A Review of Municipal Solid Waste Gasification Technologies for Possible Fixed Bed Hybridization

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Abstract: ***The present paper assesses current municipal solid waste (MSW) gasification process, carryout a critical overview of MSW fixed bed gasifiers. The overview has also focused on the comprehensive evaluation of various gasification process operating parameters and its effects on syngas production for the aforementioned reactors and outline key suggestions for gasifier performance improvement. Thorough evaluation of these gasification process models and evaluation of operating parameters would further assist in the development of gasifiers technology for future MSW gasification. This review discusses gasification technology including its challenges for MSW, propose possible hybrid gasification technology. Results show that fixed bed gasifier design modification by the combination of gasifier features has shown better results in terms of clean producer gas.***

Keywords: Gasifier, Gasification, Waste-to-energy, Municipal solid waste management, hybridization

1. Introduction

Globally energy has been the key resource for economic development particularly due the increase in industrialization and urbanization. At present, about 81% of all the energy used globally is derived from fossil fuels (Siedlecki *et al.*, 2011). Over dependence on fossil fuels have resulted in the increase of greenhouse gases emission which in turn intensify multiple challenges including the effect of global warming, geopolitical conflicts and significant fuel price fluctuations (Schwartz, 1993; Dewallef, 2015). These problems indicate unsustainable situation. Notwithstanding their negative impacts on the environment, fossil fuels are however known to deplete with time as depicted in Hubbert curve (Dewallef, 2015). With the intention to meet the growing demand for energy, a major challenge remains for scientists and researchers in having an alternative clean and sustainable energy supply from renewable sources (Adra, 2014).

Municipal solid waste (MSW) is one of the potential renewable energy source which comprises of daily use, thrown bits and pieces of food waste, furniture, glass, papers, plastics and all wastes similar to household waste excluding hazardous wastes form industries and hospital (Shin, 2014; Tozlu *et al.*, 2016). Moreover, MSW is a result of human daily activities which produce solid waste that need to be collected and thereafter be either disposed off or processed for further reuse in different purpose including energy production. Therefore it is a wrong concept to consider waste as worthless (Baran *et al.*, 2016). However, despite that it is potential renewable energy source; MSW has become catastrophe to many municipalities due to its side effects when not disposed properly. These side effects includes: blockage of drainage and spread of some diseases due to the increase in insects breeding (Ejaz *et al.*, 2010; Singh *et al.*, 2014).

There has been an increase of MSW generation which does not march with the capacity of many municipalities to dispose it. Globally, the generation is dramatically increasing despite several measures being undertaken. Worldwide the generation is expected to increase to about 2.2 billion tonnes per year in 2025. While MSW generation is increasing, open landfill has remained to be the major method for waste disposal although to some extent metal and plastic wastes have been recycled. With this method there has been a concern on health issues and environmental pollution especially in air, water and land (Sipra *et al.*, 2018).

Waste to Energy (WtE) technologies is becoming an attractive area of interest for MSW management (MSWM). These technologies includes bio-chemical, chemical and thermal conversion (Moya *et al.*, 2017). Among the three technologies thermal conversion technology is the most attractive for MSWM (Arena, 2012; Pilusa and Muzenda, 2014). There are several advantages associated with the use of WtE technology in comparison with other methods as detailed in Table 1.

Table 1: Capital Costs, Advantages and Disadvantages of WtE Technology

Technology	Capital cost (US$/tonne of MSW/year)	Advantages	Disadvantages
Land filling (Kalyani and Pandey, 2014; Tozlu *et al.*, 2016)	10–30	-Most economical technology -Require less skilled personnel	-Leachate from the system contaminate underground water -Require Large land area -Pollution in rain season due to Surface runoff -Transportation cost is high -Can Yields about 30%–40% of the total gas generated -Risk of exploration due to methane build up
Biochemical Conversion (Barrows, 2011)		-Require less land area -Does not require external source of power for turning and mixing up wastes -Better leachate and GHG emission control	Waste sorting for feedstock with highly organic matter is required
Anaerobic digestion (Balat, 2006; Themelis and Ulloa, 2007)	50–350	-It does not require any external source of power -The land require for the system is ideal	-Has low efficiency when feedstock sorting is not done - Require feedstock with much higher organic content
Gasification (McKendry, 2002; Belgiorno *et al.*, 2003; Kalyani and Pandey, 2014)	250–850	- Biomass gasification is well proven technology -The process produce fuel gas which can be used for power generation -The use of gas fuel is helpful in the reduction of CO, NOx, furans, and dioxins hence better Pollution control. -Processing system can be located within the cities to reduce transport costs.	-Less efficient with highly moisture content above 30% as it create ignition difficult and reduces the syngas CV
Pyrolysis (Roos, 2010; Wang, 2013)	400–700	-Better air pollution control	-Less efficient with high moisture content -The burning and transportation of pyrolysis oil is difficult due to high viscosity - It is less mature technology in comparison to gasification
Incineration (Srivastava *et al.*, 2015; Ouda *et al.*, 2016)	400–700	-Less land area is required -Provides maximum volume reduction	- Require skilled personnel -High Initial cost -High Toxic metal concentration in ash, particulate emissions, SOx, NOx,

Thermal conversion technology is characterized by large mass and volume reduction of about 80% and 90% respectively (Zhang *et al.*, 2010; Maya *et al.*, 2016). Furthermore, it can be employed in a limited space as compared to landfill (Mutz *et al.*, 2017; Abdel-Shafy and Mansour, 2018). In thermo-chemical conversion process wastes are heated in different amount of oxygen and different temperature range. This results into the three common thermal technologies namely: incineration, pyrolysis, and gasification (Kumar *et al.*, 2009; Moustakas and Loizidou, 2010; Kumar and Samadder, 2017).

