Regional Center of Competence
Environmental Risk Analysis and Monitoring

Department of Environmental Sciences
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Fluidized Bed Gasifier

for Alternative Fuels

Technical manual edited by:

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Indice

The framework

As the quantity of solid wastes continues to rise, decision-makers are looking for more sustainable waste management techniques, which focus on greater value recovery from waste and easier plant acceptance by the interested people.

In the last decade, a number of novel and, in some cases, innovative technologies utilizing gasification (and pyrolysis) processes have emerged to address these issues and to improve the value of energy or materials outputs. Several technical reports [1-4] shoved that such systems offer some benefits in terms of recycling and public acceptance [5]. This is mainly due to the possibility of combining the type of starting waste, the operating conditions and the features of the specific reactor in order to obtain a syngas that can be utilized in different applications. The range of products immediately obtainable from syngas extends from bulk chemicals like ammonia and methanol, through industrial gases, to utilities such as clean fuel gas and electricity. Many of these direct products are only intermediates toward other products closer to the consumer market (such as acetates and polyurethanes). However, most of these processes of solid waste gasification are new, and then are less proven in operation than conventional technologies [1, 4, 6].

AMRA aims to cover some of the areas of technical uncertainty by proposing research projects that utilize fluidized bed gasifiers of different size (from bench scale to pre-pilot and pilot scale), operated under various operating conditions, with various gasification agents and with wastes and alternative fuels of high interest.

Why gasification?

In its widest sense the term gasification covers the conversion of any carbonaceous fuel to a gaseous product with a useable heating value. This definition excludes combustion, because the product flue gas has no residual heating value. It does include the technologies of pyrolysis, partial oxidation, and hydrogenation [6].

The gasification of carbon-based solid and liquid materials has been around for nearly two hundred years and was used extensively for the production of town gas in the latter part of XIX and XX centuries. Numerous advancements have been made since its introduction, leading to a more cost-competitive, thermally efficient, and environmentally friendly technology.

The main advantages that gasification has over incineration can be listed as in the following:

- **gasification is the only technology that offers both upstream** (*feedstock flexibility*) **and downstream** (*product flexibility*) **advantages.** All C-containing feedstocks, including municipal solid wastes, RDF, sewage sludge, biomass and plastic wastes, can be gasified after proper preparation to produce clean synthesis gas for further processing, i.e. for the production of electricity, steam, hydrogen, transportation fuels, and chemicals.
- **gasification produces an energy carrier.** Feedstock energy of the waste is transferred to the syngas, rather than all converted into thermal energy of flue gas. In this way it can be stored and used when and where it is more useful. The following reactions

  $C + {}^{1}/_{2}\, O_2 \rightarrow CO$ -111 MJ/kmol
  $CO + {}^{1}/_{2}\, O_2 \rightarrow CO_2$ -283 MJ/kmol
  $C + O_2 \rightarrow CO_2$ -394 MJ/kmol

  show that by “investing” 28% of the heating value of carbon in the CO production, 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, in modern processes, generally between 75 and 88%. Were this value only 50% or lower, gasification would probably never have become such a commercially successful process [6].
- **gasification can reach high thermal efficiencies with competitive capital costs.** On-going projects for power generation indicate that efficiencies between 45 and 50% will be rea-

ched within 2010 (with capital costs of about 800€/kWe) and between 50 and 60% within 2020 (with capital costs of about 700€/kWe) [7].

- **gasification can be readily adapted with advanced technologies for the concentration of CO_2 with limited impact on cost and thermal efficiency.** The ability of a technology to achieve higher efficiencies and concentrate CO_2 with minimal impact on the cost of final products will be major factors in technologies selection for future energy plants.
- **gasification provides a feasible and economical route to produce an H_2-rich gas**, which can then be used as syngas for production of chemicals or hydrogen.
- **gasification is economically competitive with combustion for municipal and industrial waste management** having capital costs that, for the various proposed technologies, can range from 60 to 250€ per t/y installed (to be compared with a range 130-230 for incinerators) and gate fee that range between 30 and 100€ per t/y installed (to be compared with a range 40-60 for incinerators with capacity larger than 200,000t/y) [8-11].
- **gasification produces a flue gas that is typically about 1/3 of that from a conventional combustion plant.** These lower volumes of gas to be processed translate to lower capital costs for pollution prevention.
- **gasification generates non hazardous solid residues that can be used in construction materials without added disposal costs or further processed to produce value-added products.** Together with the easy removal of sulphur and nitrogen oxides, volatile mercury and other pollutants, this determines the possibility to approach "a near-zero" levels of emissions when required.

