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Sustainable Co-generation Plant: Refuse-Derived Fuel Gasification Integrated with High Temperature PEM Fuel Cell System

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Abstract. Alternate energy sources are very vital for sustained economic growth. Fossil fuels are not only non-renewable, their rising consumption has been reported to be the principal cause of climate changes worldwide. Sustainable energy sources are potential alternatives to the fossil fuel-dominated energy industry. Biomass is uniquely a renewable energy sources that are not location-dependent. Municipal Solid Wastes (MSW) is continuously generated with no threat of depletion. Thermochemical conversion of MSW for materials and energy recovery continue to generate research interest. Gasification of refuse-derived fuel (RDF) is a very efficient route to generate heat (for power generation) and exhaust gas rich in hydrogen from MSW. In the proposed system, the hydrogen produced is fed to a high temperature polymer electrolyte membrane fuel cell in the combined heat and power plant. This study proposed a MSW treatment and conversion system integrated with a fuel cell system for material and energy recovery, thereby eliminating the environmental footprints of the conventional MSW management processes in South Africa. The options also generates power from an hitherto unwanted wastes hence providing a sustainable options to the energy security challenges.

Keywords: Sustainable energy, Municipal solid wastes; Refuse-derive fuel; Gasification; Fuel cell

1. Introduction

The ever increasing world population has resulted into a steep rise in demand for energy as standard of living improves with rising in average households income, particularly in the developing countries. This has also resulted in the dilemma of how to manage in an environmentally-benign and sustainable way, the huge volume of household and commercial solid wastes being generated daily. In this respect, municipal solid wastes (MSW) will become increasingly important in the search for sustainable alternatives to fossil fuels alongside renewables such as solar, wind, tidal and nuclear energy. Supply of MSW unlike the other renewable sources of energy, is not intermittent or site-dependent, and can be used to produce not only energy, but also chemicals and materials [1]. Processes that recover materials and energy from the MSW and hence solved the problem of energy production and waste conversion same time, have been suggested and are currently at various stages of implementation worldwide.

Incineration, burning and land filling are the common MSW disposal and management approach in most developing countries. An insignificant amount particularly the plastics and glass components is being recycled. These practices are not only grossly inadequate, but also pose an avoidable threat to public health, the environment, air quality, ground water, land and landscape. Biomass thermo-chemical conversion methods including pyrolysis and gasification processes are promising for producing medium calorific streams for power generation and synthesis gas (a mixture of hydrogen and carbon monoxide). Further processing and conversion of the synthesis gas is used to produce high purity hydrogen and fed to polymer electrolyte membrane (PEM) fuel cell for cogeneration purposes. The use of MSW avoid competition with

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the food sector and unlike virgin biomass is not to be cultivated. The major impediment to biomass use is the development of economically viable methods (physical, chemical, thermochemical and biochemical) to separate, refine and transform it into energy, chemicals and materials [2]. For technical and economic reasons, the indirect conversion of the combustible materials in the MSW to energy and materials has been suggested.

Refuse derived fuel (RDF) is produced from dried combustible portions of MSW. It is homogeneous, highly dense material with a higher energy content and hence suitable for material and energy recovery processes. The gasification of the RDF to produce clean and energy-carrying hydrogen as fuel for high temperature polymer electrolyte membrane (HTPEM) fuel cell for cogeneration (heat and electricity) plants will be an ideal energy source. A brief description of the various potential processes required to recover energy and material (energy) from MSW is the focus of this paper.

2. Municipal Solid Waste

Municipal solid wastes includes wastes from households, commercial activities, farms, and educational institutions and is regarded as a sustainable biomass resources. Generally, its compositions include papers, plastics, wood wastes, leather, glass, debris, metals, textiles, bones, ashes, putrescible, food wastes, yard wastes, inerts etc [3]. Approximately 900 million tonnes of MSW is generated worldwide each year, with over 200 million tonnes from China alone [4]. Table 1 shows the typical composition of MSW from a number of regions. In South Africa, the city of Cape Town alone generated in excess of 800 tons/day of MWS [5]. About 4.6 million tonnes of total waste is being incinerated per year which has led to the generation of a large amount of solid residues including fly and bottom ashes; and hazardous and greenhouse gases [6]. MSW contents is classified as combustible, non-combustible, organic, inorganic and inert wastes.

