	A-AG-BFB-LT-(BA + VS)-HEG	MSW, RDF	9	10–100
JFE (Japan); (Kawasaki Steel and NKK)	A-(EAG)-DD-HT-VS-PWG	MSW, RDF, IR, IW, EW	10	30–110
JFE (Japan); Thermoselect (Switzerland)	A-(OXG)-DD-HT-VS-PWG	MSW, RDF	7	30–200
Kobelco (Japan)	A-AG-BFB-LT-(BA + VS)-HEG	MSW	12 (+1)	20–170
Mitsui (Japan)	A-AG-RK-HT-VS-HEG	MSW, ASR	7 (+2)	60–150
Nippon Steel Engineering (Japan)	A-EAG-DD-HT-VS-HEG	MSW, IR, IW	32 (+5)	30–230
Plasco Energy Group (Canada)	A-PG-HT-VS-PWG	MSW, RDF	2	5–35
Takuma (Japan)	A-AG-RK-HT-VS-HEG	MSW, ASR	2	40–100

^a Acronyms from Table 6.

^b ASR = auto shredded residue; EW = excavated wastes; IR = incineration residues; IW = industrial waste; MPW = mixed plastic waste; MSW = municipal solid waste; RDF = refuse-derived fuel; TDF = tire-derived fuel.

and mixed plastic waste, because they can be slurried to make solid fuel feeding at high-pressures inexpensive and have an energy content high enough to sustain the gasification reaction (with the addition of a supplementary fuel if necessary). In an entrained flow gasifier, fine fuel particles (well smaller than 1 mm, usually obtained by a grinder step) are added to water to produce the slurry, with a solids concentration >60%. Water serves as a transport medium and temperature moderator but even as a reactant, as it promotes hydrogen formation (Table 2). The slurry is fed into a gasifier with pressurized oxygen (or air). A turbulent flame at the top of the gasifier burns some of the fuel, providing large amounts of heat, at high temperature (1200–1500 °C, anyway above the ash melting temperature) for fast conversion of waste into a high quality syngas. The ash melts onto the gasifier walls, and is discharged as molten slag into the quench chamber for cooling: metals present are encapsulated in the cooled slag (NETL, 1995).

5.4. Rotary kiln gasifiers

This reactor is largely used in several applications, from the industrial waste incineration to the cement production. The rotary kiln concept accomplishes two objectives simultaneously: moving solids into and out of a high-temperature reaction zone and mixing the solids during reaction. A kiln is typically comprised of a steel cylindrical shell lined with abrasion-resistant refractory to prevent overheating of the metal. It is generally inclined slightly toward the discharge end (about 0.03 m/m), and the movement of the solids being processed is controlled by the speed of rotation (about 1.5 rpm). Rotary kilns are used as first stage of a two-step process in the Mitsui Recycling 21 process. The waste is gasified at 450 °C in a gasification drum and converted into gas and char with other residue of metals, ash and debris. After separation and recovery of aluminum, iron and other residue, the exit stream is fed into a high temperature combustion chamber and burnt at 1300 °C and low excess air ratio (about 1.2), where ash also fed into is melted and slag (UCR, 2009). The waste is gasified with high temperature air obtained in a high temperature air heater, then no additional external fuel is needed. The recovery of iron, aluminum and slag, which can be sold, leads to a very high waste volume reduction ratio, which can reach 1/200 of the original waste volume (JAEE, 2011). A similar process is offered by Takuma.

Moving grate gasifiers. Mechanical grates is the most utilized reactor type for combustion-based WtE units. This constant-flow grate feeds the refuse continuously from the refuse feed chute to the incinerator furnace, provides movement of the refuse bed and ash residue toward the discharge end of the grate, and does some stoking and mixing of the burning material on the grates. The grate furnace has been recently proposed for gasification process by Energos (which has several plants in operation in Norway, Germany and United Kingdom) to improve the fuel flexibility of MSW gasifiers (Okuwaki, 2004). The thermal conversion takes place in two stages: the primary chamber for gasification of the waste (typically at an equivalence ratio of 0.5) and the secondary chamber for high temperature oxidation of the syngas produced in the primary chamber. The gasification unit is equipped with a horizontal oil-cooled grate that is divided into several separate sections, each with a separate primary air supply, and a water-cooled guillotine installed at the inlet of the gasification unit to control the thickness of the fuel bed. The oxidation in the secondary chamber is facilitated by multiple injections of air and recycled flue-gas (Grimshaw and Lago, 2010).

