PYROLYSIS AND GASIFICATION OF MUNICIPAL AND INDUSTRIAL WASTES BLENDS

by

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Gasification could play an important role in the treatment of municipal solid wastes. However, some problems may arise when using unsorted materials due to the difficulties of obtaining a feed with consistent physical characteristics and chemical properties. To overcome this problem, a new type of gasifier consisting of three stages, namely a pyrolytic stage followed by gasification and a reforming stage, was considered. Theoretical calculations made on the proposed gasification scheme shows better performance than a previously studied two-stage gasifier because of its ability of reaching the same final temperature of the syngas with a lower oxygen injection and a better oxygen partition ratio between the stages. The reduced amount of oxygen allows to obtain an improved syngas quality with higher return in the final products, such as hydrogen, electricity and so on.

Key words: *municipal solid wastes, no-hazardous industrial waste, gasification, three-stage gasifier, thermodynamics*

Introduction

The gasification could play an important role in the treatment of municipal solid wastes (MSW). However, unsorted MSW is not suitable for gasification technologies because of its varying composition and size of some of the constituent materials, furthermore, an increase of the dry/wet ratio to values higher than those normally available from MSW is required. All these objectives are usually obtained by the production of refuse derived fuel (RDF) or by a separate waste collection, while the increase of the dry/wet ratio can be obtained by mixing MSW with high heating value materials like no-hazardous industrial waste (NHIW). This solution, although, encouraged in some countries because the reduction of the environmental damage caused by the storage of NHIW do not solve the problem of heaving a homogeneous blend with constant characteristics for feeding the gasifier. To overcome this problem, a new type of gasifier, consisting of three stages was considered. Aim of this paper is to perform some theoretical evaluations on the energy performance of the proposed gasification system, comparing the results with those obtained in a two-stage gasifier under the same conditions.

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Process and plant description

Process

In the hypothesized process, due to the high heterogeneity of the selected wastes and the high water content of MSW, on average of 30%, a premixing and dry step of the blend was considered necessary before its use as a feedstock in a gasifier.

After water reduction to about 7%, the homogenized blend is fed to the gasifier, which consists of three stages. Stage one is a pyrolytic stage which converts the charge into char, oil, and volatile compounds and facilitates the reactions that take place at stage two where gasification occurs producing a crude syngas. At this stage an addition of CaO and Na_2CO_3 have to be considered for reducing the contents of chlorine and sulphur in syngas down to acceptable limits.

The raw syngas, which still contains a large amount of light and heavy hydrocarbons, reaches stage three where the gasification reactions are completed and reforming occurs, at this stage the raw syngas is turned into a high quality syngas [1-3] necessary if its final destination is a chemical application (methanol for instance). Both the excess of syngas and the by-product of the transformation process can be used for electric power generation.

Plant

Figure 1 shows the scheme of a hypothetical gasification plant. A real plant may differ from that to fit the local situation.

Figure 1. Hypothetical gasification plant lay-out

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The plant consists of four main sections, namely a waste storage section (not shown), a blending wastes section, the three-stage reactor, and the devices for syngas utilization (methanol and electric power production).

Taking into account the benefits already described by Plescia [4], it was included into the scheme a ball-mill, which homogenizes the wastes blend and can dry it to a water amount of about 7%.

The blend is fed into stage one by an appropriate tool. Its dropping-down is set by fins protruding the refractory wall. At the bottom of stage one, the pyrolysed blend is sent into stage two by an appropriate feeder system. Into this stage the gasification occurs and a large amount of tar and gas are produced. The ashes are collected on the bottom. Tar and gases reach stage three where they react with oxidising blends in a bed consisting of granular alumina. At the top of this stage, a Ni catalyst could be necessary if a high production of hydrogen is required. In this way, the gasifier can turn crude syngas into clean syngas. The content of tar is reduced below the law limits and the content of methane is as low as foreseen by the thermodynamic analysis.

