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Efficiency Evaluation of RDF Plasma Gasification Process

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Abstract

The waste management in Greece is a very important issue by virtue of the increasing of waste material. This paper is concerned with the efficiency evaluation of a plasma gasification process using RDF (Residual Derived Fuel) to produce Syngas. Plasma gasification is an advanced waste management and thermal treatment technology with exceptional environmental and energy performance. This process converts materials such as coal, biomass or other organic waste into carbon monoxide and hydrogen using very high temperatures with an amount of oxygen and/or steam (Leal-Quiros, 2004).

Regarding to the previous studies and using a previous thermodynamic chemical equilibrium model, we devised a new to be appropriate for the RDF to study the efficiency of the plasma gasification process. The total amount of waste materials was supposed 300 tn/day and the produced synthesis gas was composed of CO, H_2, CH_4, H_2O, CO_2, N_2, S and H_2S. Then, at constant temperature and humidity parameters and oxygen, using the results of thermodynamic analysis, is calculated the efficiency of the process according to the thermodynamics laws.

Conclusively, the thermodynamic modeling of plasma gasification process for the RDF treatment resulted in positive energy values. These energy results, along with the environmental characteristics of the process, demonstrate that the plasma gasification process is very useful technology for waste treatment and electricity production.

Keywords: plasma, gasification, exergy, modelling

1. Introduction

Nowadays, many countries face the problem of the excessive amounts of waste material. The developed world is presently facing major environmental problems with garbage as landfills fill up, forcing governments to transport their garbage farther away at greater expense and environmental impact. Recent studies have focused on an innovative technology, the plasma gasification that has been demonstrated as one of the most effective and environmentally friendly methods for solid waste treatment and energy utilization (Pfender, 1999).

Plasma gasification works by treating garbage and any carbon-based materials, such as plant matter or fossil fuels, with high heat from plasma torches in a controlled-air environment. Rather than burn, the materials vaporize into their basic molecular elements as gasses. The gasses are cooled and cleaned and can then be converted into electricity, or a variety of valuable fuels such as ethanol, hydrogen or natural gas. The inorganic materials are melted by the plasma torches and pour out. The molten materials then cool and harden into a vitrified glass called slag. The high heat from the gasses is recycled back into the system as steam. At the most basic level, a plasma waste converter is a plasma torch applied to garbage. A plasma torch uses gas and powerful electrodes to create plasma, sometimes called the fourth state of matter (Higman & Van der Burgt, 2007; Mountouris, 2007).

The principal product of plasma gasification is a low to medium calorific value synthesis gas composed of carbon monoxide and hydrogen. This gas can be burned to produce heat and steam, chemically scrubbed and filtered to remove impurities before conversion to various liquid fuels or industrial chemicals/polymers, or used once cleaned as a turbine or engine fuel to produce electricity. Heat energy can also be recovered via water tube heat exchangers as the hot syngas is cooled from about 2,200 to 400 ºF (Rezaiyan & Cheremisinoff, 2005).

2. Process Design

2.1 Materials

The physical and chemical features of RDF are directly dependent from the respective features of his components. Moreover, both the qualitative and quantitative features of gas and solids waste of gasification depend on the composition of RDF. Finally, the creation of RDF depends on the heat capacity. The features of RDF waste from the mechanical and composting plant of Ano Liossion (Attica Region) is:

- Produced quantity RDF: 300 tn/day.
- Moisture of RDF: 27.1%.
- Elemental analysis of RDF: The elemental analysis is shown in table below.

Table 1. Ultimate analysis for materials

Materials	RDF%	C%	H%	O%	S%	N%	Cl%	W%	A%*
Paper	78,45	27,44	3,76	25,60	0,16	0,16	0,27	36,80	5,81
Plastic	11,30	63,57	8,78	9,02	0,34	0,90	3,38	4,20	9,81
Miscellaneous	10,25	24,92	3,14	15,06	0,18	0,73	0,41	33,40	22,16
RDF composition	100	31,26	4,26	22,71	0,37	0,43	1,05	32,75	7,94

*A%: The percentage of aggregate materials in each component of the RDF.