5.5. Plasma gasifiers

Untreated waste is dropped into the gasifier, often a moving bed gasifier, coming into contact with an electrically generated plasma, usually at atmospheric pressure and temperatures of 1500–5000 °C. Organic matter is converted into a high quality syngas, and inorganic matter is vitrified into inert slag. Plasma gasifiers use plasma torches, as for instance in the WtE units proposed by Hitachi Metals Env. Syst. Co. and Alter NG (Williams et al., 2003; Willis et al., 2010), where plasma torches are located in the bottom of the gasifier, firing into a bed of carbon to melt inorganics in the MSW, forming glass aggregate and metal nodules that emerge from the bottom of the unit. Westinghouse Plasma has designed a donut-shaped chamber in the upper half of the gasifier, above the moving bed, where tars and other hard-to-gasify molecules reside for 0.5–1 min and are cracked. Plasma gasification facilities require a large amount of electricity to operate the plasma torch. It is generally indicated that it is necessary about 1200–2,500 MJ/t_{waste}, then in the range 5–10% of the energy of the feed waste. These electrical consumptions are in the order of 15–20% of the gross

Table 8

Comparison between different gas–solid reactors for solid waste and gasification. Main sources data are: Grace (1986), Heermann et al. (2001), Arena and Mastellone (2005), Knoef (2005), E4tec (2009), UCR (2009), Juniper (2009), Grimshaw and Lago (2010).

	Downdraft Fixed Bed	Updraft Fixed Bed	Bubbling Fluidized Bed	Circulating Fluidized Bed	Entrained Flow	Rotary Kiln	Moving Grate	Plasma
<i>Fuel requirements</i>								
Particle size	Waste particle diameter up to 100 mm. Due to the poor temperature control, there is risk of sintering		Waste particle must be not larger than 150 mm. Bed particle diameter between 0.08 and 3 mm. Attrition of bed particles (and their entrainment) may be severe	Waste particle must be not larger than 100 mm. Bed particle diameter between 0.05 to 0.5 mm	Fine fuel particles (smaller than 1 mm, usually as a result of a grinder) are added to water to produce the slurry (with a solids concentration >60%) that is fed to the gasifier	No problem for size. Any size can be treated, from fines to large lumps	Waste particle must be not larger than 200 mm	No problem for size
morphology	uniform	almost uniform	uniform	uniform	uniform	no problem	no problem	no problem
moisture content	<20%	<50%	<55%	<55%	<15%	no problem	< 60%	no problem
ash content	<5% db	<15% db	<25% db	<25% db	< 20% db	< 40% db	< 20% db	no problem
ash melting point	>1250 °C	>1000 °C	>1000 °C	>1000 °C	< 1250 °C	no problem	> 1200 °C	no problem
bulk density	>500 kg/m ³	>400 kg/m ³	> 100 kg/m ³	> 100 kg/m ³	> 400 kg/m ³	> 100 kg/m ³	250–350 kg/m ³	>100 kg/m ³
Temperature profile	Large temperature gradients can occur. Frequent presence of hot spots	Large temperature gradients . Frequent presence of hot spots. Relatively low gas exit temperatures	Temperature is almost constant in vertical direction. Very small variation in radial direction. The range is 550–1000 °C	Small temperature gradients in the direction of solids flow can be limited by high solid flow rate circulation. The range is 900–1000 °C	The range is 1200–1500 °C, anyway above the ash melting temperature	Longitudinal as well as transversal gradient may be large and not easy to control	Longitudinal and transversal gradients are present	Defined by the specific process, but usually very high, typically between 1,500 and 5,500 °C)
Heat exchange and typical suspension-to-surface heat transfer coeff. (W/m ² K)	Inefficient exchange. Necessity of large surface of heat exchanger. (20-100)		Very efficient exchange. Large heat transfer activated by solids circulation. (200-700)	Efficient exchange, particularly along longitudinal direction. (100-350)	Poor exchange (dominated by radiation)	Very poor exchange. There is often the necessity of long cylinder kilns. (dominated by radiation)	Poor exchange. (dominated by radiation)	Very high temperatures imply that heat exchange is dominated by radiation
Residence time	Particles stay in the bed until their discharge		Particles spend substantial time (minutes or hours) in the bed. Gas residence time depends on gas velocity that is below 2 m/s	Particles pass repeatedly trough the circulation loop: residence time for each circuit is few seconds. Gas velocity is from 3 to 15 m/s	Very short (few seconds)	Very long (1–2 hours)	Longer (>1hour) than that for combustion process	–
Conversion	Very high conversion is possible with gas plug flow and adequate temperature control	High gasification efficiency	Mixing of solids and gas bypassing can determine performance poorer than that of other reactors	High conversion is possible	–	Conversion can be high	Conversion efficiency of the process can be over 90%	Conversion can be as high as 100%
Process flexibility	Very limited. Any change in process variables often needs a new reactor design		Excellent. It can be used for low- and high-temperature pyrolysis and gasification, in presence or not of a catalyst. Different solid wastes can be treated	Excellent. Different gasifying agents can be add at different heights of the riser	Very limited. Size and energy content of the waste must be in a narrow range. Pre-treatment steps are usually adopted	Limited. The operating parameters (residence time, temperature, etc.) can be varied in a narrow range. Generally used to produce fuel gas for energy recovery	Limited. Solid residence time and temperature profile can be varied in a narrow range	Excellent
Non-catalytic process	High temperatures gasifiers provide reliable continuous operations		Excellent for continuous operations, yielding a uniform product	Excellent for continuous operations	Excellent for continuous operations	Widely used. Suitable for solids, which may sinter or agglomerate	Widely used	Very interesting for industrial and hazardous wastes
Catalytic process	It can be used for very slow, non deactivating catalyst		Excellent temperature control allows large-scale operations	Attrition of catalyst is serious	Not used	Not used	Not used	Not used