Combustion plants are widely used and offer a great reliability, but gasification plants are however utilized worldwide: more than 128 plants in operation, with more that 400 gasifiers that produce about 45,000MWth of synthesis gas.
It is utilized:
- 21% for power production;
- 28% for fuel production;
- 42% for chemicals production.

There is a general belief that in the 21st century gasification will be the hearth of a new generation of energy plants, possessing both feedstock and product flexibility, near-zero emission of pollutants, high thermal efficiency and capture of carbon dioxide, and low feedstock and operating and maintenance costs. In particular, with the development of CO_2 sequestration technologies and the large reserves of different C-based feedstocks in the world, gasification-based systems are poised to be the technology of choice during the transition from a *Carbon-based* to a *Hydrogen-based* economy [1, 12].

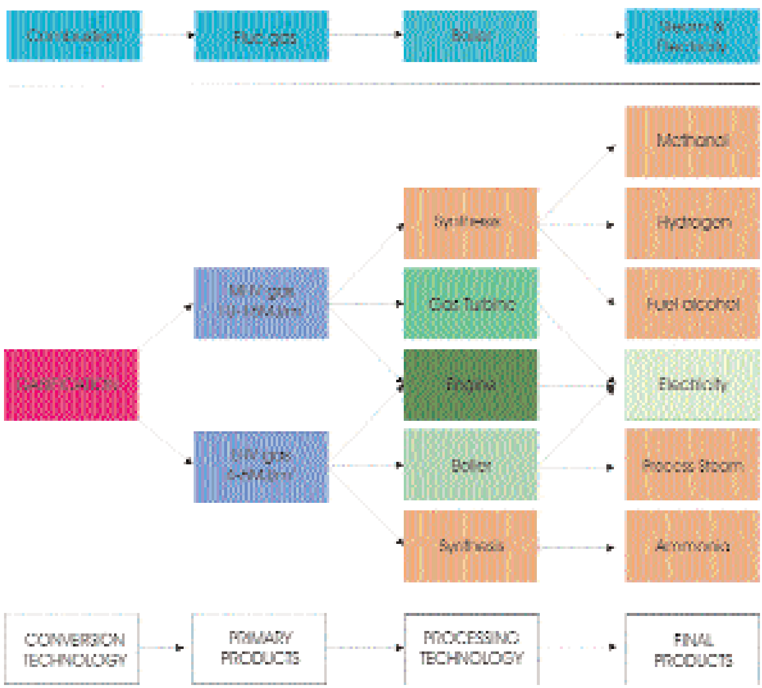

Fig. 1. Comparison between combustion and gasification technologies, with an indication of possible final products [3].

Why fluidized bed reactors?

Different technical reports analyzed in details technical and economical features of the main gasification (and pyrolysis) processes for municipal solid wastes, plastic wastes, auto-shredder residues, tires and other wastes, carried out with different gas-solid reactors [10, 13, 4].

The results confirm that fluidized bed technology appears now mature and particularly attractive. This comes from several reasons.

The rapid and good mixing of solids leads to almost uniform isothermal conditions throughout the reactor, so allowing a reliable process control. The large thermal flywheel of well-mixed bed solids resists to rapid temperature changes and avoids formation of cold or hot spots. The heat and mass transfer between gas and particles are high when comparing with those of other gas-solid reactors. This provides for uniform products (that are not constrained in their application) and allows short residence times in a range of operating temperatures generally lower than that of the same process carried out in other gas-solids reactors. The good quality of contact between gas and solids reactants increases their fractional conversions [4, 14]. The liquidlike flow of particles allows continuous controlled operations with easy handling. In particular, the circulation of solids between two fluidized beds makes possible to design and operate modular systems with two fluidized reactors connected to each other (for instance, to remove or add the high quantities of heat produced or needed in large reactors) as well as to substitute part of the (sticky or agglomerated) bed materials with fresh solids. The great operating flexibility makes possible to utilize different fluidizing agents, reactor temperatures and gas residence times, to add reactants along the reactor freeboard or riser and to operate with or without a specific catalyst. The absence of moving parts in the hot regions and the lower operating temperatures reduces maintenance times and costs. The possibility to implement the process also on a reduced scale (about 30kt/year) makes wider the range of investment alternatives. Moreover, the gasi-

fication processes in a fluidized bed reactor appear really flexible, as demonstrated by the pilot-plant and demonstration-scale investigations that several companies and research groups are carrying out [14].
On the other hand, the risk associated with a less proven technology is a main disadvantage, particularly taking in mind the highly heterogeneous nature of feeds like MSW. Some technical challenges yet present are: higher power production efficiency, improved syngas cleaning to meet required specification, ability to produce a vitrified slag, the necessity to limit the chlorine content in the inlet stream. Moreover, and above all, there is still a lack of reliable assessments on the scale and operating conditions under which a full economic convenience of the fluidized bed gasification of wastes is obtainable [15, 4].
On the basis of the considerations schematically reported above, it appears of interest to acquire a deeper knowledge of fundamental and technological aspects related to the fluidized bed gasification process. The focus of the research activity will be on the reactor performances (in terms of yield and composition of products) necessary to obtain an adequate environmental and economic exploitation of produced syngas.

