Energy from gasification of solid wastes

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Abstract

Gasification technology is by no means new: in the 1850s, most of the city of London was illuminated by “town gas” produced from the gasification of coal. Nowadays, gasification is the main technology for biomass conversion to energy and an attractive alternative for the thermal treatment of solid waste. The number of different uses of gas shows the flexibility of gasification and therefore allows it to be integrated with several industrial processes, as well as power generation systems. The use of a waste–biomass energy production system in a rural community is very interesting too. This paper describes the current state of gasification technology, energy recovery systems, pre-treatments and prospective in syngas use with particular attention to the different process cycles and environmental impacts of solid wastes gasification.

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1. Introduction

Today, the world demand for renewable energy sources is the key factor in the revival of the use of gasification systems, which was in strong decline after the advent of petroleum (Cuzzola et al., 2000). Gasification systems are successfully applied to the production of energy from biomass. They also represent an attractive alternative to the well-established thermal treatment systems for the recovery of energy from solid wastes. Gasification is particularly suitable to treat industrial wastes but there are some problems with municipal solid wastes related to their heterogeneity.

In this paper, the relative complexity of technology needed for feasible gasification process cycles is discussed with particular reference to the different reactors, energy recovery systems and gas clean up systems.

The aim of this paper is not to determine or to demonstrate whether gasification is the best process for the thermal treatment of solid wastes or not. The concept of “best” is valid solely in the context of local values, limits and problems, such as characteristics of waste, environmental regulation or communities dimension. Nevertheless modern incineration is de-facto the standard for comparison of the gasification performance (Juniper, 2000).

1.1. Gasification

Combustion, gasification and pyrolysis are the thermal conversion processes available for the thermal treatment of solid wastes. As shown in Fig. 1, different products are gained from the application of these processes and different energy and matter recovery systems can be used to treat these.

Gasification can be broadly defined as the thermochemical conversion of a solid or liquid carbon-based material (feedstock) into a combustible gaseous product (combustible gas) by the supply of a gasification agent (another gaseous compound).

The thermochemical conversion changes the chemical structure of the biomass by means of high temperature. The gasification agent allows the feedstock to be quickly converted into gas by means of different heterogeneous reactions (Di Blasi, 2000; Hauserman et al., 1997; Barducci, 1992; Baykara and Bilgen, 1981). The combustible gas contains CO2, CO, H2, CH4, H2O, trace amounts of higher hydrocarbons, inert gases present in the gasification agent, various contaminants such as small char particles, ash and tars (Bridgewater, 1994a).
Direct gasification occurs when an oxidant gasification agent is used to partially oxidise the feedstock. The oxidation reactions supply the energy to keep the temperature of the process up. If the process does not occur with an oxidising agent, it is called indirect gasification and needs an external energy source (Figs. 2 and 3) (Hauserman et al., 1997; Staniewski, 1995). Steam is the most commonly used indirect gasification agent, because it is easily produced and increases the hydrogen content of the combustible gas (Hauserman et al., 1997).

Pyrolysis is an indirect gasification process with inert gases as the gasification agent. As shown in Fig. 2, resulting from the gasification process and varying with the temperature at which the process is carried out, the three major output fractions are (De Feo et al., 2000):

1. a combustible gas;
2. a liquid fraction (tars and oils); and
3. a char, consisting of almost pure carbon plus inert material originally present in the feedstock.

As shown in Table 1, the heating value of the gas is significantly affected by the presence of nitrogen. Due to the absence of nitrogen in the gasification agent, the indirect gasification process increases the volumetric efficiency and produces a gas with a higher heating value (De Feo et al., 2000; Paisley, 1998). The lowering of gas production rate, typical of indirect gasification, reduces the cost of energy recovery and gas cleanup systems but is still complex and increases investment costs (Hauserman et al., 1997).
Direct gasification with pure oxygen has the same advantages as the indirect gasification process. However, the cost of oxygen production is estimated to be more than 20% of the overall electricity production (Della Rocca, 2001).

Typically, a gasification system is made up of three fundamental elements: (1) the gasifier, useful to produce the combustible gas; (2) the gas cleanup system, necessary to remove harmful compounds from the combustible gas; (3) the energy recovery system. The system is completed with suitable sub-systems useful to control environmental impacts (air pollution, solid wastes production, wastewater).