Table 8 (continued)

	Downdraft Fixed Bed	Updraft Fixed Bed	Bubbling Fluidized Bed	Circulating Fluidized Bed	Entrained Flow	Rotary Kiln	Moving Grate	Plasma
Scale-up problems	Can be scaled, taking carefully into account the temperature control.	They must be carefully considered. A pilot plant is often necessary	Some large projects are planned	The long design and operating experience in coal gasification processes allows very large gasifiers	Generally not relevant. Various size kilns have been installed	The long design and operating experience limits the problems	The technology is offered in small scale identical modules. So there are no scale-up risks	
Costs	The major advantage is the reactor simplicity and the relatively limited investment costs.	Moderate. The possibility of small-scale plants makes wider the investment alternatives. Low costs of maintenance.	Capital costs higher than those for BFB. Generally convenient for large-scale plants.	Very high investment and operating costs that impose large scale gasification plants.	Moderate cost of investments. Large costs of maintenance due to moving parts and the fouling and erosion of inner walls	High cost of investments. Generally convenient for large-scale plants. Large costs of maintenance due to moving parts	Very high cost of investments and high operating cost. Electric energy consumptions can be relevant	

power output of the plant (Williams et al., 2003; Lombardi et al., 2012; Hetland et al., 2011).

Even though plasma is typically used to valorize solid wastes in a single-stage process, there is also a quite different, two-stage approach. The first stage utilizes a conventional gasifier while the second plasma stage is used to reduce the tar content in the syngas and increase the conversion efficiency. This approach is proposed by Advanced Plasma Power (APP) in the UK and Plasco Energy Group in Canada (Table 7). APP has so far one small-scale, demonstration plant in operation. Their process utilizes a fluidized bed gasifier fed with RDF, followed by a plasma converter, a gas cleaning section and a power generation section. The bed of silica sand particles is fluidized at about 850 °C; the produced crude syngas passes into a plasma converter, which operates at about 1200 °C and cracks tars and chars, so producing a hydrogen-rich syngas while ash and inorganic remain in the vitrified slag. Note that a supply of steam and oxygen if fed to both the fluidized bed gasifier and the plasma converter to help the process. The H₂-rich fuel gas, having a calorific value of about 10–14 MJ/m³_N, is then cooled and further cleaned before being fed into a gas engine. APP claims an output of about 1 MWh/t_{RDF} with a net electrical efficiency higher than 23% (Stantec, 2010; Morrin et al., 2010).

