Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 90 (2014) 718 – 724

Procedia Engineering

www.elsevier.com/locate/procedia

10th International Conference on Mechanical Engineering, ICME 2013

An experimental investigation of solid waste gasification using a large pilot scale waste to energyplant

SharminaBegum[a*], M. G. Rasul[a], David Cork[b] and DelwarAkbar[c]

[a]*School of Engineering and Technology, Central Queensland University, QLD 4702, Australia*
[b]*TheCorky's Group, Mayfield, NSW 2304, Australia*
[c]*School of Business and Law, Central Queensland University, QLD 4702, Australia*

Abstract

Management and treatment of solid waste can mitigate adverse impacts on environment and human health, and also can support economic development and quality of life. A number of thermo-chemical waste treatment methods (i.e. waste-to-energy conversion pathways such as, Pyrolysis, Gasification and Incineration) can transfer solid waste into energy, while gasification technology provides an efficient and environmental friendly solution to produce energy in the form of syngas. This paper presents an experimental investigation of syngas production using a pilot scale fluidised bed gasification process for energy recovery from solid waste. As feedstock preparation plays an important role to increase performance of gasification, steps of feedstock preparation (sorting, shredding and dying) are explained in detailed. Syngas production and clean-up and burning process is explained. The composition of syngas produced at different stages of the experiment is presented. Heat balance of heat engines, emission control and mass and energy balances of gasification plant used for energy recovery in this study is presented and discussed. This study found that about 65% of the original energy of solid waste is converted to syngas and 23% is converted to char with remaining 12% as residue loss. The primary energy conversion is done by burning syngas in a 0.5 MWe gas engine through an otto cycle power generation.

Selection and peer-review under responsibility of the Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET)

Keywords: Gasification; Solid waste; Fluidised bed; Syngas.

* Corresponding author. Tel.: +61-7-49309283
E-mail address: s.begum@cqu.edu.au

Selection and peer-review under responsibility of the Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET)
doi:10.1016/j.proeng.2014.11.802

1. Introduction

Food, commodity and energy consumptions have been growing very rapidly with the rapid growth of urbanization as the world is becoming a global urban village, where more than 60% of the total population will live in urban centers by 2050.Australia has one of the highest rates of waste generation per capita in the world because majority of it population live in the urban centers[1, 2]. Solid waste includes the waste that generates through municipal and industrial activities such as, garbage, recyclable materials, organic waste and hard waste. During 2009-10, there were 21.6 million tons of waste received at landfills, with 7.4 million tonnes (34.2%) coming from the domestic and municipal waste stream, 6.7 million tonnes (30.8%) from the commercial and industrial waste stream and 5.6 million tonnes (25.8%) from the construction and demolition waste stream [2].There are many cities in Australia and other developing countries in the world dealt with this problem of how to utilize large amount of solid waste in an effective and efficient manner.

Recently, a number of Alternative Waste Technologies (AWTs) have been developed for waste treatment. AWTs illustrate processes that generally, (a) redirect waste away from landfill, (b) pick up more resources from the waste stream and (c) reduces the impact on the environment [3]. Following a detailed investigation and using multi-criteria analysis (MCA), it has been established that Gasification is a suitable technology for Australia among a number of available AWTs (Anaerobic Digestion, Pyrolysis, Incineration and Gasification) [4].

Gasification is a process that changes biomass or solid waste through the addition of heat in an oxygen-starved environment. Recently, Kwon and Castaldi[5] investigated the enhanced gasification of municipal solid waste (MSW) using carbon dioxide (CO_2) as the gasification medium to achieve environmentally caring and energy efficient ways for the disposal of MSW. They found, there are two main steps of thermal decomposition of MSW: firstly thermal degradation step occurs at temperature between 280°C and 350°C and consists of the decomposition of the biomass component into light $C_{1–3}$-hydrocarbons. The second thermal degradation step occurs between 380°C and 450°C and is mainly attributed to polymer components, such as plastics and rubber, in MSW. Belgiorno et al. (2003) investigated the state of gasification technology, energy recovery systems, pre-treatments and prospect of syngas use with particular attention to the different process cycles and environmental impacts of solid wastes gasification. They identified gasification process offers energy recovery and reduce the emission of potential pollutants [6].Gasification with pure oxygen results in a higher quality mixture of carbon monoxide and hydrogen and virtually no nitrogen. Gasification with steam is more commonly called 'reforming' and results in a hydrogen and carbon dioxide rich 'synthetic' gas (syn-gas). The gas has a calorific value of 4-10 MJ/Nm^3 and can be used to generate electricity [7]. Typically, the exothermic reaction between carbon and oxygen provides the heat energy required to drive the pyrolysis and char gasification reactions [8]. There are six basic reactions (1 - 6), that must be considered during the process. All of these reactions are reversible and their rates depend on the temperature, pressure and concentration of oxygen in the reactor [9].