Table 1: Municipal Solid Waste Composition on Regional Basis

Regions	Combustible (weight %)	Non-Combustible (weight %)	Others (weight %)
Asia			
Eastern Asia	67.30	5.80	26.90
South Central Asia	69.20	7.30	23.50
South Eastern Asia	77.10	7.30	15.60
West Asia and Middle East	78.70	4.50	16.80
Africa			
Eastern Africa	76.90	7.30	15.80
Middle Africa	73.70	8.00	18.30
Northern Africa	66.60	8.00	25.40
Southern Africa*	77.20	20.30	2.50
Western Africa*	88.00	3.10	8.90
Europe			
Eastern Europe	71.70	13.60	14.70
Northern Europe	79.40	15.00	-
Southern Europe	64.50	-	-
Western Europe	62.70	-	-
Oceania			
Australia and New Zealand	90.00	-	-
Rest of Oceania	76.00	-	-
America			
Northern America	76.10	12.00	11.90
Central America	82.10	6.30	11.57
Southern America	80.80	6.20	13.00
Caribbean	83.20	10.70	6.10

Source:[7].

2.1. Environmental Assessment of MSW Management and Disposal System

Municipal solid waste management systems include collection and sorting followed by one or more of the following options: recovery of secondary materials by recycling, biological treatment of organic waste (via production of marketable compost), thermal treatment by incineration and landfilling. In Cape Town, about 2.1 million tons of waste was landfilled in the city's three landfill sites in 2007. Despite the waste-to-wealth policies put in place, the figure is still about 1.6 million tons in 2010. The problem is further compounded by the fact that one of the landfill sites will be closed by 2013 and the last by 2022 at most. Landfilling of MSW releases greenhouse gases (GHGs) and volatile organic compounds along with leachable toxic and heavy metals to the environment. In a study on a dumpsite in Kariba in Zimbabwe, accumulation of copper, lead, iron, and zinc were found around the disposal sites [8] Leachates collected from Ibadan and Lagos dumpsites in Nigeria had appreciable levels of dissolved solids, chloride, ammonia, chemical oxygen demand lead, iron, copper, and manganese. This was most likely a result of rampant dumping of lead acid car batteries and metal scraps [9].

Rabiu *et al* [5] reported some studies on environmental impact of dumpsites and MSW incineration in South Africa. High concentration of lead, iron, copper, zinc, phosphorus, coliforms, cadmium and nitrates from vicinity of dumpsites exceeds the water quality standards. Hazardous emissions (containing oxides of nitrogen and sulphur, HCl and harmful organic compounds); and fly and bottom ashes (containing heavy metals and radionuclides, dioxins, furan and volatile organic compounds) resulted from incineration of MSW [10]. Stringent environmental regulations are being imposed to control the environmental impact of MSW and incinerator residues [5, 10, 11].

3. RDF production and Gasification

Refuse derived fuel (RDF) is produced by drying the combustible constituents of MSW and compressed it into pellets or briquettes. Compared to the raw MSW, RDF is more homogeneous, has higher heat content per unit mass, has far lower moisture contents and easier to handle and store. Coarse, fluff and powder forms are the major classifications of RDF. It is considered as a medium to enhance the resource recovery from the solid wastes. RDF production from MSW involves the processes of segregating, crushing and mixing of high and low heat value organic waste. The segregating processes is other work [5]. Some studies [12, 13] reported that including the plastic content increased the calorific value of the RDF and also produces hydrogen-rich synthesis gas during the gasification process. In this work, plastics are taken to be combustible materials and included in the RDF. The combustibles (plus plastics) left after the separations, are shredded to a homogenous particles, dried and pelletized to produce RDF. Sometimes cheap and readily available high calorific materials is added as binder to increase the calorific value and the pelletizing or briquetting process. Various qualities of RDF pellets can be produced, depending on the needs of the user. A high quality RDF would possess a higher heating value, low moisture and ash contents. Characterization of the composition of RDF by proximate and ultimate analysis and chemical analysis of pulverized MSW fly ash, slag is usually carried out. The final RDF is characterized with X-ray fluorescence spectroscopy [6].