Kapetanios reported lower calorific capacity 14,200 kJ/kg for RDF, initial moisture 27.1%, which is produced in the mechanical and biological pre-treatment plant (MBT) of the Attica Region, while the European Union of 15 members reported that the average lower calorific capacity for RDF from mixed MSW, 24.4% initial moisture is 13,300 kJ/kg. The lower calorific capacity of dried RDF, with humidity 13%, is Hu = 17,918,422 kJ/kg. The lower calorific capacity of RDF is expected to be increased in the near future for the reasons cited above for the expected reduction of the moisture content and was calculated by the equation:

$$Hu = 38834c + 93868h + 101325s - 5945n - 10802o - 2449w$$

with c, h, s, n, o, w the quantities of carbon (C), hydrogen (H_2), sulphur (S), nitrogen (N_2), oxygen (O_2) and moisture respectively. The RDF flow before his drying, with initial moisture of 27.1%, is 12500 kg/h. The RDF flow after drying at 13% humidity is 1,041,375 kg/h.

The analysis of energy quantities is a complicated process for the plasma gasification since the energy outputs should also be reproducible in real scale. The lack of real data makes the problem more difficult because the information such as the adequacy of energy recovery systems of the gas, heating capacity or the combustion efficiency for gaseous mixtures are limited without having proved even in practice. It is decided to study the case of electricity generation from a combined cycle system. The gas engines are considered to have 40% electrical efficiency and thermal efficiency of 50% (Achinas & Kapetanios, 2012).

2.2 Plasma Gasification System Description

The plasma gasification is a modern process and is based in the pure gasification. In the Figure 1 (below) is given the general process flow diagram of an intergarted plasma gasification combined cycle system for energy recovery (Achinas & Kapetanios, 2012). The plasma furnace is the central component of the system where gasification is taking place. Two graphite electrodes, as a part of two transferred arc torches, extend into the plasma furnace. An electric current is passed through the electrodes, and am electric arc is generated between the tip of the electrodes and the conducting receiver, i.e. the slag in the furnace bottom. The gas introduced between the electrode and the slag that becomes plasma can be oxygen, helium or some other, but the use of air is very common due to its low cost.

