CHEMICAL ENGINEERING TRANSACTIONS Volume 24, 2011
Editor Sauro Pierucci
Copyright © 2011, AIDIC Servizi S.r.l., ISBN 978-88-95608-15-0 ISSN 1974-9791
DOI: 10.3303/CET1124005

Solid Waste and Biomass Gasification: Fundamental Processes and Numerical Simulation

Deborah Panepinto*, Giuseppe Genon

Politecnico di Torino, Dipartimento DITAG
C.so Duca degli Abruzzi 24, 10129 Torino (Italy), deborah.panepinto@polito.it

With the aim to study the fundamental processes of MSW (Municipal Solid Waste) gasification scheme and to obtain a comparison with existing thermal utilization schemes, an useful model was realized by using the tools of energy and mass balances, and of chemical homogeneous gas equilibrium (as concerns the residual solid, it was assumed that it is constituted only of inert material). By using this model, with numerical simulation we evaluated the influence of air volume on the most important operating parameters: temperature, flue gases volume, gas heating value, gasification yield (η). On the basis of existing data and the obtained results about syngas flow rate and composition we performed a comparison between gasification and direct combustion (considered environmental performances and energetic production aspects).

1. Introduction

The energetic valorization of biomass is a very important perspective, in order to give a correct destination to large flows present in many areas, and to obtain energy generation in a consistent manner, with positive aspects in terms of limitation of local impact, and also as concerns the generation of greenhouse gases. With these aims the gasification technology purpose is to transform the solid fuel into a combustible gas stream and subsequently to operate energy recovery from this gas. It is necessary to evaluate the value of this technology in terms of energy efficiency and also with reference to the creation of pollutants, in comparison with conventional combustion systems. On this basis, in this paper after a definition with a predictive calculation of the syngas quantity and quality, the energy yield has been evaluated; afterwards the emissive profile of gas combustion systems, taking into account the working conditions, has been obtained. The so determined values were compared with the energetic and environmental ones for conventional systems; this comparison will offer suitable data about the feasibility and advantages of innovative solutions.

2. Processes and technologies for gasification

The gasification treatment for a homogeneous flow of a solid fuel this is a well established technology in industrial applications: it could be applied to heterogeneous

Please cite this article as: Panepinto D. and Genon G., 2011, Solid waste and biomass gasification: fundamental processes and numerical simulation, Chemical Engineering Transactions, 24, 25-30
DOI: 10.3303/CET1124005

flows but in this case some specific aspects must be considered (feed composition, physical state, thermo-technical characteristics) (ATO-R, 2010; Belgiorno V. , 2003; Malkow T, 2004; Cuoci A. et al., 2009). From the point of view of plant, there are several constructive solutions operating on the market (ATO-R, 2010), which must be carefully evaluated. The produced syngas must be destined to energetic uses in combustion plants (for the moment we do not considerer more attractive but today not currently technologically mature options for innovative use, as production of chemicals, use in fuel-cells, production of grid immitted methane). About energetic use, the choice of the particular solution for combustion operation determines the syngas pretreatment necessity, the energetic yield of the production scheme and the quality of emissions. The first of the above mentioned topics decidedly requires difficult operations, in account of the very high presence, multiplicity and complexity of pollutants (dust, tar, acid gases) that must be removed; on the other hand this operation is fundamental in order to arrive to solutions of particular efficiency as concerns the energetic utilization (internal combustion engines, gas turbine systems), as an alternative to traditional solutions, today the most used (combustion in boiler with coupled steam cycle or Rankine organic cycle); from gross yields of 28 to 31% of conventional systems it is possible to arrive to 37 to 41% with alternative engines, and up to 50% with gas turbines in combined cycles. It is fundamental to evaluate the aspect of quality of emissions from the thermal system; reliable informations on the levels of pollutants (mainly dust, NO_x, CO) in different configurations are available. The definition of the potential environmental impact is, in addition to the aforementioned aspect of energy production, a fundamental aspect of the evaluation.

3. Calculation model

For a predictive evaluation the mass and energy balances and the chemical homogeneous gas phase equilibrium able to regulate the development of the process were defined; with this aim a model directed to the gasification simulation was built. By using this model it was possible to evaluate the syngas volume, its composition and as a consequence the energetic yield of the thermal conversion process. The constructed model has been applied, in order to evaluate the difference in the results, both at no pre-treated MSW and also to pre-treated MSW (RDF, Refuse Derived Fuel).

3.1 Equations system

In order to establish the quality and the quantity of the syn-gas arising from a solid material of known composition after gasification in presence of a fixed gasifying flux, we defined six conditions (1 energy balance, 3 mass balances conditions, 2 chemical homogeneous gas equilibrium); with these conditions it was possible to calculate, for a fixed temperature, the specific parameters, syn-gas quality and oxygen in air flux in input, that are indicated in Table 1.