Thermodynamic analysis

Thermodynamic model, its reliability and limits

Several models based on a thermodynamic approach were developed in the past years to simulate syngas production [1, 2, 5-9], most of which state a quite good accordance between experimental and calculated results. In this paper for estimating the composition and temperature of syngas one of these models, described in detail in previous works [1-3], was used. As reported in previous papers [2, 3, 10-11], experiments conducted in a two stage gasifier reactor at laboratory scale, shows that the composition of syngas is close to what is expected from thermodynamics if the final temperature is above 850 °C and this temperature decrease to 800 °C when a reforming catalyst (such as nickel) is present in the last stage. Under these conditions, the reactions at the final stage can be considered very fast and predictions made on the basis of heat and mass balance and thermodynamic equilibrium can be considered reliable. When the final temperatures are below 800 °C thermodynamics is not adequate giving wrong results due to kinetic aspects not considered here. As far as stages two and three, the model takes into account the heat and mass balance, higher heating value (HHV) of the feedstock, and is based on the chemical equilibrium the water-gas shift and reforming reactions. A system of five equations related to the mass balance of C, H, and O and the chemical equilibrium of the reactions mentioned above is obtained. This system is non-linear and was solved using the conventional Newton method. The thermodynamic data used for the equilibrium calculations are taken from the compilation of Barin *et al*. [12]. Stage one is treated as a heat-exchanger with an estimated efficiency of 90%. In this stage the enthalpy of the syngas allows the complete evaporation of water and the partial pyrolysis of the charge. The model assumes that the charge, which has undergone pyrolysis, reaches stage two, where it reacts with oxygen or with an oxygen-steam mixture. The obtained product reaches stage three, where there is an additional injection of oxygen or oxygen-steam mixture. Oxygen is fed at 25 °C while waste and the steam are fed at an appropriate temperature. The heat loss across the wall of the reactor is assumed, for each stage, to be 10% of the produced heat, which is typical for industrial reactors working at similar temperatures. It is also assumed that ashes leave the reactor through a grate at the bottom of stage two at the same temperature of this stage.

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In order to maximize the production of hydrogen and carbon monoxide and minimise the oxygen input, it is also assumed a reactor working pressure equal to 0.1 MPa (1 bar). A higher pressure results in higher methane content in syngas. This means additional oxygen for the reforming of methane with a consequent higher temperature.

Furthermore, the ratio between the oxygen injected in stage two and the total injected oxygen (OPR, oxygen partition ratio) is important [1], a range between 0.36 and 0.60 has examined. An OPR lower than 0.36 means a too low temperature of stage two, while a higher OPR leads to a too high final temperature. OPR lower than 0.36 can be reached by means of a further increase of the total oxygen injected but the quality of syngas is lowered.

The yield of methanol is calculated according to the experimental condition reported in reference [13], namely at about 150 °C and under a pressure of 2 MPa. In fact, under these conditions, the modern catalysts are able to reach the yield of methanol near the thermodynamic predictions [14].

Composition of waste

The selected composition of the charge to stage one is that reported in tab. 1. This composition is compatible with that of a high quality MSW [15] or with a blend of industrial waste and a low quality MSW in both cases with a low amount of moisture (ca. 7%).

Table 1. Physical and chemical characteristics of the waste used

Physical properties	
Humidity	7.00 mass%
Volatile substance (dry basis)	73.06 mass%
Fixed carbon (dry basis)	13.16 mass%
Ash (dry basis)	12.00 mass%
HHV	19.87 MJ/kg
Ultimate analysis (mass% dry basis)	
Carbon	47.60
Hydrogen	6.10
Oxygen	32.73
Nitrogen	1.20
Sulphur	0.30
Chlorine	0.07

Results

The selection of stage three temperature is the most important parameter for increasing the concentration of CO and H_2 in the syngas with a resulting increase in its quality. The higher the concentration of CO and H_2, more successful is its use as raw material in the production of methanol, dimethyl ether, or even electricity.

This means that the temperature of syngas leaving stage three must be around 800 °C [1]. A lower temperature brings an increase of the methane concentration, while a higher temperature means a higher content of steam and carbon dioxide. Both phenomena involve a decrease of the concentration in syngas of the hydrogen and carbon monoxide, with a consequent decrease of the yields of the final desired products.