**2. Solid waste and biomass**

For a correct and efficient gasification process, a sufficiently homogeneous carbon-based material is required. Therefore many kinds of waste cannot be treated in the gasification process and for certain types an extensive pre-treatment is required (refuse derived fuel) (Fig. 4). Instead there are several types of waste that are directly suitable for the process; they are: paper mills waste, mixed plastic waste, forest industry waste and agricultural residues (Juniper, 2000).

**3. Gasifiers**

The gasifier is the reactor in which the conversion of a feedstock into fuel gas takes place. There are three fundamental types of gasifier: (1) fixed bed, (2) fluidised bed and (3) indirect gasifier. In Table 2, the main advantages of the different type of gasifiers are summarised. Pressurised reactors, not discussed in this paper, are only suitable for coal and oil gasification.

### Table 1
**Gasification processes**

<table>
<thead>
<tr>
<th>Process</th>
<th>Gasification agent</th>
<th>Producer gas heating value (MJ/Nm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct gasification</td>
<td>Air</td>
<td>4–7</td>
</tr>
<tr>
<td>Pure oxygen gasification</td>
<td>Oxygen</td>
<td>10–12</td>
</tr>
<tr>
<td>Indirect gasification</td>
<td>Steam</td>
<td>15–20</td>
</tr>
</tbody>
</table>

Direct gasification with pure oxygen has the same advantages as the indirect gasification process. However, the cost of oxygen production is estimated to be more than 20% of the overall electricity production (Della Rocca, 2001).

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![Fig. 3. Direct and indirect gasification processes.](image)

![Fig. 4. Wastes suitable for gasification.](image)
A key factor of the reactor is the capacity to produce a gas with low tar content (condensable bituminous compounds). A high tar concentration causes a lot of problems to energy recovery systems because of its corrosive characteristics.

3.1. Fixed bed

Vertical fixed bed reactors (VFB) are the most competitive fixed bed gasifiers. As shown in Fig. 5, they are subdivided into updraft and downdraft gasifiers. Updraft is a counter-current gasifier, where the feedstock is loaded from the top while air is introduced from the bottom of the reactor. In the reactor the solid material is converted into combustible gas during its downward path (Quaak et al., 1999; Bridgwater, 1994a). Feedstock is treated in the following sequence starting from the top: drying, pyrolysis, reduction and combustion (Juniper, 2000; Quaak et al., 1999; Hauserman et al., 1997; Bridgwater, 1994a). In the combustion zone, the highest temperature of the reactor is greater than 1200 °C. As a consequence of the updraft configuration, the tar coming from the pyrolysis zone is carried upward by the flowing hot gas: the result is the production of a gas with a high tar content. Typically, the sensible heat of gas is recovered by means of a direct heat exchange with feedstock (Bridgwater, 1994a).

In a downdraft reactor, co-current, the carbonaceous material is fed in from the top, the air is introduced at the sides above the grate while the combustible gas is withdrawn under the grate (Juniper, 2000; Quaak et al., 1999; Hauserman et al., 1997; Bridgwater, 1994a). As a consequence of the downdraft configuration, pyrolysis vapours allow an effective tar thermal cracking. However, the internal heat exchange is not as efficient as in the updraft gasifier (Quaak et al., 1999; Bridgwater, 1994a).

3.2. Fluidised bed

Fluidisation is the term applied to the process whereby a fixed bed of fine solids, typically silica sand, is transformed into a liquid-like state by contact with an upward flowing gas (gasification agent) (Juniper, 2000). Fluidised bed gasification was originally developed to solve the operational problems of fixed bed gasification related to feedstocks with a high ash content and, principally, to increase the efficiency (Quaak et al., 1999). The efficiency of a fluidised bed gasifier is about five times that of a fixed bed, with a value around 2000 kg/(m² h) (Quaak et al., 1999; Bingyan et al., 1994).

Fluidised bed reactors are gasifier types without different reaction zones. They have an isothermal bed operating at temperatures usually around 700–900 °C, lower than maximum fixed bed gasifiers temperatures. The bubbling fluidised bed (BFB) and circulating fluidised bed (CFB) gasifiers are schematically presented in Fig. 6.