Table 1: Gaseous phase and input oxygen definition

α	**β**	**γ**	**δ**	**ε**	**Φ**
CO	CO_2	CH_4	H_2	H_2O	O_2

- Energy balance

$$LHV_{MSW} = LHV_{CO} \cdot \frac{\alpha}{PM_{CO}} + LHV_{CH_4} \cdot \frac{\gamma}{PM_{CH_4}} + LHV_{H_2} \cdot \frac{\delta}{PM_{H_2}} + \left[cp_{CO} \cdot \alpha + + cp_{CO_2} \cdot \beta + cp_{CH_4} \cdot \gamma + cp_{H_2} \cdot \delta + cp_{H_2O} \cdot \varepsilon + cp_{bottomAsh} \cdot \%bottomAsh + cp_{N_2} \cdot \frac{N_2}{O_2} \cdot \varphi + + cp_{S_2} \cdot \%S_2\right] \cdot T \qquad (1)$$

- Mass balance (balance for oxygen, carbon and hydrogen):

1) $$\frac{PM_O}{PM_{CO}} \cdot \alpha + \frac{PM_{O_2}}{PM_{CO_2}} \cdot \beta + \frac{PM_O}{PM_{H_2O}} \cdot \varepsilon = \%O_2 + \varphi + \frac{PM_O}{PM_{H_2O}} \cdot \%H_2O \qquad (2)$$

2) $$\frac{PM_C}{PM_{CO}} \cdot \alpha + \frac{PM_C}{PM_{CO_2}} \cdot \beta + \frac{PM_C}{PM_{CH_4}} \cdot \gamma = \%C \qquad (3)$$

3) $$\frac{2 \cdot PM_{H_2}}{PM_{CH_4}} \cdot \gamma + \delta + \frac{PM_{H_2}}{PM_{H_2O}} \cdot \varepsilon = \%H_2 + \frac{PM_{H_2}}{PM_{H_2O}} \cdot \%H_2O \qquad (4)$$

- Equilibrium conditions derived from the two main chemical reactions that regulate the process (reaction of water gas shift conversion and methanation reaction):

$$CO + H_2O \longleftrightarrow CO_2 + H_2$$

$$CH_4 + H_2O \longleftrightarrow CO + 3H_2$$

In the construction of the model the following assumptions have been used:

- the reactor is considered to be adiabatic;
- the solid residue that is derived from the gasification process has been considered as constituted only by inert material;
- the nitrogen is considered an inert in the system;
- the presence of condensed material (tar) in the syn-gas has been disregarded (it is considered that all the organic components that are present in the inlet solid flux are completely transferred in the gaseous derived flux).

3.2 Testing and results

As previously indicated the model has been applied to a feed constituted by MSW and also RDF. In the following table we report the calculated variations of operating temperature, syn-gas LHV (Lower Heat Value) and syn-gas volume as a function of the introduced air/solid ratio.

Table 2: Variation of operative parameters for a fixed air capacity

	T		**LHV**		**Flue gas**	
AIR	°C		kJ/Nm^3		Nm^3/kg	
Nm^3/kg	MSW	RDF	MSW	RDF	MSW	RDF
2,8	640	880	2.216,654	2.336,045	3,75	3,72
3,2	820	1.080	1.672,650	1.730,939	4,10	4,04
4	1.170	1.410	731,515	737,990	4,73	4,68

From the obtained results it can be observed that with the same air flow-rates, in connection with use of MSW or RDF, the gasification temperature is different. From the other side, if we keep the temperature more or less constant, we observe that the syn-gas LHV is higher in case of RDF in comparison with MSW, while the required input air volumes, and in a similar way the generated syn-gas volumes are different (they are generally higher for the feed constituted by MSW). In order to demonstrate the variation of syn-gas quality and heating value, in the following Table 3 we report the composition of it as a function of air/solid gasification ratio.

Table 3: Syn-gas composition (%) for MSW and RDF

	2,8 Nm^3/kg		**3,2 Nm^3/kg**		**4 Nm^3/kg**	
	MSW	RDF	MSW	RDF	MSW	RDF
CO	7,61	11,07	7,42	9,23	4,18	4,60
CO_2	12,43	9,51	11,29	9,70	12,01	11,73
CH_4	0,411	0,001	0,001	0,00003	0,0001	0,0003
H_2	10,28	8,70	6,83	5,24	1,89	1,46
H_2O	8,30	9,50	10,92	11,51	13,47	12,98
N_2	60,97	61,22	63,55	64,32	68,45	69,24

In the following Table 4 the results as concerns the yield calculation as a function of the type of fed material and in dependence of the gasification temperature are reported.