Comparison between processes of thermal treatments of solid wastes

The three main processes of thermal treatment of solid wastes distinguish on the basis of different oxygen content in the reacting environment:

1. **combustion**, that obtains a complete and fast oxidation of organic fraction of the feedstock, in a highly oxidizing environment, together with a remarkable release of thermal energy. The reaction products are completely oxidized.
2. **gasification**, that converts carbonaceous materials to a gaseous product with a useable heating value through a process involving reactions of the feedstock in a reducing atmosphere with oxygen-containing reactants (usually air, oxygen, steam or carbon dioxide) at temperatures generally higher than 800°C.

The chemical reactions are: combustion, Boudouard, water gas and methanation reactions. Table 1 lists all of them for pure carbon and for real fuels. Most of industrial gasification process is auto-thermal, i.e. it needs no or limited external heat. The producer gas is essentially a mixture of CO, H_2, CO_2, H_2O, N_2 and CH_4, but it also contains some pollutants, like fine particles of non-reacted carbon (char), ash, tar and condensable liquids. After the clean-up, the syngas - which has an heating value that ranges from a minimum of 4-7 MJ/m^3_N (obtained by gasification with air, which produces a nitrogen content up to 60%) and a maximum of 10-18 MJ/m^3_N (obtained by gasification with oxygen, which needs pure oxygen with high investment and operating costs) - can directly be utilized in boilers, engines or gas turbines to heat and power production or in manufacturing of chemicals like ammonia, methanol, and others.

Table 1. Main chemical reactions in the gasification process.

Reaction for pure C				
combustion reactions	1	$C + {}^1/_2\ O_2$	$\rightarrow CO$	-111 MJ/kmol
	2	$CO + {}^1/_2\ O_2$	$\rightarrow CO_2$	-283 MJ/kmol
	3	$H_2 + {}^1/_2\ O_2$	$\rightarrow H_2O$	-242 MJ/kmol
the Boudouard reaction	4	$C + CO_2$	$\Leftrightarrow 2\ CO$	+ 172 MJ/kmol
the water-gas reaction	5	$C + H_2O$	$\Leftrightarrow CO + H_2$	+ 131 MJ/kmol
the methanation	6	$C + 2\ H_2$	$\Leftrightarrow CH_4$	- 72 MJ/kmol
Reactions for real fuels				
		$C_nH_m + {}^n/_2\ O_2$	$\Leftrightarrow n\ CO + {}^m/_2\ H_2$	
		$C_nH_m + n\ H_2O$	$\Leftrightarrow n\ CO + ({}^m/_2 + n)\ H_2$	

3. **pyrolysis**, that implies not the oxidation but the thermal degradation of the organic materials, at temperatures in the range 400-800°C and in absence of oxygen. The main process products are gaseous fuels, organic liquids and a solid residue. The relative amounts of these products depend on the nature of the feedstock, the process operating conditions (in particular, lower temperatures lead to a larger fraction of

liquids while higher temperatures lead to a larger fraction of syngas). It is noteworthy that the waste must be dried before the pyrolysis reactions can occur and that both drying and pyrolysis are endothermic processes, i.e. they require an external source of heat.

Some of the key differences between the three processes are summarized in Table 2.

Table 2. Main differences between the processes of combustion, gasification and pyrolysis.

	COMBUSTION	**GASIFICATION**	**PYROLYSIS**
Aim of the process	To maximize the conversion of feedstock to CO_2 and H_2O (production of high-temperature gas)	To maximize the conversion of feedstock to CO and H_2 (production of high heating value gas)	To maximize the conversion of feedstock by means of thermal degradation to gas (hydrocarbons) and oils
Operating conditions			
Reaction environment	Highly oxidizing environment (large quantities of excess air)	Reducing environment (limited quantities of oxygen, less than the stoichiometric)	Absence of oxygen
Temperature	Below the ash melting point	Generally higher than 800°C (above the ash melting point)	Between 500°C and 800°C (below the ash melting point)
Pressure	Generally atmospheric	From atmospheric to high pressure (up to 40bar)	Slightly higher than atmospheric
Reagent gas	Air	Steam, oxygen, air, carbon dioxide	None

(continue)

Table 2. Main differences between the processes of combustion, gasification and pyrolysis *(follow)*.