In a BFB reactor, the velocity of the upward flowing gasification agent is around 1–3 m/s and the expansion of the inert bed regards only the lower part of the gasifier. Bed sand and char do not come out of the reactor because of the low velocity (CITEC, 2000; Ghezzi, 2000; Quaak et al., 1999).

The velocity of the upward flowing gasification agent in a CFB reactor is around 5–10 m/s (CITEC, 2000; Table 2

Comparison of different gasifier [modified by (Juniper, 2000; Bridgwater, 1994 a)]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Fixed bed</th>
<th>Fluidised bed</th>
<th>Indirect gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Updraft</td>
<td>Downdraft</td>
<td>Bubbling</td>
</tr>
<tr>
<td>Carbon conversion</td>
<td>****</td>
<td>****</td>
<td>**</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>*****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>CGE</td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Turndown ratio</td>
<td>****</td>
<td>**</td>
<td>****</td>
</tr>
<tr>
<td>Start-up facility</td>
<td>***</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>Management facility</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>Control facility</td>
<td>**</td>
<td>**</td>
<td>****</td>
</tr>
<tr>
<td>Scale-up potential</td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Sized feed elasticity</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>Moisture feed elasticity</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>Ash feed elasticity</td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Fluffy feed elasticity</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>Sintering safety</td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Mixing</td>
<td>****</td>
<td>****</td>
<td>****</td>
</tr>
<tr>
<td>Cost safety</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>Tar content</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>Particulate content</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
<tr>
<td>LHV</td>
<td>****</td>
<td>****</td>
<td>***</td>
</tr>
</tbody>
</table>

* poor, ** fair, *** good, **** very good, ***** excellent.
Consequently, the expanded bed occupies the entire reactor and a fraction of sand and char is carried out of the reactor together with the gas stream (De Feo et al., 2000). This fraction is captured and recycled in the reactor using an air cyclone that intercepts the gas stream (Niessen et al., 1996).

### 3.3. Indirect gasifier

Indirect gasifiers are the reactors used for the steam indirect gasification and are grouped as char indirect gasifiers and gas indirect gasifiers depending on the type of internal energy source (Fig. 7).
A char indirect gasifier consists of two separate reactors: a CFB steam gasifier that converts feedstock into produced gas and a CFB combustor that burns residual char to provide the necessary heat to gasify the feedstock. Sand is circulated between the two reactors to transfer heat. Energy is provided by combustion of residual char, reserving all gaseous and condensable products for gas production (Hauserman et al., 1997; Craig et al., 1995; Staniewski, 1995). This process is also called “fast fluidised process” because it has the highest throughputs and yields of gas (Farris et al., 1998; Hauserman et al., 1997; Niessen et al., 1996; Staniewski, 1995).

Gas indirect gasifiers use a steam fluidised bed gasifier within bed heat exchange tubes (Hauserman et al., 1997; Niessen et al., 1996). A fraction of combustible gas is burned with air in a pulse combustor and the hot combustion products provide heat to gasify the feed (Hauserman et al., 1997; Niessen et al., 1996; Staniewski, 1995). Gas indirect gasification is extremely versatile with a wide range of feeds (Hauserman et al., 1997).

The main advantage of indirect gasification is the high quality of the combustible gas produced in contrast with greater investment and maintenance cost of the reactor. Therefore it is necessary to improve the quality of gas with the adoption of a highly efficient energy recovery system.

4. Energy recovery systems (ERS)

4.1. Steam cycle

The steam cycle is the simplest option for energy recovery. It does not need gas pre-treatment, because tar is burned in the combustor and cannot damage the boiler (Quaak et al., 1999). The maximum net electrical efficiency of a gasification–steam cycle plant is about 23%, which is comparable with the efficiency of a typical solid waste incinerator (Consonni, 2000).

A limitation in the traditional waste incineration and the gasification–steam cycle boiler is the maximum metal temperature of the superheater tubes, normally limited to less than 450 °C to prevent excessive corrosion of the tubes by the HCl that may be present in the flue gas. This limitation results in a lower steam temperature to the steam turbine and thus a low overall plant electrical efficiency (Rensfelt and Everard, 1998).