$C + O_2 = CO_2$ -393 kJ/mol (exothermic) (1)

$C + H_2O = CO + H_2$ +131 kJ /mol (endothermic) (2)

$C + CO_2 = 2CO$ +172 kJ/mol (endothermic) (3)

$C + 2H_2 = CH_4$ -74 kJ/mol (exothermic) (4)

$CO + H_20 = CO_2 + H_2$ -41 kJ/mol (exothermic) (5)

$CO + 3H_2 = CH_4 + H_20$ -205 kJ/mol (exothermic) (6)

Many significant researches of waste gasification have been reported in the literature. Liu et al. [10] compared various technologies of MSW disposal and identified that thermal technologies have the most potential in China as well as the developing countries. Ni et al. [11] and Xiao et al. [12 and 13] studied the gasification characteristics of components in MSW and concluded that organic components could be gasified efficiently at 500–700°C. The gasification characteristics of MSW were studied at 500–750°C when equivalence ratio (ER) was 0.2–0.5 using a fluidized-bed gasifier by Xiao et al (2007b). They found that when temperature was 550–700°C and ER was 0.2–0.4, low heat value of syn-gas reaches to 4000–12000 kJ/Nm^3[14]. The purpose of this paper is to demonstrate a large pilot scale gasification plant's experimental investigation of energy recovery from solid waste. Feedstock preparation, i.e. feedstock sorting, shredding and dying is explained in detailed. Partial fluidisation was considered in this study in order to achieve faster dying and reaction rates. Composition of syngas at different stages of the experiment is presented. Syngas production and clean-up, emission control and mass and energy balance of the plant for energy recoveries are discussed.

2. Methodology

In this study, a pilot-scale fluidized bed gasification process plant was used for energy recovery from solid waste. The overall solid waste gasification process involves a number of steps. A schematic diagram of the whole process is shown in Figure 1.Generally, gasification process includes two main tasks: preparation of feedstock materials and plant set-up.Feedstocks are collected from neighboring City or Regional Councils. Collected wastes are prepared and sorted. To increase gasification performance, prepared feedstock was dried to reduce moisture. Gasification process is placed in reaction vessel in the presence of air producing raw syngas. Syngas cleaning is done to remove the pollution from produced raw syngas. Burning is done in an internal combustion engine depending on its requirement.

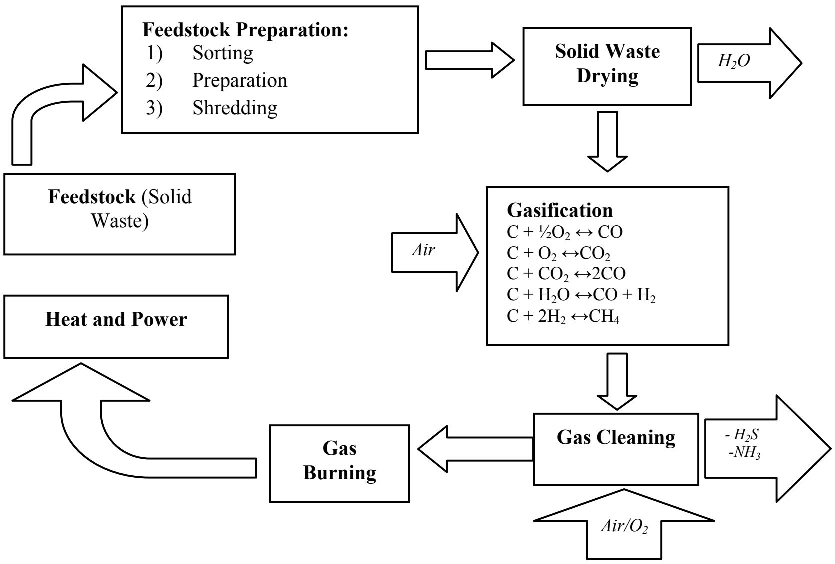

Fig. 1. Schematic diagram of solid waste gasification process.

