Municipal Solid Wastes Gasification/Polymer Electrolyte Membrane Fuel Cell Integrated CHP System

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Abstract: Secured, cheap and clean energy sources are very vital for economic growth and development. The current fossil fuel dominated energy scene is not sustainable. There is increasing interest in biomass as a sustainable energy source to arrest the fast depletion of the global fossil fuel reserves and the attendant environmental challenge posed by its end uses. Municipal Solid Wastes (MSW) is continuously generated with no threat of depletion. Over 70% of MSW is composed of combustible materials ideal for energy production. Gasification of the MSW via the refuse derived fuel (RDF) route will generate heat for power generation and synthesis gas rich in hydrogen as feed to fuel cell in a combined heat and power (CHP) systems. This study proposed a MSW treatment and processing strategy for energy and hydrogen production. It explores waste-to-energy approaches to eliminate the environmental footprints of the current MSW treatments and disposal methods in South Africa.

Keywords: municipal solid wastes; biomass; gasification; hydrogen; fuel cell.

Introduction

In South Africa, the steady economic growth and development has resulted in a steady rise in energy consumption and municipal solid waste (MSW) production necessitating more investment in the power industry on one hand and sustainable approach to management of the MSW on the other hand. The energy sector in South Africa is dominated by coal and nuclear, with approximately 93% of the electricity produced from coal-fired plants (Eskom, 2011). The over reliance on fossil fuels as primary energy source worldwide is not sustainable. It is essential not only to search for new energy carriers but also for new material sources. In this respect, virgin biomass and municipal solid wastes will become more important in the search for alternatives for fossil fuels alongside other alternatives such as solar, wind, tidal and nuclear energy. Supply of biomass 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 (Deswarte *et al*., 2008). 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.

South Africa for the first time runs out of surplus energy in 2007 resulting in power shortage and load shedding. With a reported reserve margin of around 8%, load shedding will be implemented at peak demand and supply falls due to some generating units taken offline for maintenance or repairs. There is need therefore urgent need to address this problem for sustained growth and development. To increase the generation capacity by constructing more coal-fired power plants has huge environmental consequences and hence not a way out. At the moment, South Africa is among the top 20 emitters of greenhouse gases (GHSs) in the world and is the largest emitter in Africa. So there is a need to use cleaner sources of fuel. An energy security strategy formulated by the Department of Minerals and Energy (DME) seeks to implement measures that will guarantee adequate supplies of energy in the short term; ensure accessible, affordable and reliable energy, especially for the poor and to diversify the primary energy sources to reduce the high dependency on coal. To achieve these objectives, it is imperative to put in place a mix of energy sources. Alternative sources of power from renewable and sustainable sources are currently being considered. These include biomass, geothermal, wind and solar powered plants. Of these sources, an integrated system of fuel cell coupled to a biomass gasification plant look very promising and is receiving more interest.

The Department of Science and Technology is presently promoting hydrogen and fuel cells as priority technologies under the national framework for hydrogen and fuel cell technology (DST, 2010). With the potential to produce hydrogen from biomass and the largest reserve of platinum (used in fuel cells), the country has a significant competitive advantage in developing hydrogen fuel cell-based applications. South Africa's rich platinum reserves (about 78% of the world's platinum along with 39% of the world's palladium production) could make it a key player in the development of fuel cell technology regarded as the future energy source. This will enable South Africa to extract more value from its platinum group metals (PGM) resources; diversify her energy industry, and reduce the environmental impacts of coal-fired plants. Most fuel cells use platinum-group-metals (PGM) as the electrode catalysts to convert hydrogen into electricity. The PGMs are also essential to achieve low-temperature reforming to improve the efficiency of CHP systems.

On a parallel front, the management and disposal of MSW has been a recurring problem in South Africa as elsewhere experiencing similar social and economic growth. In Cape Town, about 550-600 tons/day of MWS is produced in 2007. In sub-Saharan Africa, existing waste management practices are inadequate thus affecting human health, the environment, air quality, and the landscape. MSW supply is very much sustainable with no threat of depletion. A recent report published by the USDOE and USDA reported that the US alone could sustainably supply more than one billion dry tons of biomass per annum by 2030 (USDOE, 2005). 70% of the MSW are combustible materials that could be thermo-chemically converted to energy, fuels and chemicals thereby solving the two problems simultaneously. MSW are combustible and non-combustible wastes that come from household, municipal, commercial, and industrial sites. 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. The gasification of the RDF to produce clean and energy-carrying hydrogen gas as fuel for high temperature polymer electrolyte membrane (HTPEM) fuel cell for cogeneration (heat and electricity) plants will be an ideal energy source. The use of MSW avoids competition with 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 (European Commission, 2005). The options for economic conversion and integration of RDF gasification and HTPEM fuel cell CHP systems for domestic and industrial application is the focus of this article.

