

Syngas Generation from Organic Waste with Plasma Steam Reforming

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Abstract

A plasma steam reforming system to process waste is in the process of being set up at the University of California, Merced. The proposed concept will use two different plasma regimes, i.e. glow discharge and arc torches to process a percentage of the total liquid waste stream generated at the campus together with shredded local organic solid waste. One of the main advantages of the plasma technology to be utilized is that it uses graphite electrodes that can be fed to the reactor to achieve continuous operation, thus, electrode or nozzle life is not a concern. The waste to energy conversion process consists of two stages, one where a mixture of steam and hydrogen is generated from the liquid in a glow-discharge cell, and a second stage where the mixture of exhaust gases coming out of the first device are mixed with solid waste in a reactor operating in steam reforming mode interacting with a plasma torch to generate high-quality syngas. In this paper, the results of a thermodynamic model developed for the two stages are shown. The syngas composition obtained indicates that the fraction of CO₂ present decreases with increasing temperature and the molar fractions of hydrogen and carbon monoxide become dominant. The fraction of water vapour present in the product gases coming out of the second stage needs to be condensed before the syngas can be utilized in a prime mover.

1. Introduction

Plasma gasification of waste is a concept introduced relatively recently [1-5]. Plasma torches operating over 3000 K break the chemical bonds of waste to generate hydrogen-rich synthesis gas (syngas) from the organic compounds. In most cases, the interaction of this plasma with the organic molecules produces the dissociation of the molecules. Magmafication [5] happens from the interaction of plasma with inorganic compounds. The plasma temperature may be accurately controlled for the production of vitrified materials, which can be used to manufacture architectural tiles, bricks, and aggregates for the construction industry.

2. Status of the technology

Plasma processing of waste to generate energy, liquid fuels, and other products is a process that has not been fully characterized yet. The hydrogen-rich syngas can be used to generate power and heat by means of generator sets, lean-combustion turbines, or solid oxide fuel cells. The current state of the art of the technology includes a plant located in Utashinai, Japan operating since 2003 that processes 200-280 tonnes/day of auto shredder residue to produce electricity [6]. Another plant in Yoshi, Japan uses plasma gasification to produce bricks for construction purposes and heat. About 20 projects around the world are in the planning or construction stages. UC Merced is collaborating with the



company Foret Plasma Labs (FPL) [7] in the installation of a plasma steam-reforming unit that will process liquid and solid waste.

3. Campus waste streams

Being a relatively new campus has allowed facilities managers to obtain accurate data of the available waste streams and energy demand and their projections for the near future. Table 1 shows the waste generation at UC Merced and its estimates until 2014.

Table 1. Waste generation at UC Merced and estimate of their growth until 2014.

Predicted Waste Stream - UC Merced		2008	2009	2010	2011	2012	2013	2014
Potential Fuel Stream (kg/h)								
Single Stream		11.09	13.87	16.64	19.63	21.99	24.19	26.61
Green		14.91	18.64	22.37	26.40	29.57	32.52	35.78
Compost		0.25	0.31	0.37	0.44	0.49	0.54	0.60
OCC		7.58	9.47	11.36	13.41	15.02	16.52	18.17
Pallets		1.47	1.84	2.21	2.61	2.92	3.21	3.54
Paper		7.76	9.71	11.65	13.74	15.39	16.93	18.62
Total solids (kg/h)		30.50	38.13	45.76	53.99	60.47	66.52	73.17
Sewage Avg Volume (m ³ /h)		2.36	2.95	3.54	4.18	4.68	5.15	5.67
Sewage Avg Weight (kg/h)		2721.58	3401.98	4082.37	4817.20	5395.26	5934.79	6528.27

4. Proposed concept and description of plasma system

The proposed concept will process a percentage of the total sewage stream and solid waste generated on campus. One of the main advantages of the equipment from FPL is that it uses graphite electrodes that can be fed continuously for continuous operation, and thus, electrode life is not a concern as with traditional plasma-torch nozzles. Figure 1 shows a representation of the equipment to perform the gasification of sewage and solid waste.