2.1 Sorting and preparation of feedstock

The initial and most important step of gasification plant operation is solid waste sorting and preparation of feedstock. In this step, all recyclable steel, glass, aluminium, clean plastics and cardboard, the material that reduces process efficiency like stones, concrete, glass are removed. Alternatively, wastes that do not need sorting (i.e. council green waste, manures, and timber mill waste) are brought to site. Before using the feedstock at gasification plant, several items need to be removed and recycled or disposed from the feedstock, such as, (a) polyethylene terephthalate (PET) plastic and clean cardboard are removed when there is a viable market for the recycled material, (b) green wastes are removed when there is a viable market for the compost, (c) aluminium, glass and scrap metal are recycled to protect the shredder teeth, (d) abrasive materials like rocks, concrete, and crockery are removed to protect the shredder teeth and (e) electronic waste (E-waste) contains copper are not allowed to enter the reactor as copper can increase the rate of emission of some undesirable compounds.

Some feed stocks are predictable and are not needed sorting, which includes (a) saw dust and off cuts from saw mills, (b) manure, spilt food and sawdust which is typical of many feed lots and (c) council green waste after community education. High moisture items like fresh manure, fresh green waste or rotting fruit can have a negative effect on the productivity of the reactor. A dryer is used in this process to avoid the risk of these types of feeds entering with the feedstock. The sorted and shredded feedstocksare stored separately to ensure that contamination with unsorted material does not occur. The loading process was done manually using a small loader. Suspicious items in the waste are pulled aside using the loader. Tramp irons are removed using a magnetic separator.

2.2 Plant set-up

The gasification plant is composed of four modules: a waste pre-processing unit, the gasification/oxidation chambers, the energy recovery section and finally the flue gas cleaning module. In the pre-processing module the waste is sorted, grinded, shredded, stored and dried with the purpose of obtaining a gasification-friendly feed material, free of metals, glass and plastic bottles. The layout of the Gasification plant is shown in Figure 2. The main components of the plant are: waste receivable area, zerma shredder, reactor, hopper, scrubber, catalytic converter, combustion chamber and bag house. Brief descriptions of each steps of gasification are given below:

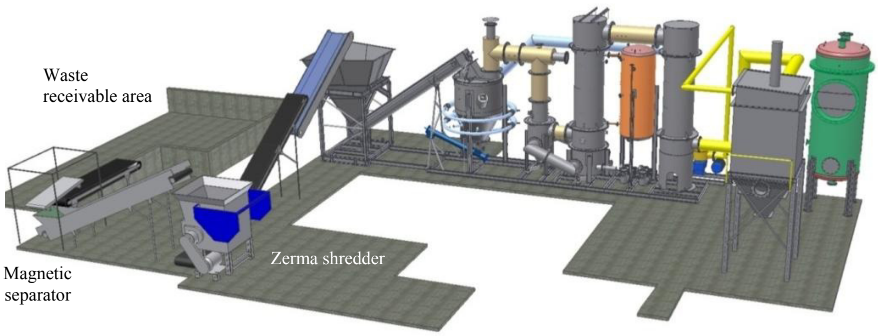

Fig. 2. Layout of gasification plant [15]

2.2.1 Shredding

Shredding is defined as the size reduction process to reflect the requirement of tearing, ripping and cutting of plastic items. Shredding reduces the average particle size to improve drying speed, reaction speed and improve flow characteristics in screws and in the reactor. Fresh wood and food scraps are somewhat malleable and therefore exhibit similar behaviour to plastic in their deformation under load. Older, dry wood and manure is brittle enough to be reduced in a chipper or hammermill. A hammermill is a machine whose purpose is to smash material into fine particles. Shredders tend to use more power than hammer mills. The smaller the largest particle size is set after shredding for the higher power consumptions.The intent of the shredder is to create a granular, free-flowing, high voidage feedstock. To ensure this, the largest feed particles are: (a) smaller than 60 mm on their largest dimension, (b) smaller than 30mm by 30mm, 45mm by 20 mm, or 60mm by 15mm. That is the largest dimension times the next largest dimension is to be less than 900 mm^2 and (c) strips of plastic, timber or paper are unacceptable.