In a gasification–steam cycle plant, this limitation could be overcome by gas pre-treatment or by integration with a thermoelectric power plant (Della Rocca, 2001).

Pre-treatment of the gas can remove the HCl before it goes into the burner, thus the firing of the clean gas in a modern boiler combination would allow a steam temperature of 520 °C, with a 6% improvement in electrical efficiency (Rensfelt and Everard, 1998).

The integration with conventional power plants is called “co-firing”: it allows to increase the performance taking advantage of the high efficiency steam cycle of the thermoelectric power plant. Usually a co-firing system is performed in two possible configurations (Consonni, 2000; Nieminen et al., 1999): adopting a gas burner in a separate boiler only for the water evaporation phase, as shown in Fig. 8, or adopting a gas burner in the same boiler as the primary fuel, as shown in Fig. 9.

4.2. Engine

Spark ignition engines, normally used with petrol or kerosene, can be run on gas alone. Diesel engines can be converted to full gas operation by lowering the com-
pression ratio and by installing a spark ignition system (Quaak et al., 1999; FAO, 1993).

Because of the low lower heating value (LHV), engines converted to gas are less efficient than those not converted; nevertheless a modern engine correctly modified can reach over 25% of net electricity output (FAO, 1993).

The engines have the advantage of being robust and having a higher tolerance to contaminants than gas turbines (Bridgwater, 1994a). Nevertheless if the gas is compressed into a turbocharger the same condition as in the gas turbine will result (Bridgwater, 1994a; FAO, 1993).

The main disadvantages of gas engines are the low increase in efficiency obtained using the combined-cycle mode and the poor economy of scale (Bridgwater, 1994a).

4.3. Gas turbine

The power plants based on advanced combined cycle gas turbine could allow an efficiency-rate of around 60% (Najjar, 1999). The effective net electrical output is lower than 40% because of the consumption for gas pre-treatment (De Lange and Barducci, 2000; Van Ree et al.,...
In fact gas turbines are very sensitive to the quality of gas, only extremely low levels of contaminants, principally tar, alkali metals, sulphur and chlorine compounds, can be tolerated (Bridgwater, 1994a).

The chemical recovery cycle is a new and very interesting option. In this case, the energy content in the turbine exhaust gas is used to feed the pre-treatment process of gas, such as catalytic cracking of tar or steam reforming process (Della Rocca, 2001; Happenstall, 1998).

Typical gas turbines must be adapted to the low LHV: for an easier start-up phase, the burners must allow dual fuel operation and longer combustion chambers are necessary to improve the control of CO emissions (Zanforlin, 1995; Becker and Schetter, 1992).

5. Future alternative use of syngas

Future alternative uses of syngas include molten carbonate fuel cells and methanol production. Molten carbonate fuel cells are very interesting because of the high efficiency-rate (more than 50%) and the easy integration with different energy recovery systems (Iacobazzi, 1995). Methanol, well known as a clean fuel, can be synthesised by a gas containing H₂, CO and CO₂ using a copper catalyst (Jung, 1999; Nowell et al., 1999). Methanol production by conversion of a homogeneous waste could be an interesting alternative.

6. Pre-treatment of gas

Pre-treatments of gas can be used to avoid environmental pollution and dangerous components, such as tar and particulate, for the energy recovery system or to increase heating value and hydrogen contents. The design of pre-treatment systems principally depends on the energy recovery technologies in use (Quaak et al., 1999; Bridgwater, 1994a).