Figure 1. Plasma gasification of sewage and solid waste using a dual plasma system (Courtesy of Foret Plasma Labs).

The reactor is comprised mainly of two plasma systems that operate in different plasma regimes. The first stage uses a plasma glow discharge to process the sewage and generate steam and hydrogen. The second stage uses a plasma torch and the output gases from the first stage to process bio-solids. Syngas, mainly CO and H₂, is produced in the second stage.

5. Plasma in the DC discharge

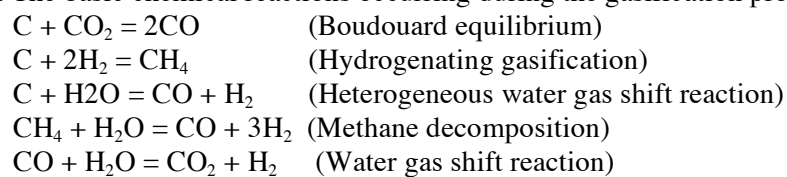
The physics of glow discharges and plasma torches have been well described in the plasma literature, for example in E. Leal-Quiros [1-5] and others. However, the objective of this paper is to develop a thermodynamic model for both processing stages described above with the intent of analyzing the composition of the products gases after the first and second stages under a variety of operating conditions.

5.1 Cascade process of ionization

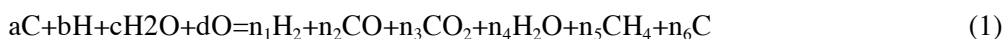
To understand the interaction between the plasma generated from the torch with the organic materials, we can visualise the phenomenon as a collision between the plasma components and the neutral atoms of the material. As a matter of illustration the cascade process can be considered as initiated by an energetic electron from the plasma. One incident electron (e^-) collides with a neutral atom to produce a second electron and an ion. Then, there are two electrons and one ion. After these two electrons have independently collided with another neutral atom, four electrons and three ions are produced. This process continues, and after about 20 successive sets of collisions, millions of electrons and ions will be rapidly formed (the mean free path between collisions is very small at atmospheric pressures). Smaller sizes of the organic materials promote a better interaction with the plasma in the cascade process and a more efficient syngas generation is obtained.

6. Thermodynamic model and basic chemical reactions

Although there are a number of chemical reactions occurring during the plasma-arc gasification process, the assumption of equilibrium of the chemical reactions allows us to develop an approximate model [4,8-10]. The basic chemical reactions occurring during the gasification process correspond to:



Low temperature or low steam content promotes the formation of soot so the first three equations are relevant. At higher fractions of steam addition and high temperature, carbon (soot) is not formed so that the last two equations become dominant [9]. Following the models presented in [9-11], an approximate thermodynamic model was developed. Obtaining the ultimate analysis of the solid waste, such as, cardboard, paper, etc, and sewage, a global gasification reaction becomes:



where the coefficients a , b , c , and d are obtained from the ultimate analysis and the coefficients n_1 to n_6 are unknowns. Performing a molar balance for each species and adding three equilibrium constants given by eqn. (2) for the methane decomposition, primary water gas shift, and heterogeneous water gas shift reaction, the system of equations is solved iteratively with constants K_1 , K_2 , and K_3 obtained from the eqn (3).

$$K_1 = \frac{y_{\text{CO}} y_{\text{H}_2}^3}{y_{\text{CH}_4} y_{\text{H}_2\text{O}}}, K_2 = \frac{y_{\text{CO}_2} y_{\text{H}_2}}{y_{\text{CO}} y_{\text{H}_2\text{O}}}, K_3 = \frac{y_{\text{CO}} y_{\text{H}_2}}{y_{\text{H}_2\text{O}}} \quad (2)$$

$$-\ln K_i = \frac{\Delta G_i^0}{RT} \quad (3)$$

7. Numerical results

The results obtained with the thermodynamic model are presented in the following sections.

7.1 Generation of steam and hydrogen in the first stage

When the sewage interacts with plasma glow discharge, steam and hydrogen are produced, as shown in Figure 2, where the hydrogen comes from a plasma electrolysis process. Other species, such as CO_2 , CO , etc., are also formed but their molar fractions in the product-gas composition are small. The figure shows the molar fraction vs. the temperature of the products generated from the plasma glow interaction with sewage for a flow rate of 250 kg/hr. The sewage and solid waste properties have been obtained from an ultimate and proximate analysis.