Current Municipal Solid Wastes Management of Cape Town

MSW is a mixture of wastes from households, commercial activities, industrial wastes, farm wastes, and educational institutions. Generally, MSW compositions include paper, plastics, sawdust, wood wastes, leather, glass, rubber, e-wastes, ceramics or debris, metals, textiles, bones, ashes, putrescible, food wastes, yard wastes, inert (Parfitt and Bridgwater, 2008; Burnley *et al*., 2011). Table 1 shows composition of MSW from a number of regions.

Table 1: The 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: IPCC Guideline for National Greenhouse Gas Inventories (2006)

The variation in the waste composition has been linked to the economic level of countries, geographical location, energy resources, climate, living standards and cultural habits. The typical composition of Cape Town MSW is presented in Figure 1.

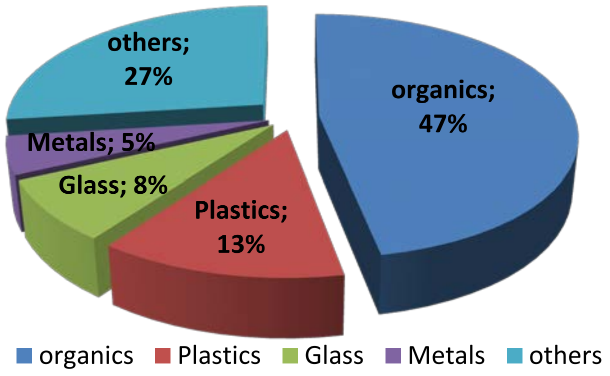

Figure 1: Typical composition of Cape Town MSW

In South Africa, current solid waste management systems include waste collection and sorting, followed by one or more of, recovery of secondary materials by recycling, biological treatment of organic waste for production of marketable compost, thermal treatment by incineration to recover energy in the form of heat and electricity and landfilling. In Cape Town alone, 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 GHGs and volatile organic compounds along with leachable toxic heavy metals to the surrounding environment. Soil is contaminated by the heavy metals and radionuclides content and leachate. In a study on a dumpsite, trace metal concentrations in soil within a 50 meter radius of land fill sites had been contaminated by trace metals, lead, iron, copper, zinc, and phosphorus (Mangizvo, 2008; Chifamba, 2007). Leachates collected from various dumpsites revealed level of *coliforms*, cadmium, iron, lead, and nitrates above the water quality guideline (Ikem *et al.*, 2006). Okonkwo and Mothiba (2004) attributed the high concentration of lead in the Madanzhe and Mvudi Rivers in Thohoyandou, South Africa to the nearby waste dumping site.

Incineration to generate energy has become the most common method of dealing with combustible waste as it decreases the volume and mass of MSW. But, it has many drawbacks, particularly releasing hazardous emissions (NO_x, SO_x, HCl), harmful organic compounds (Gordon, 2002; Zhang, *et al*., 2011) and harmful process residues (Floyd and Anthony, 1996). Globally, about 4.6 million tonnes of solid waste is being incinerated per annum. This has led to the generation of a large amount of solid residues including fly ash and bottom ash and emission of hazardous gases to environment (Kwak *et al.*, 2006). Incineration of MSW generates fly and bottom ashes which release leachable toxic heavy metals, dioxin, furans and volatile organic compounds. Stringent environmental regulations are being imposed to control the environmental impact of MSW and incinerator residues (Zhang, *et al*., 2011).

Refuse Derived Fuel (RDF)

MSW is heterogeneous consisting of combustible, non-combustible, organic, inorganic and inert materials. It also exhibits a low bulk density and relatively high water content. Processes must therefore be designed to reduce the cost of collection, transportation and storage for any MSW conversion technique to be competitive (Gravitis, 2007; Wright and Brown, 2007). This is achieved by densification of the MSW via pelletization or briquetting to form RDF. Density increase of up to a factor of three is obtained with the RDF (Deswarte *et al.*, 2007). Briquettes has a density of about 800–1300 kg/m^3 compared to loose biomass with a bulk density of 10–20 kg/m^3 (Hedman *et al.*, 2005). The RDF is more homogeneous and has higher heat content per unit mass than raw MSW (Dalai *et al.*, 2009). Untreated MSW typically has a heating value of around 5815 kJ/kg while processed (and dried) municipal solid waste has a fuel value as high 9304 -16282 kJ/kg. The economics of the thermo-chemical conversion processes therefore would be dramatically improved through the reduced volume and water content. The gasification of the RDF with higher carbon and hydrogen contents is advantageous.