The need of keeping constant the syngas temperature therefore affects the efficiency of the gasifier and hence all the comparisons carried out for the evaluation of the three-stage gasifier are performed by keeping constant the selected temperature.

To obtain a final temperature of syngas equal to 800 °C, enough for the thermal needs of the process including the steam production, stage one is preheated up to 450 °C, while the temperature of stage two is about 550 °C. The final aim is to limit the need of oxygen and to favour the consequent increasing of the quality of syngas.

As above-mentioned, an important parameter influencing the quality of syngas, at constant temperature, is the OPR. Lower is this parameter lower is the amount of oxygen injected into stage two and lower is the oxidation level of the hydrogen and carbon monoxide that reach stage three with consequent increase of their concentration, in the clean syngas. As a drawback, OPR has to be not lower than 0.36, otherwise the temperature of the final stage could be too low for obtaining a sufficient reaction rate. Moreover the need of not overcoming 800 °C in order to obtain a high-quality syngas and the need to maintain a temperature of syngas adequate for chemical utilisations after preheating, constrain the preheating and the consequent possibility to further reduce OPR and oxygen.

Table 2 quantifies this effect showing an important decrease of the amount of oxygen necessary to reach 800 °C and the consequent increase in the productivity of methanol as a function of OPR.

As the table shows, the decrease of OPR from 0.60 down to 0.36 involves a decrease of the oxygen feeding of about 12% together with an increase of 7.6% in the productivity of methanol and, therefore, without any increase of the production cost. At the same time, such a decrease of OPR involves a raise of the by-produced CO that in turn, can increase the capacity of producing electric power. Before entering in the reactor for methanol production, syngas is cooled to 150 °C giving up its excess of enthalpy for the production of steam.

Table 2. Effect of OPR on oxygen feeding and methanol productivity

OPR	O_2 [m³ (STP) per kg_{waste}]	CH_3OH [kg per kg_{waste}]
0.60	0.391	0.353
0.50	0.376	0.362
0.45	0.366	0.367
0.36	0.343	0.380

Figure 2 shows the dependence of the yield of methanol, selected as final product, on the hydrogen concentration in syngas. This dependence is justified considering that carbon exceeds hydrogen in the waste composition and this has as a consequence an excess of carbon monoxide. This excess is important in all the analysed situations and may be utilised; for instance, to produce electric power. In this figure, the regression line is calculated by taking into account the data relevant the feeding of syngas (pure O_2) and the moisture content of the waste (7%).
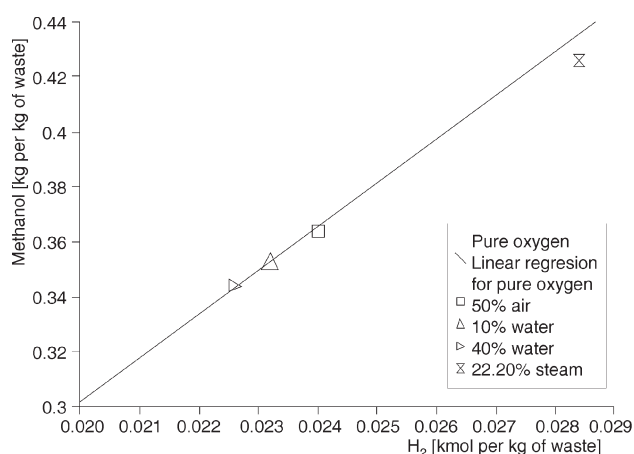

Figure 2. Methanol (kg per kg of waste) as a function of H_2 (kmol per kg of waste) in syngas

It is worthwhile to remember that the points relevant for the comparisons shown in the figure are obtained at the same operating conditions (OPR and preheating temperature of stage one) and of course at 800 °C as it regards the final syngas temperature. As far as the effect of drying the waste, fig. 2 indicates that the difference between a waste dried until to 10% and the one dried until to 7% is negligible, as the point on the line is located at the same abscissa of the point "10% water". On the contrary the difference is about 2.5% if the gasifier is fed with a waste not dried (moisture content 40%) as the difference between the point "10% water" and the point "40% water" shows. A comparison between the line at abscissa 0.025 (kmol per kg of waste), and the point "50% air", shows that the use of the mixture containing air, lowers the yield of hydrogen and methanol of about 4%, consequently.