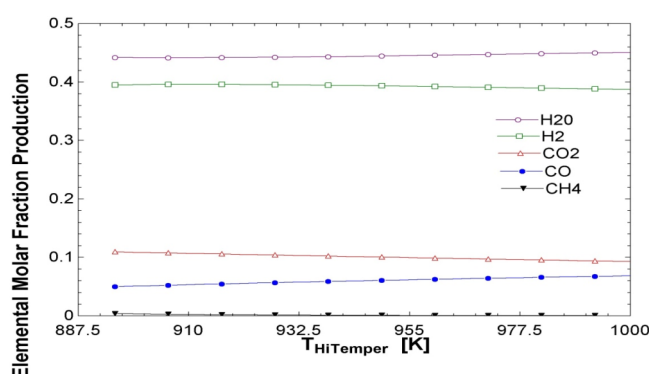


Figure 2. Molar fraction vs. temperature of the products generated in the first stage of the reactor for a flow of sewage of 250 kg/hr.

7.2 Synthesis gas generation on the second stage

Figure 3 shows the molar fraction for the composition of syngas produced in the second stage. The syngas is the result of the interaction between the plasma torch, the product gases from the first stage, and the organic solids being fed at a rate of 30 kg/hr. The temperature of the syngas depends on the temperature from the product gases from the first stage and the energy added for the plasma torch in the second stage. The syngas acquires a high temperature but far less than the plasma torch temperature.

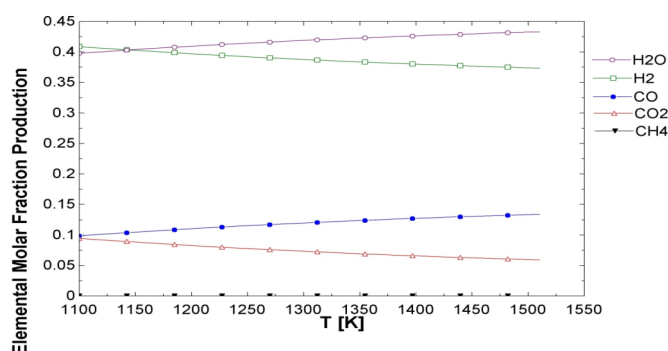


Figure 3. Molar fraction of the syngas vs. temperature acquired by the syngas during the steam reforming process in the second stage. Solid flow rate of 30 kg/hr for a sewage flow rate in the first stage of 250 kg/hr have been used. The temperature of the syngas varies depending on the power utilized for the plasma torch.

In practice, the vapour content in the syngas is condensed before the gas is supplied to a prime mover, such as, a generator set, turbine, etc. Different flow rates of sewage and bio solids produce different syngas compositions. The syngas composition also varies depending on the type of liquid and solid waste utilized.

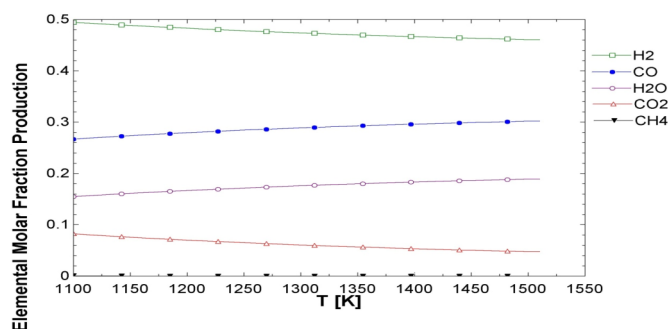


Figure 4. Molar fraction of the syngas generated vs. temperature acquired by the syngas. Solid flow rate of 200 kg/hr for a sewage flow rate in the first stage of 250 kg/hr.

Figure 4 shows the syngas composition produced by the system for a flow rate of bio-solids of 200 kg/hr. The molar fraction of CO_2 decreases as the temperature increases. The molar fractions of H_2 and CO are significantly larger, but there is still a percentage of water-vapour present.