Pelletization of MSW involves the processes of segregating, crushing, mixing high and low heat value organic waste material and solidifying it to produce RDF. It is prepared by the pelletizing machine or compactor after it has been shredded to homogenous particles. Various qualities of RDF pellets can be produced, depending on the needs of the user. A high quality RDF would possess higher heating value, and lower moisture and ash contents.

Proposed Process Design

The process flow diagram for the proposed RDF gasification/PEM fuel cell co-generation plant is presented in Figure 2. The detail of each stage is discussed in detail in the following section.

Characterization and pre-treatment of MSW
To determine the moisture content and hence the suitable drying method, a sample of the MSW was put in a specially designed oven set at 100^oC. The weight and hence the moisture loss is recorded every one hour for 24 hours. After the period, the oven temperature was increased to 120^oC and the same procedure repeated. A further reduction in mass of the MSW was noted implying that at 100^oC, only the free water was removed and to remove more water higher temperature is required. To confirm these results, the method of Laurent *et al.* (2005) was used for the same sample. Based on this, a drum dryer or hot air contactor at 120^oC for the required time is proposed to remove the free water and as much as the trapped water. Characterization of the composition of MSW by proximate and ultimate analysis of dried MSW and fly ash from the bomb calorimeter is carried out. Chemical compositions of these samples were analyzed with x-ray fluorescence spectroscopy, atomic absorption spectroscopy (AAS).

RDF Production
Magnetic separation and Eddy current separations is proposed to separate the ferrous and non-ferrous metals while glass and plastics would be separated by optical scanning system, pneumatic and NIR sensor sorting system. The plastics content is suggested to be first removed during sorting and added backed to the MSW after drying. The presence of the plastics will increase the cost of shredding and pelletizing, but the plastics contents is expected to give higher heating value and hydrogen content (Wu and Williams, 2010a, 2010b; Ahmed and Gupta, 2009; Dalai, *et al.*, 2009).

The combustibles materials (plus plastics) after the separation are dried, shredded and pulverized to form a fluff, which is then pelletized to produce RDF. The pelletizing process can be achieved by different techniques, by adding a binder or by direct compacting without any binder. In this work, used vegetable oil is proposed as a binder. Previous works done shown that emission of obnoxious compounds during gasification is not changed. The net calorific heat value of pellets is about 24 MJ/ kg. The pellets should be secured in close containers to prevent adsorption of water. The characteristics of the final pellets will depend on the gasifier design. An optimum gasification process depends on the pellets particle size, and particle size distribution, pellet density (measured and controlled by the pore volume and pore volume distribution), and hence need to controlled as desired.

Gasification of RDF
Gasification is the thermochemical conversion of a carbon-containing material through the addition of heat in an oxygen-starved environment (Basu, 2010) using air or oxygen and their mixtures to produce gaseous products, rich in hydrogen and carbon monoxide (or synthesis gas). RDF gasification reduces corrosion and emissions by retaining alkali and heavy metals (except mercury and cadmium), sulphur and chlorine within the process residues (Chen *et al*., 2011) and reduces thermal NO_x formation due to lower temperatures and reducing (He *et al*., 2009).

The hydrogen-rich gas would be directly used in the production of electrical power in fuel cells (Chaudhari *et al*., 2003). The product yield during the gasification of MSW depends on temperature, pressure, time, reaction conditions and reactor type. RDF gasification processes have been studied using several different types of reactors such as fixed bed, fluidized beds, rotary kilns and plasma furnace (Xiao *et al*., 2006; Min *et al*., 2005; Galvagno, *et al*., 2006; Mountouris, *et al*., 2006). Basu (2010) reported that a survey of gasifiers in Europe, the United States, and Canada show that downdraft gasifiers are the most common, 75 % are downdraft, 20 % are fluidized beds, 2.5 % are updraft, and 2.5 % are of various other designs. The fixed bed gasifier air-blown downdraft is simple type gasifier compared to other fixed bed types. It is one of the simplest and cheapest biomass conversion technologies (McIlveen-Wright, *et al*., 2011). Updraft fixed bed gasifier is proposed because of tar formation and removal.