In Table 3, gas properties related to pre-treatments are briefly described. While the required gas properties for different energy recovery systems are given in Table 4. Finally, Table 5 shows issues and cleanup processes related to flue gas contaminants.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Presence</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulates</td>
<td>Derive from ash, char, condensing compounds and bed material for the fluidised bed reactor</td>
<td>Cause erosion of metallic components and environmental pollution</td>
</tr>
<tr>
<td>Alkali metals</td>
<td>Alkali metals compounds, specially sodium and potassium, exist in vapour phase</td>
<td>Alkali metals cause high-temperature corrosion of metal, because of the stripping off of their protective oxide layer</td>
</tr>
<tr>
<td>Fuel-bound nitrogen</td>
<td>Cause potential emissions problems by forming NOₓ during combustion</td>
<td>NOₓ pollution</td>
</tr>
<tr>
<td>Sulphur and chlorine</td>
<td>Usual sulphur and chlorine content of biomass and waste is not considered to be a problem</td>
<td>Could cause dangerous pollutants and acid corrosion of metals</td>
</tr>
<tr>
<td>Tar</td>
<td>It is bituminous oil constituted by a complex mixture of oxygenated hydrocarbons existing in vapour phase in the producer gas, it is difficult to remove by simple condensation</td>
<td>Clog filters and valves and produce metallic corrosion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Boiler</th>
<th>Engine</th>
<th>Gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHV (MJ/Nm³)</td>
<td>&gt; 4</td>
<td>None</td>
<td>&gt; 4</td>
</tr>
<tr>
<td>Particulate (mg/Nm³)</td>
<td>None</td>
<td>None</td>
<td>&lt; 5–50</td>
</tr>
<tr>
<td>Tars (g/Nm³)</td>
<td>None</td>
<td>None</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>Alkali metals (ppm)</td>
<td>None</td>
<td>None</td>
<td>&lt; 1–2</td>
</tr>
</tbody>
</table>
6.2. Catalytic cracking

Catalytic processes for the conversion of tars need reaction temperatures of around 800–900 °C. Tar removal efficiency is 90–95% and dolomite is an effective and inexpensive tar cracking catalyst (Rensfelt and Everard, 1998; Delgado et al., 1996; Orio et al., 1996; Bridgwater, 1994b; Mudge et al., 1987). Dolomite demand is around 0.03 Kg/Nm³ of raw gas (De Lange and Barducci, 2000; Rensfelt and Everard, 1998).

![Catalytic processes in gasification systems](Bridgwater, 1994b).

6.3. Steam reforming and CO-shift

Shift and reverse methanation reactions allow an increase of up to 10% of the gas volume of hydrogen content by conversion of methane and steam (Aznar et al., 1998; Caballero et al., 1997). A commercial catalyst is used for steam reforming and for CO shift; catalysts are activated at a low temperature.

Steam reforming and CO-shift need a preliminary abatement of tar because catalysts are easily deactivated when the tar content is greater than 2 g/Nm³ (Aznar et al., 1998).

![Catalytic processes in gasification systems](Bridgwater, 1994b).

### Table 5
Fuel gas contaminants: problems and cleanup processes

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Range</th>
<th>Examples</th>
<th>Problems</th>
<th>Cleanup method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate (g/Nm³)</td>
<td>3–70</td>
<td>Ash, char, fluid bed material</td>
<td>Erosion, emission</td>
<td>Filtration, scrubbing</td>
</tr>
<tr>
<td>Alkali metals (g/Nm³)</td>
<td>1.5–3.0</td>
<td>Sodium and potassium compounds</td>
<td>Hot corrosion, NOₓ formation</td>
<td>Condensation and filtration, Scrubbing, SCR</td>
</tr>
<tr>
<td>Fuel nitrogen (g/Nm³)</td>
<td>10–100</td>
<td>Mainly NH₃ and HCN</td>
<td>Clog filters, deposit internally</td>
<td>Tar cracking, scrubbing</td>
</tr>
<tr>
<td>Tars (g/Nm³)</td>
<td>2.5–3.5</td>
<td>H₂S, HCl</td>
<td>Corrosion, emission</td>
<td>Lime scrubbing</td>
</tr>
<tr>
<td>Sulphur, chlorine (g/Nm³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The process can be carried out both in a fluidised bed gasifier with catalysts added to the bed or in a special reactor below the gasifier (Bridgwater, 1994b; Mudge et al., 1987). The first solution uses the temperature of the reactor but the catalyst life is not very long. With a secondary reactor, the catalyst is protected by deactivators but requires added oxygen to oxidise gas and increase the temperature.

Fig. 10 shows catalytic processes in gasification systems.
6.4. Scrubber or saturator

Modified scrubbers called saturators are adopted as a tar control system (Larson, 2000).