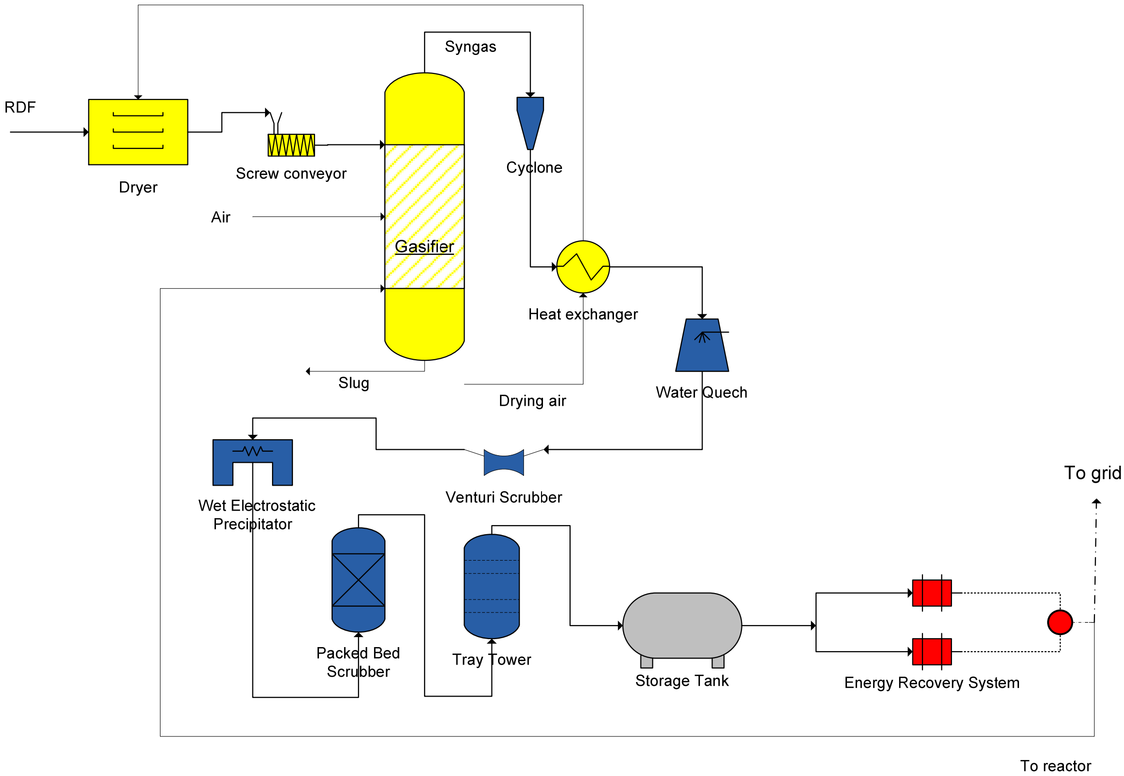

Figure 1. Process flow diagram of RDF plasma gasification for energy recovery

The RDF, after drying, will be led in gasification unit, which will produce a gas mixture and a small percentage of sludge and metal (oils and tar). In the process of drying the RDF, before cracking, will include a multi-cyclone for the retention of suspended particles RDF, which will be then driven gasification reactor. The fluidized bed will be supplied with lime (CaO) from silo to capture mainly emitted sulfur dioxide (SO_2) during gasification, and urea from the tank, to capture the various oxides of nitrogen (NOx).

The following part includes the gas cleaning step in order to reduce up to zero the quantity of acids, metals and other substrates from the syngas before to introduce it in the energy recovery installation (Laurence & Ashenafi, 2012). The syngas from the PG reactor must be cooled down and cleaned before it can be used as fuel in a gas turbine combined cycle. Immediately after leaving the unit, the gas will pass through deducting unit consisting of multi-cyclone and remove the bulk of the produced dust an ash. Dry scrubbing is followed by semi-dry cleaning, through semi-dry scrubber.

The energy recovery system can be based on a combined cycle system, gas turbine and steam turbine (Imris et al., 2005). The sludge is collected from the bottom of the reactor while the gas is led into a combined cycle gas turbine unit, which will produce superheated steam (Global Environmental Solutions Inc.). The steam turbine will be driven at two levels (high and low pressure). The gasification installation of RDF in Athens will include all the necessary anti-pollution systems, in order to comply with the relevant national legislation and the relevant directives of the European Union.

3. System Modelling

3.1 Development of Gasification Process

Gasification is closely related to combustion and pyrolysis, but there are important distinctions. Gasification is like starved-air burning because oxygen is strictly controlled and limited so that as heat is applied the feedstock is not allowed to actually burn (Littlewood, 1977). Instead of combusting, the raw materials break down and go through the process of pyrolysis that produces char and tar. At its simplest form, pyrolysis is commonly used to produce charcoal from wood. As the process continues and the heat is taken higher, the char and tar completely break down into gasses. Depending on the process used and the precise chemistry, the resulting gas may come in a few different forms: synthesis gas, producer gas, town gas, wood gas or others (Bonizzoni & Vassallo, 2002).