Existing processes make use of downdraft gasifiers are the most common, because of its simple design compared to other fixed bed types. It is one of the simplest and cheapest biomass conversion technologies [14]. Updraft fixed bed gasifier however is proposed in this study because of tar formation and removal [10]. The various reactions during the gasification process are represented by Equation 1 through 9 [10, 11, 15, 16]. Equations 1 to 6 represent the dehydration, decarboxylation, partial gasification, producer gas reaction, heavy oil gasification and water gas shift (WGS) reactions respectively. The tar formed is converted in equations 7 to 9:

Dehydration $C_mH_nO_q \rightarrow C_mH_{n-2q} + qH_2O$ (1)

Decarboxylation $C_mH_nO_q \rightarrow C_{m-q/2}H_n$ (2)

Partial Gasification $C + 0.5O_2 \rightarrow CO$ (3)

Producer Gas Reaction $C + H_2O \rightarrow CO + H_2$ (4)

Heavy Oil Gasification $C_nH_m + (n/2)O_2 \rightarrow nCO + (m/2)H_2$ (5)

Water Gas Shift: $$CO + H_2O \rightarrow CO_2 + H_2 \quad (6)$$

$$C_nH_m + nH_2O \leftrightarrow nCO + (n + \frac{m}{2})H_2 \quad (7)$$

$$C_nH_m + nCO_2 \rightarrow 2nCO + (m/2)H_2 \quad (8)$$

$$C_nH_m + xH_2O \rightarrow yCO + zH_2 + wC_pH_q \quad (9)$$

Relatively pure hydrogen can be obtained from synthesis gas produced via the 2-stages water gas shift (WGS) reactors. During the WGS reaction, CO and H_2O react in a 1:1 molar ratio on a catalytically active metal site to form CO_2 and H_2 (as in equation 10). This is a reversible reaction and therefore steam is added in excess to shift the equilibrium towards the product side. The WGS reaction occurs in two steps: the high temperature reaction is carried out using Fe/Co supported on alumina at temperature between 350 and 500 ^{0}C. The low temperature WGS reaction is carried out over Cu-Zn oxide catalysts at 200-250 ^{0}C. The use of the high performance catalyst lowers the CO content to the less than 10 ppm level that can be safely fed to the high temperature PEM fuel cell.

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad -14000KJ/KMol \quad (10)$$

4. High Temperature PEM Fuel Cell Stack

The hydrogen-rich stream from the LTWGS reactor is fed to anode side of the fuel cells stack. A compressed air/oxygen is fed to the cathode. The stack is maintained at 160 ^{o}C which is tolerable by the phosphoric acid doped polybenzidamisole (PBI) membrane [17]. A cooling loop of water/alcohol mixture is used to remove and recover the heat co-produced with power in the stack and so maintain the operating temperature. The stack exit containing unreacted hydrogen is fed to an afterburner for heat production. The waste heat and H_2O generated are integrated back into the system (Figure 1). The heat loop or the heat from the afterburner is used to pre-heat the air supply to the stack operating temperature, to lower the start-up time. The air compressor isentropic efficiency is 85 %. The fuel cell stack characteristics and performance is as described by Nomnqa *et al.* [18]