Reducing particle size increases the particles' rate of drying and gasification. The size reduction device, be it a shredder or hammer mill, is by far the largest internal power consumer on site. Therefore the size reduction is fundamental to the success of the reactor and overall power output. A poorly maintained shredder or hammer mill can reduce net power available to the grid or if the process is primarily producing char, can require high levels of electricity. The Zerma Shredder is a good compromise for general duty shredding, is used in this experiment.

2.2.2 Drying

Typically waste has two types of water content, surface moisture and inherent moisture. Surface moisture is water on the surface of waste particles and held by capillary action within the micro fractures of the waste and fibres of the green waste. Inherent moisture is water held within the waste organic compounds and in the crystal structure of hydrous silicates such as clays.Drying is important to remove excess water from feedstock. With dry feed the excess water is removed in the reactor. Normal solid waste, however, needs an extra dryer to remove the surface moisture after shredding but before the reactor. Water vapour is beneficial to the process, as it reduces soot and carbon deposits in the scrubbers. Liquid water in the feed is detrimental, as a mere 1% increase at 25% moisture content reduces productivity by 2%. At 50% moisture, a 1% increase reduces productivity by about 3% [15].

For most solid wastes, the fresh surface moisture is typically about 25% to 30% and the inherent moisture is also typically about 25% to 30%. That is the waste can feel very dry and still contain 25% moisture. If the waste is dried significantly below the inherent moisture then on hot high humidity days the waste reabsorbs moisture and self heats. The risk of spontaneous combustion is reduced if the waste is stored in low heaps rather than a single large pile. The feed screw can be heated using hot oil so that some moisture flashes off the waste as it enters the reactor.

2.2.3 Reaction vessel

A reaction vessel is used either to convert waste to large amounts of char and ash with small amounts of syngas (called *carbonisation*) or to convert waste to small amounts of char and ash with large amounts of syngas (called *gasification*).In the reaction vessel: (a) waste's surface moisture is dried, along with all of the inherent moisture, (b) waste is further heated, (c) waste generates volatiles (oils, tars and methane which appears as yellow smoke), (d) partial combustion (yellow smoke) generates heat and evaporates plastics and (e) char is gasified by reacting with oxygen (O_2), steam (H_2O) and (carbon di-oxide) CO_2 to form (hydrogen) H_2 and (carbon monoxide) CO.

The experimental reaction vessel has a nominal volume of 2.5 m^3, a waste and char capacity of approximately 1.75 m^3 and a freeboard capacity of 0.75 m^3. The freeboard is the space above the fluidised bed, where the gas slows down after leaving the bed and most of the solids fall back into the bed. The waste is partially fluidised in the reactor by a gaseous mixture of waste gas (burnt syngas - N_2, CO_2, H_2O) and fresh air (N_2, O_2).

The reactor is initially heated by a LPG burner which ignites the waste.After the reactor is at working temperature, the burner is turned off and the burner slipped to isolate it from the reactor. The heating from this point on is perpetuated internally by sub-stoichiometric combustion gasification inside the reactor, by pre-warming the waste to approximately 160^{o}C to 200^{o}C in the screw feeder, and by pre-warming the fluidisation air.

2.2.4 Syngas cleaning

This step removes pollution or pollution-forming trace compounds before syngas use. During solid waste gasification, various pollutants may be produced depending on gasifier operational parameters (temperature, feed-rate and size distribution) and the composition of the solid waste material. The pollutants can include sub-micron particulate matter, phenol, cresol, heavy tars, ammonia (NH_3), hydrochloric acid (HCl), and sulphur compounds. These compounds can reform to produce dioxins and furan if not managed well. The management plan includes, (a) restricting the feedstock to exclude PVC, Gortex and Teflon which control Chlorine and Fluorine in the process, (b) drying high moisture waste before reaction which leads to less heavy (long carbon chain) tar yield and greater gas yield, (c) acid scrubber to mop up SO_x, NO_x, Cl^-, F^-, phenol and cresol which operates under reducing conditions, (d) catalytic conversion of phenol, cresol, ammonia and heavy tars into light gas under anoxic conditions (the scrubber must be over 400^{o}C for this to work, preferably over 500^{o}C), (e) rapid indirect quench of waste gas to stop formation of dioxins and furans, (f) light compression and cooling in liquid rind vacuum pump to remove gaseous moisture and fine dusts from the syngas and push them into the water phase and (g) capturing post combustion particles in the bag house.