The plasma torch, i.e. the device which provides energy in the form of electric current in the reactor is deemed to have 85% yield. The reason it did not be supposed a price equal to 100% is the flares cooling requirements for safe operation. Companies give for torch performance a range from 70 to 90% (Alter NRG & Westinghouse Plasma Corporation, 2008; Minutillo et al., 2009). As we know from the bibliography it is difficult to simulate all the chemical reactions which take place in the gasifier. The chemical reactions below depict the basic gasification process (Mountouris et al., 2008):

$C(s) + H_2O = CO + H_2$	(Heterogeneous water gas shift reaction – endothermic)
$C(s) + CO_2 = 2CO$	(Boudouard equilibrium – endothermic)
$C(s) + 2H_2 = CH_4$	(Hydrogenating gasification – exothermic)
$CH_4 + H_2O = CO + 3H_2$	(Methane decomposition – endothermic)
$CO + H_2O = CO_2 + H_2$	(Water gas shift reaction – exothermic)

The principal reaction for the modeling for RDF gasification process is written as follows:

$$C_xH_yO_zS_kN_l+wH_2O+mO_2+3{,}76mN_2 \Leftrightarrow n_1CO+n_2H_2+n_3CH_4+ n_4H_20+ n_5CO_2+n_6N_2+n_7S+n_8H_2S \quad (1)$$

The three main independent reactions that are selected for the equilibrium calculation are shown below:

$CH_4 + H_2O \Leftrightarrow CO + 3H_2$	(Methane decomposition-endothermic)
$CO + H_2O \Leftrightarrow CO_2 + H_2$	(Water gas shift-exothermic)
$H_2 + S(g) \Leftrightarrow H_2S$	(Sulfur reaction)

The equilibrium constants are:

i) for the methane decomposition

$$K_1=[CO]*[H_2]^3/[CH_4]*[H_2O]=(n_{CO}*n_{H2}^3)/(n_{CH4}*n_{H2O})=(n_1*n_2^3)/(n_3*n_4*n_{total}^2) \quad (2)$$

ii) for the water gas shift reaction

$$K_2=[CO_2]*[H_2]/[CO]*[H_2O]=(n_{CO2}*n_{H2}) / (n_{CO}*n_{H2O})=(n_5*n_2)/(n_1*n_4) \quad (3)$$

iii) for the sulphur reaction

$$K_3=[H_2S]/[H_2]*[S(g)]=n_{H2S}/(n_{H2}*n_{S(g)})=(n_8*n_{total})/(n_2*n_7) \quad (4)$$

3.2 Model Analysis

As we see above, we have eight variables and ase we describe below we need seven equations which represent the seven unknown stoichiometric coefficients of the products and the oxygen content for the reaction (Nikolaou, 2010; Mountouris et al., 2006). Therefore, seven equations are required, which are formulated based on the following:

$$\text{Carbon: } x=n_1+n_3+n_5 \quad (5)$$

$$\text{Hydrogen: } y+2w=2n_2+4n_3+2n_4+2n_8 \quad (6)$$

$$\text{Oxygen: } z+w+2m=n_1+n_4+2n_5 \quad (7)$$

$$\text{Sulfur: } k=n_7+n_8 \quad (8)$$

$$\text{Nitrogen: } l+7{,}52m=n_6 \quad (9)$$

$$\text{Ολικά kmol: } n_{tot}=n_1+n_2+n_3+n_4+n_5+n_6+n_7+n_8 \quad (10)$$

$$\boldsymbol{H^0_{f,waste}}+\boldsymbol{wH^0_{f,H20(l)}}+\boldsymbol{mH^0_{f,O2}}+\boldsymbol{3,76mH^0_{f,N2}}+ Electricity = n_1\boldsymbol{H^0_{f,CO}}+n_2\boldsymbol{H^0_{f,H2}}+n_3\boldsymbol{H^0_{f,CH4}}+ n_4\boldsymbol{H^0_{fH2O(g)}}+n_5\boldsymbol{H^0_{fCO2}}+n_6\boldsymbol{H^0_{f,N2}}+n_7\boldsymbol{H^0_{f,S}}+n_8\boldsymbol{H^0_{f,H2S}}+Parameter \quad (11)$$

$$Parameter = n_1c_{p,H2}(T)+n_2c_{p,CO}(T)+n_3c_{p,CH4}(T)+n_4c_{p,H20}(T)+n_5c_{p,CO2}(T)+n_6c_{p,N2}(T)+n_7c_{p,S}(T)+n_8c_{p,H2S}(T)dT \quad (12)$$

The formation enthalpies H_i are reported in bibliography.