6. Environmental performance of MSW gasifiers

Environmental performance of a MSW thermal treatment technology is crucial for the overall feasibility of the process. Recent technical reports (E4Tech, 2009; UCR, 2009) indicate that thermochemical and biochemical solid waste conversion processes can be operated with no greater threat to the human health or environment than other common industrial or commercial processes. While biochemical processes, and those of anaerobic digestion in particular, recently gained a widespread acceptance (DEFRA, 2007b), gasification processes still met resistance from the environmental community, mainly due to the misperception that they are only minor variations of incineration. As it has been mentioned above, an essential difference is that the gasification is an intermediate process for producing a fuel gas that can be used in a wide variety of applications. It is also evident that, even though chemical and fuel production from gasification of MSW is possible, and it is likely the true goal for the close future, nowadays the most prevalent process is the use of syngas for onsite electrical and/or thermal energy production. It has been already highlighted in the previous paragraphs that this type of indirect-combustion processes differs from conventional incineration in several key aspects, which appear to contribute to make air pollution control less costly and complex than that required for conventional combustion process. On the other hand, although exhaust gas cleanup of non-combustion thermochemical conversion processes may be easier than that associated with incineration, a proper design of the process and emissions control systems is necessary to ensure that health and safety requirements are met. The output products of gasification reactors can contain a variety of potential process and air pollutants that must be controlled prior to discharge into the ambient air. These include particulate matter, tars, nitrogen and sulphur oxides, dioxins and furans, hydrocarbons, and carbon monoxide. Different strategies can be adopted to control emissions from gasification processes, and, as above mentioned, they are strictly dependent on the adopted plant configuration and, in particular, on the peculiar requirements of specific energy-conversion device (Table 3). In any case, there is the evident advantage that air pollution control can be applied at the reactor outlet as well as the exhaust gas outlet, in several cases by using a combined approach. Moreover, the low levels of oxygen present in gasification processes (where equivalence ratio ranges between 0.25 and 0.50)

Table 9

Some certified emissions from waste gasification plants. Main sources data are: Harada (2003), Kenou-Kennan and Kanyou-Kumiai (2006), Juniper (2007), TÜV Nord (2007), UCR (2009), Zeus GGD (2011).

Company	Nippon Steel	JFE/Thermoselect	Ebara TwinRec	Mitsui R21	Energos	Plasco En.	EC Standard/ Japanese standard
Plant location	Kazusa, Japan	Nagasaki, Japan	Kawaguchi, Japan	Toyohashi, Japan	Averoy, Norway	Ottawa, Canada	
Gasifier type ^a	DD-EAG-HT	DD-OG-HT	ICFB-AG- (LT + HT)	RK-AG-LT	MG-AG-LT	PG-HT	
Waste capacity	200 tons/day	300 tons/day	420 tons/day	400 tons/day	100 tons/day	110 tons/day	
	MSW	MSW	MSW	MSW	MSW	MSW	
Power production	2.3 MWe	8 MWe	5.5 MWe	8.7 MWe	10.2 MWth	–	
Emissions, mg/m ³ _N (at 11% O ₂)							
Particulate	10.1	<3.4	<1	<0.71	0.24	9.1	10/11
HCl	<8.9	8.3	<2	39.9	3.61	2.2	10/90
NO _x	22.3	–	29	59.1	42	107	200/229
SO _x	<15.6	–	<2.9	18.5	19.8	19	50/161
Hg	–	–	<0.005	–	0.0026	0.0001	0.03/–
Dioxins/furans, n-TEQ/m ³ _N	0.032	0.018	0.000051	0.0032	0.0008	0.006	0.1/0.1

^a Acronyms from Table 6.

strongly inhibits the formation of dioxins and furans, even though however hydrogen chloride in the syngas must be managed if combustion for heat or power follows gasification. Emission data that are so far collected from independent sources appear to indicate that gasification technologies is able to operate within existing regulatory constraints (UCR, 2009). A synthesis of these data is presented in Table 9, together with the limits of the European Community and Japanese standards.