2.2.4 Syngas burning

The syngas is burned and used in an internal combustion engine or an external combustion engine depending on the requirements. An external combustion system was used at the plant. Electricity can be generated from this activity. Syngas can be used in a number of ways. These uses are consistent with 'off-the-shelf' technology. It can be burnt in the thermodynamic systems are:gas engine (Otto cycle), gas turbine (jet engine also known as

Braytoncycle) and burnt externally and the heat collected to run: steam or refrigerant turbine (Rankine cycle), stirling engine (Carnot cycle), absorption chillers or used as process heat.

3. Results and Discussions

3.1 Syngas production

Solid waste is the initial energy source. Using solid waste, gasification is done in a single vessel (reactor vessel). The wastes are heated and dried in the drier which uses hot oil at 220°C. The solid wastes are heated about 700°C to 1100°C in a reduced oxygen environment inthe reactor. In the reactor raw syngas are developed which is a mixture of CO, CO_2, H_2, H_2O, N_2 and CH_4. The raw syngas is contaminated with tar H_2S, NH_3 and trace HCl. The fine solid waste leaves the reactor and settles on the top of the scrubber and forms a network of fine carbon char. The tar gets trappedon the char network and burnt dolomite at the top of the scrubber and is subsequently broken down into C, CO, and H_2 and H_2O. The H_2S and NH_3 are converted to SO_2 and NO and H_2O in the scrubber. The dolomite mops up the acid gases like SO_2, NO, NO_2 and HCl. Oxygen are added at the scrubber to maintain the scrubber temperature at about 600°C.

The hot syngas is indirectly cooled using heat transfer oil. The heated oil is used for drying the solid waste. The hot syngas is further indirectly cooled using fluidising gas.The heated fluidising gas is used in the gasifier. The warm syngas is further cooled and compressed the syngasusing liquid ring compressors. This is a final scrub for acid gases and also removes about 80% of the water out of the syngas. The clean syngas is a mixture of CO, CO_2, H_2, N_2 and H_2O. The compounds of syngas found at different stages are shown in Table 1. Approximately 65% of the original energy in the solid waste is converted to syngas. Approximately 23% of the original energy is converted to char, and about 6% is converted to hot oil. The remaining 6% is lost in heat. These results are a function of the small size of the experimental plant.

Table 1. Compounds of syngas at different stages of gasification.

Compound, %	Raw syngas, %	Scrubbed syngas,%	Dewatered syngas, %
H_2	19.0	20.0	20.8
CO_2	11.4	12.0	12.5
CO	28.5	30.0	31.3
CH_4	1.9	2.0	2.1
H_20	5.7	6.0	2.1
N_2	28.5	30	31.3
Phenol, cresol, tars, H_2S and NH_3	5	-	-

3.2 Power generation

The primary energy conversion is done by burning syngas in a number of 0.5 MWe gas engines, running in parallel. This is called an Otto cycle power conversion. The energy partition of the syngas is shown in Figure 3 which is based on gas engines designed for syngas.The conversion of low grade heat to electricity is not very efficient. An ORC (organic Rankine cycle) power plant is used to convert this low grade heat to generate electricity.

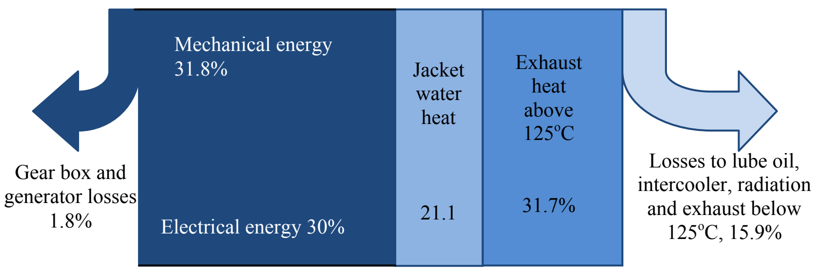

Fig. 3. Heat balance of a gas engine.