4. Plasma Gasification Process Performance - Results

4.1 Energy and Exergy Analysis

In energy transformation processes such as combustion, gasi$cation and reforming of fossil and renewable fuels, the conservation of energy (first law of thermodynamics) as well as the qualityof energy (second law of thermodynamics) is important. This study focuses on the conversion of RDF into gaseous components and char (Prins et al., 2003).

Exergy analysis is based upon the second law of thermodynamics, which stipulates that all macroscopic processes are irreversible. Every such irreversible process entails a non-recoverable loss of exergy, expressed as the product of the ambient temperature and the entropy generated. The elementary irreversible phenomena that generate entropy are: mechanical or hydraulic friction, heat transfer with a finite temperature gradient, diffusion with a finite gradient of concentration, and the mixing of substances with different parameters and chemical composition. Combustion is also a typical irreversible phenomenon; however, it is a complex process comprising all the above mentioned elementary irreversibilities (Szargut, 2005).

Some of the components of entropy generation can be negative, but the sum is always positive.Mountouris et al. support applied the exergy analysis for the main section of the process. An exergy analysis is a fundamental tool for evaluating processes and systems. Exergy analysis is a combination of the First and Second Laws of Thermodynamics and accounts for irreversibilities (Mountouris et al., 2006).

The formula of chemical exergy is:

$$\varepsilon_{0,m} = \sum x_i e_{0,i} + RT_0 \sum x_i ln x_i \tag{13}$$

Table 2. Chemical exergy of different substances at atmospheric conditions

Substance	ε (kJ/kmol)
N_2	720
CO_2	19,870
H_2O	9,500
H_2	236,100
CO	275,100
CH_4	831,650

4.2 Efficiency Evaluation with Thermodynamic Approach

Efficiency can be estimated calculated in using the two thermodynamics laws which means that the gas efficiency is calculated by the following formula (Qiu & Hayden, 2004), (Mountouris et al., 2006):

$$E=HV_{Synthesis\ gas}/LHV_{Waste}+Electricity \tag{14}$$

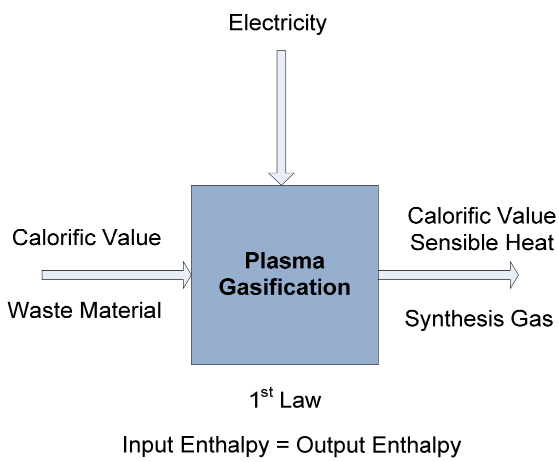

Figure 2. Flow diagram of plasma gasification according to 1nd law

On the other hand, second law is a generic term for a group of concepts that define the maximum work potential of a system, a stream of matter or a heat interaction; the state of the (conceptual) environment being used as the datum state (Reddy et al., 2010).

The second law efficiency is calculated with the same way using the formula (Mountouris et al., 2006).

$$E=Chemical\ exergy_{Synthesis\ gas}/Chemical\ exergy_{Waste}+Electricity \quad (15)$$