Table 4: Influence of temperature on yield for different original materials

	T [°C]				
	800	**900**	**1.000**	**1.100**	**1.200**
η_{MSW}	0,59	0,51	0,44	0,35	0,26
η_{RDF}	0,68	0,62	0,59	0,56	0,43

These results can be considered the calculated starting point for the following elaboration (energetic yield and emission pollutant flux) that will be discussed.

4. Comparison between gasification and direct combustion

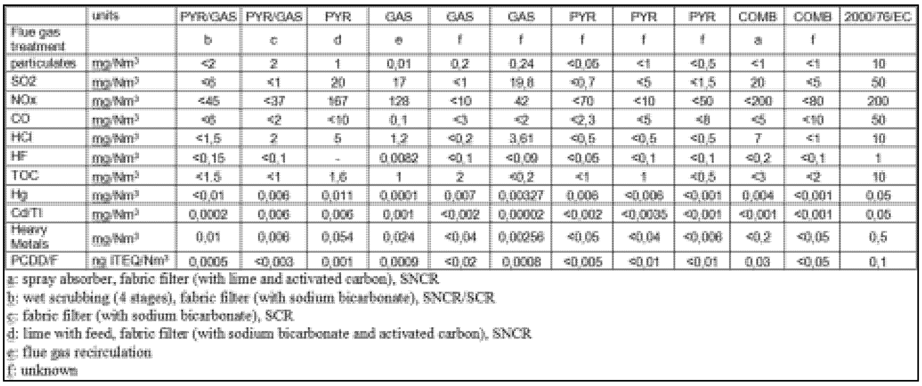
A comparison between incineration and gasification has been carried out as concerns the energy recovery and the environmental impact (in terms of air emissions), by using both literature data and specific evaluations. From the point of view of the energetic aspect, from the indicated analysis it was possible to observe that by using a boiler recovery system, the yield is higher in direct combustion (see the literature data showed in Table 5). On the contrary in case of syn-gas energetic utilization in engines or turbo gas systems the yield is higher in comparison with the previously indicated modalities.

Table 5: Net electrical efficiencies claimed by technology suppliers (Fichtner, 2004)

	Combustion	**Gasification and Pyrolysis**		
	Steam Cycle	Steam Cycle	Gs Engine	CCGT
η electric [%]	19 - 27	9 - 20	13 – 24	23 - 26

Now it is very interesting to examine the environmental aspects, as they are reported in Table 6 (Arena U. et al., 2010; Waste Management Plan, 2009), where real scale experimental results are considered. In this table the considered concentrations are measured in the flue gas at chimney (data derived from the analysis of a large number of plants). As concerns the data it is necessary to specify that all the considered processes use, for the energetic recovery, a steam cycle and that all the concentrations are referred to the same conditions (dry gas, 11 % of O_2).

Table 6: Environmental performances of main thermal waste treatment processes



	units	PYR/GAS	PYR/GAS	PYR	GAS	GAS	GAS	PYR	PYR	PYR	COMB	COMB	2000/76/EC
Flue gas treatment		b	c	d	e	f	f	f	f	f	a	f	
particulates	mg/Nm^3	<2	2	1	0,01	0,2	0,24	<0,06	<1	<0,5	<1	<1	10
SO2	mg/Nm^3	<6	<1	20	17	<1	19,8	<0,7	<5	<1,5	20	<5	50
NOx	mg/Nm^3	<45	<37	167	128	<10	42	<70	<10	<50	<200	<80	200
CO	mg/Nm^3	<6	<2	<10	0,1	<3	<2	<2,3	<5	<8	<5	<10	50
HCl	mg/Nm^3	<1,5	2	5	1,2	<0,2	3,61	<0,5	<0,5	<0,5	7	<1	10
HF	mg/Nm^3	<0,15	<0,1	-	0,0082	<0,1	<0,09	<0,06	<0,1	<0,1	<0,2	<0,1	1
TOC	mg/Nm^3	<1,5	<1	1,6	1	2	<0,2	<1	1	<0,5	<3	<2	10
Hg	mg/Nm^3	<0,01	0,006	0,011	0,0001	0,007	0,00327	0,006	<0,006	<0,001	0,004	<0,001	0,05
Cd/Tl	mg/Nm^3	0,0002	0,006	0,006	0,001	<0,002	0,00002	<0,002	<0,0035	<0,001	<0,001	<0,001	0,05
Heavy Metals	mg/Nm^3	0,01	0,006	0,054	0,024	<0,04	0,00256	<0,05	<0,04	<0,008	<0,2	<0,05	0,5
PCDD/F	ng ITEQ/Nm^3	0,0005	<0,003	0,001	0,0009	<0,02	0,0008	<0,005	<0,01	<0,01	0,03	<0,05	0,1

a: spray absorber, fabric filter (with lime and activated carbon), SNCR
b: wet scrubbing (4 stages), fabric filter (with sodium bicarbonate), SNCR/SCR
c: fabric filter (with sodium bicarbonate), SCR
d: lime with feed, fabric filter (with sodium bicarbonate and activated carbon), SNCR
e: flue gas recirculation
f: unknows