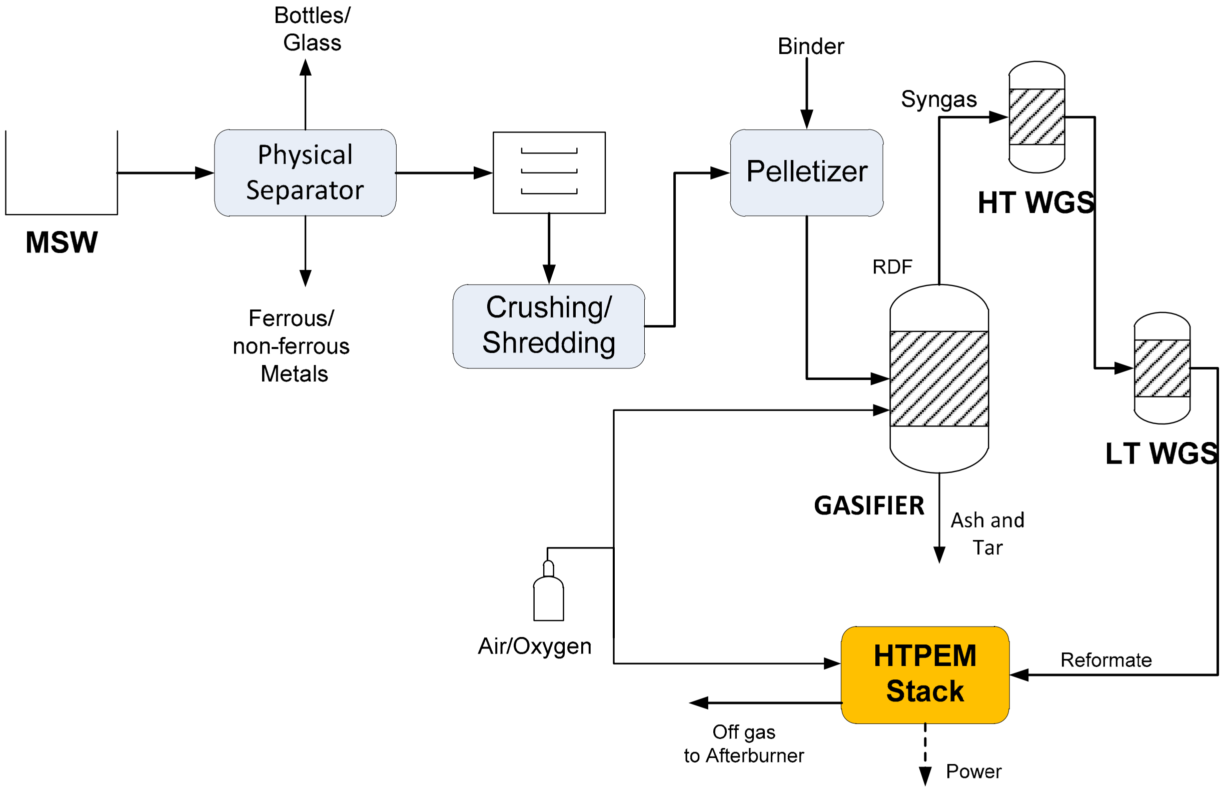

Fig. 1: The Proposed Cogeneration System

5. Conclusions

The proposed design generates heat and electricity via the electrochemical conversion of hydrogen clean fuel for material (hydrogen) and energy (electrical and thermal) recovery. The co-generation system is made of three major sub-systems: the fuel processing sub-system, the fuel post-processing and cleaning and the high temperature PEM fuel cell stack sub-system. The HT PEM fuel cell-based CHP system produces little emission and gave high total system efficiency. This system provide solution to the twin problem of waste management and energy security and with very little environmental footprint..

6. References

[1] F. E. I. Deswarte, J. H. Clark, A. J. Wilson *et al.* Toward an Integrated Straw-Based Biorefinery, *Biofuels, Bioprod. Bioref*. 2007, **1**:245–254.