A gaseous feeding containing an important amount of steam (22.20% of the mass of waste) and oxygen (0.383 m^3 (STP) per kg of waste) makes the yield of methanol less dependent on the hydrogen in syngas. The steam addition, in fact, renders the hydrogen input close to the carbon input. As a consequence, the point relevant this situation is below the regression line.

Comparison between two-stage gasifier and three-stage gasifier

A comparison was carried out in order to assess the performance of a three-stage reactor with respect to a two-stage one, from a thermodynamic point of view.

In the case of the two-stage reactor, the mixing of MSW and NHIW is homogenized obtained by grinding and the obtained blend is fed directly into stage one of the gasifier. Table 3 shows the results.

Table 3. Comparison between two-stage and three-stage gasifiers

	Two-stage	Three-stage	Ratio
H_2 [kmol per kg_{waste}]	0.0200	0.0249	1.083
CH_3OH [kg per kg_{waste}]	0.3400	0.3490	1.026
CO [kg per kg_{waste}]	0.5310	0.5830	1.098
O_2 [m^3 (SPT) per kg_{waste}]	0.3990	0.3430	0.860
OPR	0.5000	0.3600	0.720
Syngas [m^3 (SPT) per kg_{waste}]	1.5600	1.5600	1.000

In tab. 3, column 4 represents the ratio between the performance of the three-stage gasifier and that of two-stage gasifier. The key for analysing the result is the different amount of injected oxygen and the difference between the values of OPR. In the two-stage gasifier, the OPR should be not lower than 0.5 because otherwise the reached final temperature is too low. This results in a higher amount of oxygen necessary for reaching the final temperature of 800 °C. Taking into account the temperature of 530 °C into stage one (two-stage gasifier) or in stage two (three-stage gasifier), the preheating performed into three-stage gasifier allows at injecting a lower amount of oxygen for reaching this temperature, while the amount of injected oxygen into the final stage is the same for both gasifiers. As already mentioned, less oxygen leads to a lower amount of

steam and a higher concentration in hydrogen in the final syngas with the consequent higher yield in methanol. Moreover also the amount of CO, by-product of the methanol production, is higher.

Taking into consideration the negligible concentration of the methane in syngas, the amount of syngas produced is equal in both the case. In fact CO and H_2 are partially substituted by an equal number of moles of CO_2 and H_2O.

Regarding the impurities, as sulphur and chlorine, the result of this thermodynamic approach is that the three-stage gasifier behaves as the two-stage gasifier, reported to produce a syngas with a level of impurities below the limits of law [2, 3, 11]. This infers the ability of the gasifier at three-stages of producing a clean syngas directly.

This analysis makes it possible to assert that the performance of three-stage gasifier is higher than that of a two-stage configuration.

Conclusions

The gasifier proposed in this paper consists of a process that uses a three-stages reactor, namely a pyrolytic stage followed by a gasification and reforming stage that behaves as that of a two-stage gasifier.

This configuration allows the production of a homogeneous and clean syngas. The critical condition for the increase of the hydrogen content in syngas, and then the yield of methanol, is the temperature of syngas and therefore the amount of oxygen and steam injected.

The proposed gasifier shows better performance than a two-stage gasifier because of its ability of reaching a lower OPR and a less oxygen injection, for obtaining the same final temperature of the syngas. The need of increasing the quality of syngas and of maintaining the temperature adequate for its further uses, restricts the possibility of reducing OPR below 0.36.

In prospective, it will be necessary to go beyond of the theoretical considerations carried out and to assess the economic feasibility by a comparative cost analysis and by a life cycle assessment, verifying also the actual operability of the plant and his compliance with the best available techniques.

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