A saturator has two separate towers. In the first tower the gas is saturated by water droplets at a temperature of 40–80 °C (Quaak et al., 1999; Bridgwater, 1994a). Temperature and water saturation allow tar condensation on the droplet (Larson, 2000; Cernuschi, 2000). In the second tower a scrubbing process eliminates suspended droplets and condensed tar. A humidified packed bed is usually applied to increase the contact surface between gas and wash water (Quaak et al., 1999; Cernuschi, 2000).

In Table 6, the main advantages and disadvantages of tar removal systems are described.

6.5. Baghouse

A baghouse is a very effective and proven technology that allows the removal of particulate matter larger than 0.1 μm with an efficiency-rate of around 99% (Conti and Lombardi, 2000; Urbini, 2000).

6.6. Alkali condenser

Alkali metals condense at 550 °C on the particulate. Consequently if the gas reaches 550 °C and is treated by a baghouse, alkali metals are removed with the particulate (Quaak et al., 1999; Craig et al., 1995).

7. Process cycles

Several elements of a gasification system can be combined to follow both the wastes characteristics and energy recovery requirements. In the following paragraphs four different process cycles adopted in different situations are presented.

7.1. Gasification/steam cycle, stand-alone configuration

This effective and reliable configuration can be easily integrated with industrial processes for onsite use of heating and electricity and for the recycling of gasifier inert residues (SAFI, 1995).

Gas is burned directly to give heat at a stand-alone steam cycle. Absence of a cleanup system simplifies the process and reduces the plant cost, nevertheless an air pollution control system may be necessary to meet emission limits (SAFI, 1995; Barducci, 1992). The overall electricity output is around 20% and it can be increased by 6% if an acid gas control systems is adopted (De Feo et al., 2000; Rensfelt and Everard, 1998).

Fig. 11 shows a synthetic scheme of TPS installation in Grève in Chianti (Italy).

7.2. Gasification/steam cycle, co-firing configuration

A co-firing plant uses gas to give energy to a steam cycle power generation plant. Gas can be used in the same fuel boiler or in a secondary one which produces steam, later superheated in the first boiler (Figs. 8 and 9). Efficiency of this process cycle can allow an electrical output of over 30%.

In the first configuration acid gases are diluted, whereas in the secondary boiler the temperature of the steam tubes remains below 180 °C and corrosive action is not effective (Della Rocca et al., 2001; Consonni, 2000). Moreover, a co-firing plant allows the use of high moisture content feedstock because of the superheated temperatures, which do not depend on the heating value of the combustible gas (Consonni, 2000; Nieminen et al., 1999).

Fig. 12 shows a scheme of an installation in Lahti (Finland).

7.3. Gasification/engine

The gasification of coal and carbon containing fuels and the use of gas as fuel in internal combustion engines is a technology that has been utilised for more than a century (FAO, 1993). The main innovation for waste and biomass gasification/engine process are cleanup systems used for removing dust, tar, and alkali metals from the raw gas (Quaak et al., 1999). Experience leads to a use of a modified downdraft gasifier for tar thermal cracking and a hot gas filter for dust removal. Electrical efficiency is around 25%, because of the low heating value of gas (Bridgwater, 1994a; FAO, 1993).
7.4. Integrate gasification combined cycle (IGCC)

IGCC could be competitive in a few years (Larson, 2000). An IGCC plant uses a clean gas in a gas turbine combined cycle to produce energy. Net electrical output is over 30% and can increase up to 40% if total thermal power is over 50 MW (Morris and Waldheim, 1998).

The main disadvantage of this plant is the need for a cleanup system for the control of corrosive gas phase compounds such as tar, acid gas and alkali metals (Quaak et al., 1999; Bridgwater, 1994a; Larson, 1992).
The most interesting element is the system of tar control through catalytic tar cracking or wet scrubbing. The first solution is implemented in the Termiska Processer ARable Biomass Renewable Energy (TPS/ARBRE) installation in Eggborough (UK), as shown in Fig. 13. Fig. 14 shows the second solution as adopted in the Thermie Energy Farm (TEF) installation in Cascina (Italy).

8. Environmental impacts

8.1. Air pollution

Atmospheric emissions of gasification systems depend on the installed air pollution control equipment and energy recovery systems in use. Therefore it is difficult to compare the air pollution impact of gasification systems with a conventional combustion process.