	COMBUSTION	GASIFICATION	PYROLYSIS
Process output			
Produced gas	CO_2, H_2O	CO, H_2, CO_2, H_2O, CH_4	CO, H_2, CH_4 and typically C_nH_m with n>5
Pollutants	SO_2, NO_x, HCl	H_2S, HCl, COS, NH_3, HCN, tar	H_2S, HCl, COS, NH_3, HCN, tar
Ashes	Often dry (mineral matter converted to bottom ash and fly ash)	Often glassy (mineral matter converted to glassy slag and fine particulate matter)	Often with a not negligible carbon content
Gas clean up			
	At atmospheric pressure	Even at high pressure	At atmospheric pressure
	Treated flue gas discharged to atmosphere	Treated syngas used for chemical production and/or power production (with subsequent flue gas discharge)	Treated gas used for chemical production and/or power production (with subsequent flue gas discharge)
	Fuel sulphur converted to SOx and discharged with flue gas	Recovery of sulphur as by product	
Residue and Ash/Slag Handling			
	Bottom ash and fly ash collected, treated, and disposed as hazardous or non-hazardous wastes depending on composition	Slag is non-leachable, non-hazardous and suitable for use in construction materials	Bottom ash and fly ash collected, treated, and disposed as hazardous wastes or recycled in construction materials
		Fine particulate matter recycled to gasifier or processed for metals reclamation	

The market of main thermal processes for solid wastes

Recent technical investigations about the more interesting technologies for municipal and industrial solid wastes [2, 4] indicate that gasification or pyrolysis processes, including those that combine both of them, are in several countries at the development state and, in some cases, are ready for industrial utilization. In Japan, in particular, and in the oriental area in general, the activity has been frenetic since 2000 and so far the market is not yet saturated [3, 15]. Since 2001 the number of new gasification plants for waste treatment is higher than that of new incinerators. In Europe there is a great interest and several programs, even though the failures of some initiatives created some perplexities. The situation is similar in Canada and in Australia.
In the USA the large availability of sites for landfills and the low cost of disposal created an increase in the interest of operators only in the last months.

The FluGas gasifier

Researchers of the "Waste management and industrial emissions" group of AMRA are active since several years in the field of thermolysis of different wastes. They form one of the rare European research centres focused on experimental investigation on fluidized bed gasification and pyrolysis of plastic wastes[1].
This AMRA research group completed in 2004 the preliminary design of a pilot scale fluidized bed gasifier, having a feedstock

[1] They cooperate with some foreign Universities; carried out more Ph.D. projects in the last years; produced more than 15 papers on international scientific journals (*Polymer Degradation and Stability*, *American Institute of Chem. Eng. Journal*, *Fuel*, *Chemical Eng. Science*, etc.); not less than five research projects in the specific field already financially supported by European Community, National programs or private companies.

capacity of about 60kg/h and received a financial support from European Community equals to 540k€ for the reactor and 800k€ for the diagnostic apparatus. The executive design and the construction was given to ANSALDO RICERCHE s.p.a. that installed the plant inside the industrial site of Le Calorie S.p.A. in Caserta, close to Naples (Figure 2).

Fig. 2. The Le Calorie S.p.A. industrial site with the indication of area for activity of Amra and that of Department of Environmental Sciences of Second University of Naples.

AMRA proposes research projects that utilize this fluidized bed gasifier under different operating conditions of gasification process for pre-treated municipal solid wastes and post-consumer packagings.
The final aim is making clearer and better defined the technical and economic framework of waste gasification. This will allow an easier and more reliable transfer to companies, even of a medium-small size, that operate in the field of energy and material recovery from municipal solid wastes, in particular those coming from post-consumer packagings.

In the following, some items of research interest are listed:

- it is not yet well investigated the possibility of obtaining different type of products (in gaseous, liquid and solid phases) by varying the operating conditions (mainly, temperature and residence time), the type of gasification agent (air, air and steam or others) and the hydrodynamic conditions (by modifying fluidization velocity and bed material type). As a consequence, the potential market of gasification processes, in particular those carried out in fluidized bed reactors, is likely to be under-estimated.
- there is yet a large lack of knowledge about the gasification behaviour of mixtures of packaging-derived fuels.
- it is very limited the knowledge about the possible improvement of yield and selectivity by means of the addition of various reactants (oxygen, carbon dioxide and steam) at different levels along the freeboard.
- the *in-bed* and *over-bed* feeding systems do not reached so far an acceptable level, in terms of both design of components and criteria of operation.
- the extent of different safety aspects (in the start-up and shut-down, in the normal operation, during reactor and line maintenance, in the storage and handling of solids and blast agents), is always a crucial part of understanding the technology itself and, in this respect, gasification is no different from many other technologies. The possibility of applying the waste gasification process on smaller scales makes then crucial all the aspects related to safety management [16].