[2] European Commission. Biomass – Green Energy for Europe. Available online http://www.managenergy.net/download/ r1270.pdf accessed on 12 March 2012.

[3] S. Burnley, R. Phillips, T. Coleman, T. Rampling. Energy implications of the thermal recovery of biodegradable municipal waste materials in the United Kingdom. *Waste Management*. 2011, **31** (9–10): 1949-1959.

[4] National Bureau of Statistics of China. Statistics year book of China in 2004. in, Statistics Press, Beijing, China, 2005, pp. 438-439.

[5] A. Rabiu, I. Adefeso, D. Ikhu-Omoregbe. MSW gasification/polymer electrolyte membrane fuel cell integrated CHP system. *Proceeding of International Science and Technology Conference*. Istanbul, 2011, pp. 567-572.

[6] T. H. Kwak, S. Maken, S. Lee, J.-W. Park, B.-r. Min, Y.D. Yoo. Environmental aspects of gasification of Korean municipal solid waste in a pilot plant. *Fuel*. 2006, **85** (14–15): 2012-2017.

[7] International Panel on Climate Change. Guidelines for GHG Inventories, Vol. 5, Waste. Available online from http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html, accessed 25 March 2012.

[8] P. C. Chifamba. Trace metal contamination of water at a solid waste disposal site at Kariba, Zimbabwe. *African Journal of Aquatic Science.* 2007, **32** (1): 71-78.

[9] A. Ikem, O. Osibanjo, M.K.C. Sridhar, A. Sobande. Evaluation of groundwater quality characteristics near two waste sites in Ibadan and Lagos, Nigeria. *Water, Air, & Soil Pollution*. 2002, **140** (1): 307-333.

[10] Q. Zhang, L. Dor, D. Fenigshtein, W. Yang, W. Blasiak. Gasification of municipal solid waste in the plasma gasification melting process. *Applied Energy*. 2012, **90** (1):106-112.

[11] C. Chen, J. H. Yan *et al*. Simulation of MSW gasification in two different types of fixed bed reactors. *Fuel*. (2012).

[12] A.K. Dalai, N. Batta, I. Eswaramoorthi, G.J. Schoenau. Gasification of refuse derived fuel in a fixed bed reactor for syngas production. *Waste Management*, 2009, **29** (1): 252-258.

[13] I. I. Ahmed, and A.K. Gupta. Hydrogen production from polystyrene pyrolysis and gasification: characteristics and kinetics. *International Journal of Hydrogen Energy*. 2009, **34** (15): 6253-6264..

[14] D. R. McIlveen-Wright, M. Moglie, S. Rezvani, Y. Huang, M. Anderson, D. Redpath, A. Dave, N.J. Hewitt. A techno-economic analysis of biomass gasifiers integrated with high and intermediate temperature solid oxide fuel cells. *International Journal of Energy Research*. 2011, **35** (12): 1037-1047.

[15] M. He, Z. Hu, B. Xiao, J. Li, X. Guo, S. Luo, F. Yang, Y. Feng, G. Yang, S. Liu. Hydrogen-rich gas from catalytic steam gasification of municipal solid waste (MSW): Influence of catalyst and temperature on yield and product composition. *International Journal of Hydrogen Energy*. 2009, **34** (1): 195-203.

[16] P. Basu. Biomass gasification and pyrolysis practical design and theory. Elsevier Academic Press, Burlington, MA 01803 USA, 2010.

[17] M. Mamlouk, and K. Scott. Phosphoric acid-doped electrodes for a PBI polymer membrane fuel cell. *International Journal of Energy Research*. 2011, **35** (6): 507-519.

[18] M. Nomnqa, N. Dlangamandla, D. Ikhu-Omoregbe, A. Rabiu.Optimization studies on the performance of a high temperature proton exchange membrane fuel cell. *In: International Conference of Science and Technology*. Istanbul, Turkey, 2011, pp. 608-613.