However, the use of gas allows for a successful combustion control, better than solid combustion resulting in an effective reduction in the emission of CO, NOₓ, dioxins and unburned compounds (Giugliano, 2000; Tchobanoglous et al., 1993). Moreover gas pre-treatment can be performed to remove pollution precursors such as nitrogen and chlorine compounds and improve emissions (SAFI, 1995; Staniewski, 1995; Tchobanoglous et al., 1993).

8.2. Solid waste production

Solid waste production is related to char and ash extracted from the gasifier, the particulate control equipment and the possible boiler, with a production of 2–9, 5–10 and 3–6% of treated feedstock, respectively (SAFI, 1995).

Gasifier residues could be used to fertilise the ground (rarely if the feedstock is not agricultural waste) or disposed in a sanitary landfill. Instead, solid residues of gas pre-treatment and air pollution control systems are typically disposed in landfills, because of their high heavy metal concentration level. Sometimes, solid residues can be used in industrial processes, such as cement mills, for a complete integration between gasification and industrial processes (SAFI, 1995).

8.3. Wastewater

In the gasification process, wastewater may be produced by the gas cooler and the wet scrubber containing many soluble and insoluble pollutants, such as acetic
acid, sulphur, phenols and other oxygenated organic compounds (Bridgwater, 1994a). The insoluble fraction of the wastewater consists mainly of tars.

Wet scrubber effluent production is around 0.5 kg/Nm³ of treated gas (Barducci et al., 1997). If a scrubber is used for tar removal the effluent needs expensive treatment, otherwise the usual problems are a low pH and a high salt content, which can be easily controlled by neutralisation and chemical precipitation, respectively (Cernuschi, 2000).

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 (Barducci et al., 1997; Barducci and Neri, 1997):

- precipitation of sulphur by iron sulphate addition;
- recovery of sulphur and dust by filtering;
- disposal of filter cake;
- stripping off gases dissolved in the water and the major part of the hydrocarbons;
- partial evaporation of water and usage of condensate as scrubber make-up;
- discharge of evaporator blow down to conventional bio-treatment.

The salt recovered has a very low polluting potential, and is conveyed to a sanitary landfill. Hydrocarbons and other stripper gases are recycled in the combustor for destruction, so that the tar energy content is recovered (Barducci et al., 1997; Barducci and Neri, 1997).

Because of the complexity of treatment and disposal, the present trend is to develop a system that does not produce a liquid effluent (Bridgwater, 1994a), nevertheless this is possible only for wastes that do not contain many contaminant precursors.

9. Gasification and waste management

Gasification represents a future alternative to the waste incinerator for the thermal treatment of homogeneous carbon-based waste and for pre-treated heterogeneous waste. As shown in Fig. 15, gasification should be considered as an option for the thermal treatment of wastes in an integrated waste management system. For example, co-firing and co-gasification (gasification of solid waste with coal or biomass in the same gasifier) are interesting solutions for both decentralised energy systems and waste management systems in rural communities.

It is difficult to compare the costs of gasification processes with conventional combustion on a direct basis. This is due to the fact that the costs available refer to different specifications of plant, for example to meet different emission standards or have a varying ash content or water treatment requirements (Altmann and
Kellett, 1999). Moreover it is incorrect to compare the cost of new technology with the cost of old technology, because the former also includes the R&D cost.

10. Conclusions

The gasification process offers considerable energy recovery and reduces the emission of potential pollutants. It is considered an interesting alternative to the conventional technology for the thermal treatment of solid wastes.

The principal difficulties of solid waste gasification, especially for municipal solid waste (MSW), are related to the heterogeneity of wastes. A possible solution is the production of a refuse derived fuel (RDF) with homogeneous and controlled characteristics. In any case, gasification is particularly suitable for many homogeneous agricultural and industrial wastes (waste tyres, paper and cardboard wastes, wood wastes, food wastes, etc.).

Gasification plants could be integrated with pre-existing industrial and thermoelectric plants, because of their flexibility and compactness. The most significant choices of design are the reactor type and process cycle, which can be conveniently adopted according to waste characteristics.

The main components of gasification plants for the recovery of energy from solid wastes are discussed while describing and comparing the possible technological options and their environmental impacts. Several industrial scale applications are discussed and future perspectives of gasification are introduced.

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