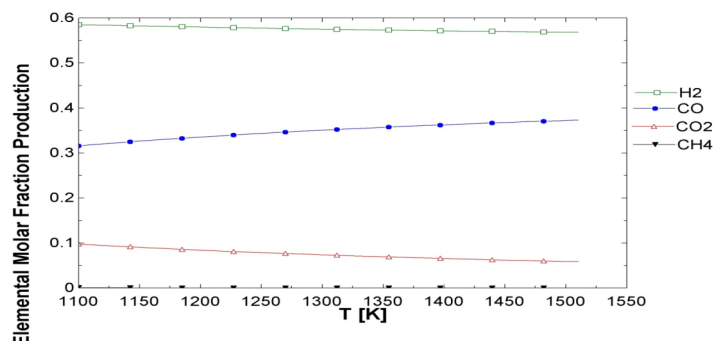


Figure 5. Molar fraction of the syngas generated vs. temperature acquired by the syngas, without water vapour in the products of the second stage.

Figure 5 shows the syngas composition on a dry basis, i.e. after the water vapour has been condensed. The larger fraction of hydrogen obtained is the consequence of adding the hydrogen content generated in the first stage, through glow discharge electrolysis, and the hydrogen generated by the steam reforming of bio-solids in the second stage.

8. Conclusions

A two-stage system for plasma gasification of waste is in the process of being installed at the University of California at Merced. A thermodynamic model has been developed to predict syngas composition based on operating-condition parameters, such as, flow rate of solid and liquid waste, power supplied, and waste composition.

The results of the model indicate that a large molar fraction of hydrogen and carbon monoxide is obtained with the system. The flow rates of solid and liquid waste, as well as, the power required, and the composition of waste utilized affect the final syngas composition which shows a fraction of

water vapour present. In practice, this water vapour has to be condensed before the syngas is supplied to a prime mover. The benefits of the proposed concept not only relate to the reduction of solid waste that is sent to landfills or the reduction of the amount of sewage that is sent to the sewer network. This project will also provide an invaluable source of information about the operating parameters and performance of a plasma waste gasification plant.

9. Acknowledgements

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10. References

- [1] Edbertho Leal-Quiros. "Plasma processing of municipal solid waste". Brazilian Journal of Physics, Vol. 34, no. 4B, pp 1587-1593, Dec (2004).
- [2] Leal-Quiros, E, Villafane, C.R. "An assessment of the power generated with plasma processing of sludge from wastewater treatment plants". IEEE Transactions on Plasma Science, Vol. 35, no. 6, pp 1662-1627 Dec (2007).
- [3] Edbertho Leal-Quiros, Igor Matveed. "Plasma Coal Ignition for Utility Power Plants," 29th ICPIG July 12-27, 2009. Cancun, Mexico.
- [4] G. Diaz, E. Leal-Quiros "Sustainable Waste Management Using Plasma Gasification at University of California-Merced." 29th ICPIG, July 12-27, 2009, Cancun, Mexico.
- [5] Edbertho Leal-Quiros, "Magmafication, Vitrification, Gasification, and Generation of Energy with High Temperature Plasma Processing of Waste," Current Trends in International Fusion Research – Proceedings of the Fifth Symposium, pages: 341-357. Edited by E. Panarella and R. Raman. NRC Research Press, National Research Council of Canada, Ottawa, ON K1A 0R6 Canada, 2008.
- [6] K.C. Bhasin. Plasma arc gasification for waste management. Part 2 of 2. Electronics for you. February (2009).
- [7] Foret Plasma Labs, LLC (<http://www.plasmawhirl.com>). US Patents #7,422,695, #7,578,937, and # 7,622,693.
- [8] Shuster, G. et al. Biomass steam gasification – an extensive parametric modeling study. Bioresource Technology, 77 (2001) 71-79.
- [9] Zainal, Z.A. et al. Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. Energy Conversion and Management, 42 (2001) 1499-1515.
- [10] Mountouris, A. et al. Plasma gasification of sewage sludge: Process development and energy optimization. Energy Conversion and Management. 49 (2008) 2264-2271.