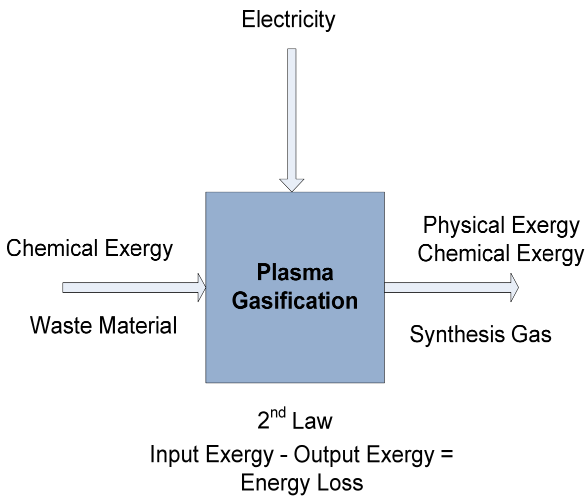

Figure 3. Flow diagram of plasma gasification according to 2nd law

The method which was described in the previous paragraphs gives the following results (Table 3) based on calculations in MATLAB.

Table 3. Results for the efficiency for RDF plasma-gasification

Efficiency according to the 1st law	Efficiency according to the 2nd law
$HV_{Synthesis\ Gas}$ = 140091,36	Chemical Exergy $_{Synthesis\ Gas}$ = 1598401
LHV_{Waste} = 17918,422	Chemical Exergy $_{Waste}$ = 5498778
Electricity = 394115	Electricity = 394115
ε = 0,34	**ε = 0,27**

5. Conclusion

The application of plasma gasification in RDF with fluidized bed technology for power generation is interesting, especially the case studied. The international experience from the implementation of plasma gasification with fluidized bed technology is very small which increases the investment risk. Also for the plasma gasification fluidized bed technology is beyond technical implementation and the limitation of only small and medium sized facilities. But the above should not discourage investments for further development of the existing plasma gasification technology, so it can be increased the expertise and be resolved remaining technical problems because plasma gasification technology can be clearly demonstrated one state-of-the-art, environmental and techno-economic method and in the near future will be fully prepared to give very beneficial solutions to large-scale thermal recycling of solid waste (Malkow, 2004).

The plasma gasification process is a future method for treating solid waste. The option of oxygen and the humidity rates is crucial issue and depends on the exploitation mode of synthesis gas. The process is an effective and environmentally friendly option for treatment and energy recovery of RDF. Based on that energy evaluation from our study, the RDF can be used for energy recovery using a process that includes the milestones of plasma gasification, drying and electricity production. The effective implementation of the proposed process shows that plasma gasification process is not only energy independent but can lead to a net production of electricity.

The first conclusion drawn from the analysis is that the price of electricity and the waste disposal fee are what could make the plasma gasification concept more financially viable. The electricity can be subsidized if the energy production by exploiting waste is considered as a renewable form of energy. The disposal waste fee is important to integrate the unit revenue plasma gasification. From the side of a state disposal fee can replace council tax paid currently in landfills. A good combination of grant, refuse disposal fee and sales price of electricity could make the plasma gasification very attractive, but should not be neglected the high cost of electricity production. This value is very high compared with both the more expensive renewable electricity (photovoltaic - wind) and conventional energy sources (oil-gas).

The impacts study of major economic parameters (price electricity production, waste disposal fee subsidy) can be showed how much the concept of a plasma gasification system can be advantageous with appropriate policies promoted by the state. The various toxic substances are destroyed by high temperatures and this plasma gasification is particularly suitable for the treatment of hazardous waste such as medical waste and some industrial. The treatment of hazardous waste can justify the choice of the high waste disposal fee per tonne which as mentioned above it could contribute positively to the profitability of the investment (Diaz & Leal-Quiros, 2009).

In the process, harmful pollutants can be removed from the syngas before they reach the gas turbine; thus, back-end exhaust gas clean up is not necessary. The SOx, NOx, mercury, metals, and particle emissions from the plant are fractions of those of a conventional pulverized coal boiler power plant. Consequently, IPGCC plants require significantly less effort and time to meet air emissions regulations and to obtain local and state governmental environmental permits. The process is approximately 5% more efficient than other coal power technologies, thus, CO_2 emissions per kW are also 5% lower.

Summarizing what we have been said above, we reach the undeniable fact that the gasification of RDF can produce numerous environmental advantages at a time when such energy technologies are a powerful investment for man and nature.

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