In order to define the overall environmental performance of gasification-based WtE facilities, it is crucial to report some considerations about the management of solid residues, i.e. bottom ash and APC residues (that include the fly ash). The type and composition of these residues strongly depend on the specific gasification technology as well as on the type of treated wastes (Heermann et al., 2001; DEFRA, 2007a; E4tech, 2009; Stantec, 2010). Table 7 already highlights that several commercially-available gasification technologies are able to produce solid residues that are completely, or for a large part, recyclables. Table 10 reports some leaching tests carried out on the slags of two large-scale, high-temperature gasification units. All the values appear remarkably lower than the target references, then the low impurity content and the good homogeneity allow to sold these slags for different utilization, such as aggregate for asphalt paving mixtures. The metal recovered from the melting section can be also recovered while the fly ash are chemically treated and then disposed in landfill. It could be therefore deduced that for large part of the MSW gasification processes the amount of solid residues that must be disposed in landfills can be dramatically reduced.

Table 10

Results of some slag leaching tests in two high-temperature MSW gasifiers.

Element	Regulation ^a	Measured ^b	Measured ^c
	mg/L	mg/L	mg/L
Cd	<0.01	<0.001	<0.001
Pb	<0.01	<0.005	<0.005
Cr ⁶⁺	<0.05	<0.02	<0.02
As	<0.01	<0.001	<0.005
T-Hg	<0.0005	<0.0005	<0.0005
Se	<0.01	<0.001	<0.002
F	<0.8	–	<0.8
B	<1.0	–	<0.01

^a Quality standard for soil (in agreement with the Notification No. 46, Japanese Ministry of the Environment, and the JIS-Japanese Industrial Standard K0058).

^b Test carried out in a Nippon Steel-high temperature shaft furnace having a capacity of 252 tons/day of MSW, bottom ash from other MSW incinerators and residues from recycling centers (Tanigaki et al., 2012).

^c Test carried out in a JFE-high temperature shaft furnace plant having a capacity of 314 tons/day of RDF from MSW (Suzuki and Nagayama, 2011).

7. Conclusions

Recent policy to tackle climate change and resource conservation, such as the Kyoto Protocol, the deliberations at Copenhagen in 2009 and the Landfill Directive of the European Union, stimulated the development of renewable energy and landfill diversion technology, so providing gasification technology development a renewed impetus.

Gasification could now be proposed as a viable alternative solution for waste treatment with energy recovery. On the other hand, it still faces some technical and economic problems, mainly related to the highly heterogeneous nature of feeds like municipal solid wastes and the relatively limited number of plants (about 100) worldwide based on this technology that have continuous operating experience under commercial conditions. In the aggressive working environment of MSW management, with its uncompromising demand for reasonable cost, high reliability and operational flexibility, it could be premature to indicate the gasification as the thermal processing strategy of the future or even as a strong competitor for combustion systems, at least for any size of WtE plants. The success of an advanced thermal technology is determined by its technical reliability, environmental sustainability and economic convenience. The first, and then mainly the on-line availability, appears today supported by years of successful continuous operations of about one hundred gasification-based WtE plants, mainly in Japan but now also in Korea and Europe. The environmental performance is one of the greatest strengths of gasification technology, which often is considered a sound response to the increasingly restrictive regulations applied around the world: independently-verified emissions tests indicate that gasification is able to meet existing emissions limits and can have a great effect on the reduction of landfill disposal option. Economic aspects are probably the crucial factor for a relevant market penetration, since gasification-based WtE tends to have ranges of operating and capital costs higher than those of conventional combustion-based WtE (in the order of about 10%), mainly as a consequence of the ash melting system or, in general, of the added complexity of the technology. Anyway the evidence of the last few years would indicate a convenience of gasification plants for size smaller than about 120 kt/y. The greatest technical challenges to overcome for a wider market penetration of commercial advanced gasification technologies appears still to be that of an improved and cheaper syngas cleaning, able to conveniently meet defined specifications and to obtain higher electric energy conversion efficiencies. The next few years will tell us if the results of R&D programs worldwide active along with performance data and know-how from several

commercial waste gasifiers in operation will allow us to consider the gasification process as a strong competitor of conventional moving grate or fluidized bed combustion systems.

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