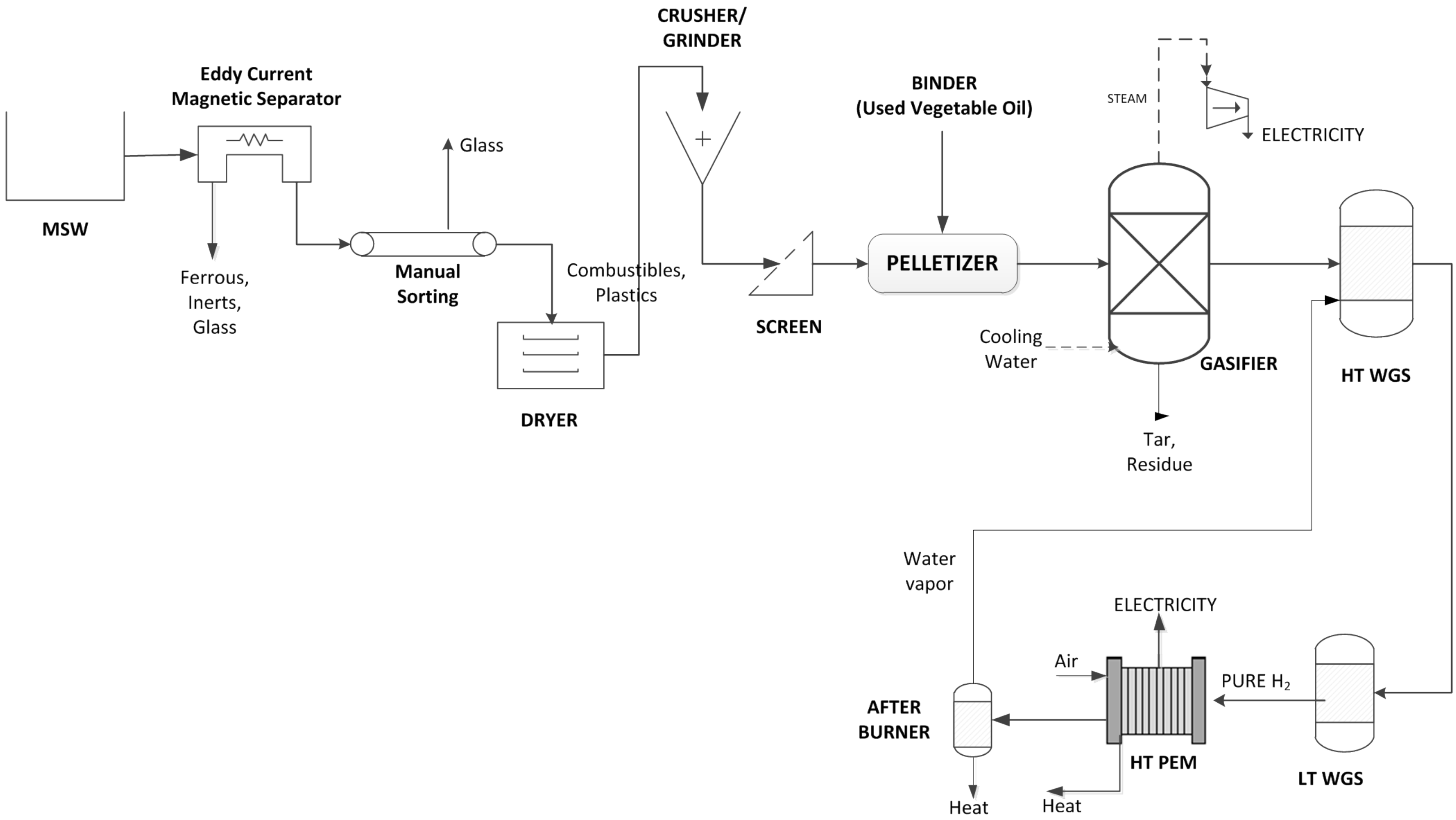

Figure 3: The Proposed Ideal Cogeneration System

Syngas Post Processing and Cleaning

The synthesis gas from the gasifier is sent to the Water Gas Shift (WGS) reactors to convert the CO into more hydrogen. This increases the total yield of hydrogen and also reduces the CO content of the gaseous products. During the WGS reaction, CO and H_2O react in the presence of a catalyst to form CO_2 and H_2. 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 temperature ranges: 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. Otherwise an additional preferential oxidation (PROX) reactor may be necessary.

The High Temperature PEM Fuel System

The predominantly hydrogen product from the Lower Temperature Water Gas Shift (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 ^{0}C which is tolerable by the phosphoric acid doped Polybenzimidazole (PBI) membrane. 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 to re-use the materials for heat production. The waste heat and H_2O generated are integrated back into the system. 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 Rabiu *et al*. (2011) to be presented in the next paper. The stack simulation study was implemented in Engineering Equation Solver (EES).

Conclusion

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 system is made of three major sub-systems: the fuel processing sub-system, the fuel post-processing and cleaning and the High Temperature Polymer Electrolyte Membrane (HTPEM) fuel cell stack sub-system. All these are shown in Figure 2. The HTPEM fuel cell-based CHP system produces little emission and gave high total system efficiency. Further studies are being conducted on the use of process integration technique to optimally integrate the various sub-systems and hence improve its overall economics. This system provides solution to the twin problems of waste management and energy security and with very little environmental footprint.

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