The AMRA FluGas reactor is very well equipped as it can be deduced by the main technical features listed in Table 3. This should allow a wide investigation on the matters listed above, by providing a potentially useful technological transfer to companies active in the field.

Moreover, the Department of Environmental Sciences of the Second University of Naples already located in the same area of AMRA gasifier, a group of laboratory scale reactors (Figure 3). These will allow, on a reduced scale, all the necessary preliminary tests to evaluate the potential problems that have to face under the different operating conditions with the pilot plant. In the same area, inside an adequately conditioned envi-

ronment, AMRA also located some high-level diagnostic and analytical instrumentations.
Table 4 schematically describes the *facilities* that are already available in the experimental area AMRA-Le Calorie.

Table 3. Main design and operating features of the FluGas gasifier.

Geometrical parameters	Internal diameter: 0.381 m Total height: 5.90 m Reactive zone height: 4.64 m Wall thickness:12.7 mm
Fuels	RDF, pre-treated residual wastes, plastic wastes, biomass and pulper residues
Feedstock capacity	30-60 kg/h (depending on the type of fuel)
Feeding equipments	In-bed (water cooled) and Over-bed (air cooled) screw feeders
Gasifying agents	air, oxygen, steam, carbon dioxide (alone or as mixture)
Nominal temperature	850°C
Flue gas treatments	Cyclone Scrubber Flare
Safety equipments	Water seal Safety valves Rupture disks Alarms Nitrogen line for safety inerting
Mean process variables	Reactor temperature Reactor pressure Bed height Fluidizing velocity Blast flow rate Equivalence ratio*

* The equivalence ratio is the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio.

Table 4. Main facilities available in the experimental area AMRA – Le Calorie.

Reactor	Available auxiliary equipments	Utilization
BFB 25mmID, batch operated	Withdrawal of gas from the reactor top. Discharge of the whole bed in a special apparatus for the instantaneous quenching of bed components.	It can be used in order to obtain kinetic data since it allows to recover the bed at fixed times by stopping any reaction by means of a fast quenching.
BFB 55mmID, with continuous fuel feeding	Withdrawal of gas from the reactor top. Sampling line with quenching of gas and liquids. Feeding device for fuel pellets. On-line gas-cromatograph. Acquisition system for pressure and temperature data.	This BFB reactor has been already used to study the problems related to the interactions between bed particles and molten polymers fed during pyrolysis process. It can be utilized also as gasifier in order to give information about syngas composition obtainable under various operating conditions.
BFB 102mmID, with continuous fuel feeding	Withdrawal of gas from the reactor top and from an intermediate height corresponding to the bed surface. Sampling line with quenching of gas and liquids. Feeding device for fuel pellets. On-line gas-cromatograph. Acquisition system for pressure and temperature data.	This BFB reactor can be used as pre-pilot gasifier and it can give information about syngas composition and yield. It is possible to obtain data about the scale effect by analysing data obtained by the two BFB reactors (55mmID and 102mmID). The possibility to obtain samples of gas at bed surface will allow to distinguish the effect of primary reactions from those of freeboard reactions.

(continue)

Table 4. Main facilities available in the experimental area AMRA – Le Calorie *(follow)*.

Reactor	Available auxiliary equipments	Utilization
BFB pilot-scale 381mmID, with continuous feeding of fuel and inert material	Withdrawal of gas from the reactor top and from an intermediate height corresponding to the bed surface. Feeding devices for fuel pellets. On-line gas-analyzer. Software for pressure, temperature and flow rate data acquisition and control. Scrubber for gas treatment and flare for syngas combustion.	This gasifier can be operated under the same conditions investigated with the lab- and pre-pilot- scale BFBs. The aim is to verify the performance of the process in a reactor having a scale comparable with those of commercial plant.
Laboratory for chemical analyses and other diagnostic investigations	On-line analyser for CO, CO_2, O_2, H_2, CH_4. TG-DTG coupled with MS. Gas-cromatograph with MS. HPLC with MS. ICP with MS. SEM microscope.	

Fig. 3. Laboratory scale fluidized bed reactors in the area of Le Calorie S.p.A. that is available for the experimental activity of the Department of Environmental Sciences of Second University of Naples.

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