The working fluid is R245 and the heat supplied by hot oil at about 140°C (2.0MW_t) and water at 85°C (0.4MW_t). The residual useful heat is 1.2 MW_t at 80°C.

4. Concluding Remarks

This paper described the gasification processes to convert solid waste to energy in the form of syngas, along with a detail description of a waste treatment plantincluding the plant set-up and working processes of each component. The analysis of compounds of syngas at different stages and mass energy balance of integrated dryer gasification process were examined. In this gasification process, approximately 65% of the original energy in the solid waste is converted into syngas, 23% of the original energy is converted to char, and about 6% is converted to hot oil. The remaining 6% is lost in heat.

Acknowledgements

This work was supported by The Corky's Group: Corkys Carbon and Combustion (http://www.corkys.net.au/).

References

[1] N.Marchettini, V.Niccolucci, F. M.Pulselli, and E.Tiezzi, Environmental sustainability and the integration of different methods for its assessment, Env. Sci. Pollut. Res, 14 (2007) 227-228.

[2] Australian Bureau of Statistics (ABS), Waste Management Services, http://www.abs.gov.au/, (2010), retrieved at 9th October 2012

[3] Begum, Sharmina, M. G.Rasul, Akbar, Delwar., An Investigation on Thermo Chemical Conversions of Solid Waste for Energy Recovery, World Academy of Science, Engineering and Technology, 62 (2012a),624-630.

[4] Begum, Sharmina,M. G. Rasul, and Akbar, Delwar, Identification of an Appropriate Alternative Waste Technology for Energy Recovery from Waste through Multi-Criteria Analysis, *World Academy of Science, Engineering and Technology*, 63 (2012b) 944-949.

[5] E. Kwon, Eilhann., J. Castaldi, Marco, Urban energy mining from municipal solid waste (MSW) via the enhanced thermo–chemical process by carbon dioxide (CO_2) as a reaction medium, Bioresource Technology, 125 (2012) 23–29

[6] V. Belgiorno, G. D. Feo, C. D. Rocca, R. M. A. Napoli, Energy from gasification of solid wastes. Waste Management, 23(2003) 1-15.

[7] S. Zafar, Gasification of Municipal Solid Wastes, *Energy Manager*, 2(1) (2009) 47 – 51

[8] EREN,Gasification Based Biomass, *http://www.eren.doe.gov,*(2002),retrieved at 10 Oct 2012

[9] H. Krigmont, IBGCC power generation concept: A gateway for a cleaner future, Allied Environmental Technologies, http://www.alentecinc.com/papers/IGCC/advgasification.pdf, (1999) retrieved at 10 Oct 2012

[10] X. F. Liu, Y. Z. Liao, K. X. Liu, Technology of comprehensive disposal and utilization of municipal solid waste (MSW), *Journal of Environmental Sciences*, 11(3) (1999) 378–380.

[11] Ni M J, Xiao G, Chi Y, Study on pyrolysis and gasification of wood in MSW, Journal of Environmental Sciences, 18(2) (2006) 407–415.

[12] G. Xiao, Y. Chi, M.J. Ni, Fluidized bed gasification of PE palstic in municipal solid waste, *Journal of Chemical Industry and Engineering*, 57(1) (2006) 146–150.

[13] G. Xiao, Y. Chi, M. J. Ni, Fluidized-bed prolysis and gasification of waste paper in MSW, *Journal of EngieeringThermophysics*, 28(1)(2007) 161–164.

[14] G. Xiao, J.Bao-sheng, Z. Zhao-ping, C. Yong, N. Ming-jiang, C.Ke-fa, Xiao, Rui., H.Ya-ji., H. He, Experimental study on MSW gasification and melting technology, *Journal of Environmental Sciences*, 19 (2007b), 1398–1403.

[15] The Corky's Group, Gasifier Operator Manual, (2010) New Castle, Australia.