If we carefully examine the data that are reported in Table 6 it is possible to observe that for acid gases (SO_2, HCl, HF) the emission concentrations are dependent on abatement devices, for suspended particles, CO and NO_x on combustion conditions (T, air excess, residence time), for metals and for the micro-pollutants on gasification conditions (T, oxygen content, residence time, etc). More in general we can establish that if we compare the performances of the two systems in term of concentrations in the flue gas, the results are similar and convenient after an adequate treatment system.

In comparison with these results in Table 7 we report a comparison obtained by means of mass balance, by using the same procedure previously indicated in paragraph 3.1.

Table 7: Energy and environmental performances

	COMBUSTION	**PYR/GASIFICATION**
RDF input (kg/h) @3600 kcal/kg	956	885
Thermal input (kW)	4.000	3.704
Overall gross electrical efficiency (%)	25	27
fuel utilization (%)	25	58
power OUT (kW)	**1.000**	**1.000**
thermal OUT (kW)	0	1.148
WASTE GAS (Nm3/t RDF dry O2 referred)	6.510 (O2@11%)	4.069 (O2@5%)
particulates (mg/Nm3 O2 referred)	10	1
NOx (mg/Nm3 O2 referred)	200	100
CO (mg/Nm3 O2 referred)	50	50
TOC (mg/Nm3 O2 referred)	10	150
particulates (g/t RDF)	**65**	**4**
NOx (g/t RDF)	**1.302**	**407**
CO (g/t RDF)	**326**	**203**
TOC (g/t RDF)	**65**	**610**

With reference to the results of Table 7 it is important to observe that, as concerns the comparison of pollutant fluxes, the gasification technology seems to lead to an advantage, in particular with reference to the pollutant parameters dust and NO_x; this result arises from the fact that considerably lower NO_x and dust emissions can be obtained when syngas is recovered by gas engines equipped with the best available techniques (LEANOX, SCR, CATOX).

5. Conclusion

The aim of this work is a critical evaluation of the applicability of the gasification process for MSW treatment. For this purpose an elaboration of energy and mass balance and analysis of the chemical homogeneous gas equilibrium were used to construct a model suitable for the simulation of the gasification process. By applying this model to different feeds it was possible to establish the syn-gas volumes, the compositions and the yield of the process. Subsequently a comparison of the performances of incineration and gasification was carried out. The main derived considerations are the following:

- direct combustion of MSW lead to higher power productions if compared to syngas recovery by boilers; the use of gas engine or gas turbine for energetic recovery could allow very good fuel utilization yields without decreasing power generation;
- incineration and pyro-gasification plants in connection with a conventional steam boiler and steam turbine cycle can largely meet the fixed emissions limits; from the point of view of stack concentrations the emission levels are quite similar;
- considerably lower NOx and suspended particles emissions can be obtained for pyrolysis/gasification when syngas is recovered by gas engines equipped with the best available techniques (LEANOX, SCR, CATOX).

References

Arena U., Zaccariello L., Mastellone M.L., 2010, Fluidized Bed Gassification of Waste-Derived Fuels, Waste Management, 30, 1212-1219;

ATO-R, 2010, Verifica della fattibilità di un impianto di trattamento termico dei rifiuti a tecnologia innovative nella provincia di Torino, Ingegneria Ambientale, Quaderno 51, number 10/11;

Belgiorno V., 2003, Energy from gasification of solid wastes, Waste Management, 23, 1 – 15;

Fichtner Consulting Engineers Ltd, 2004, The viability of advanced thermal treatment of MSW in the UK, for ESTET;

Malkow T., 2004, Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal, Waste Management, 24, 57 – 79;

Waste Management Plan, 4th Annual Report June 2009-June 2010, Limerick/Clare/Kerry 2006-2011, <www.managewaste.ie> accessed 23.11.2010;

Cuoci A., Faravelli T., Frassoldati A., Grana R., Pierucci S., Ranzi E., Sommariva S., 2009, Mathematical modelling of gasification and combustion of solid fuels and wastes, Chemical Engineering Transactions, 18, 989-994.