In incineration process the wastes are decomposed at high temperature above 800 °C to generate ash, heat and flue gases under excess air. In pyrolysis process wastes are heated under oxygen free environment to release gases, tars and char (Agarwal, 2014). The bio char produced by pyrolysis can be further treated through gasification process to release the remaining constituents (Brownsort, 2009). On the other hand gasification is carried out with limited amount of air/oxygen to produce syngas (CO, N_2, CH_4, H_2O, CO_2 and H_2) (Kadafa *et al.*, 2012; Kumar and Samadder, 2017). Now days Hydrothermal Carbonization (HTC) is an emerging technology where high moisture wastes are heated under pressure and temperature below 204 °C to produce hydrochar (Stanley, 2013).

Gasification

Gasification process converts organic compound in the MSW to produce synthesis gases primarily hydrogen, carbon monoxide and small amount of gases such as methane, carbon dioxide, nitrogen etc, through oxygen starved environment as represented in the following chemical reaction:

$$CH_xO_y + O_2 = CH_4 + CO + CO_2 + H_2 + H_2O + C + Tar$$

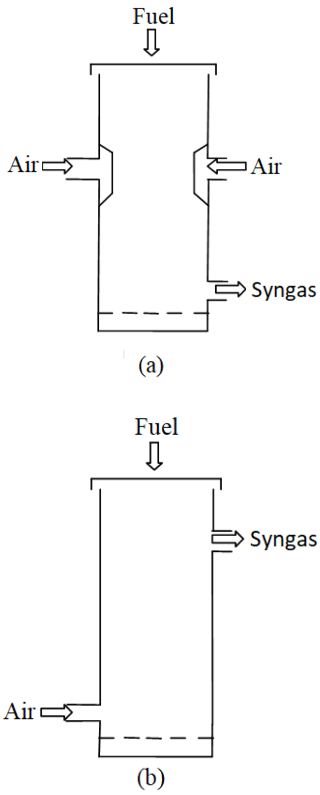
(Kumar *et al.*, 2009). The quality of syngas produced is characterized by among other factors, the type of feedstock, temperature and the type of gasifying agent (Air, oxygen, water) (Kumar *et al.*, 2009). According to Pilusa and Muzenda (2014) gasification of MSW in form of refuse-derived fuel (RDF) is more effective for heat generation and production of syngas. The chemical reaction aforementioned and some other reactions take place in the device known as gasfier in which some of MSW is combusted to generate heat for facilitating gasification process (Klein, 2002).

Generally, fixed bed, fluidized bed and entrained flow are the common gasifier design in use depend on the intended purpose. However fluidized bed gasifier has high initial cost as well as complexity in design as compared to fixed bed gasifier. Fluidized bed gasifier design is more preferred for large scale application while fixed bed is commonly employed for small scale range (Kramreiter *et al.*, 2008).

Fixed bed Gasifier History

The history of fixed bed gasifier is referred to some years back when Bischaf introduced the updraft gasifier for coke gasification in 1839, and later on in 1881 there was an attempt to use gasifier products for running the internal combustion engines (Chopra and Jain, 2007). Fossil fuels came in as cheap energy source at the end of the second war hence lower the interest of research in gasification. However, in 1970 there was global energy crisis which forced the scientists to move back to biomass gasification technology so as to cover the gap on energy demand (Demirbas, 2006) . Now days the interest has shifted to MSW gasification for two reasons: energy recovery and secondly MSWM. Although, there have been different MSW gasification system, this study focuses on fixed bed system due to its low initial cost.

Commonly there are three types of fixed bed gasifier (FBG): downdraft, updraft and cross flow (Figure 1). These are named with respect to the direction of the flow of gasifying media (air, oxygen, carbon dioxide and steam). In these three types of gasifiers the feedstock enters from the top and flows downward, their difference being the gasifying media flow direction as well as the direction of produced sygas.



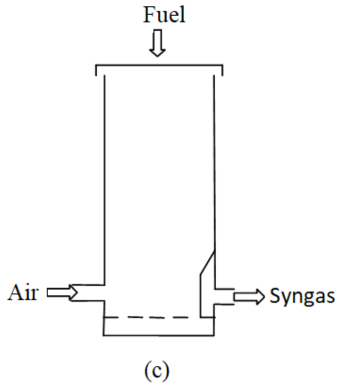


Figure 1: Types of fixed bed gasifiers: (a) Downdraft, (b) Updraft, (c) Cross draft

Updraft gasifier (Figure 1 b) is one of the mostly common FBG in use especially when the temperature of producer gas is taken into consideration. It produces gases with low temperature as compared to the other two types since the gas produced dries the feedstock before exit. The gasifying media enters at the bottom and flows up the gasifier against the feedstock flow direction. However, the tar content in the syngas is higher than that obtained in the other two types therefore requires extensive clean up. Hence for these reasons this study will consider downdraft and cross draft gasifier.

In downdraft gasifier (DDG), (Figure 1 a) gasifying media enters at the center and flow downs the gasifier in the same direction with the feedstock. Two main designs are employed in this type: imbert and stratified designs. The imbert also known as throated type is designed with small cross section area known as throat at a convinced height in a combustion zone. The stratified also known as throttles the entire gasifier is cylindrical. These designs have advantages and disadvantage as outlined in Table 2.

Table 2: Advantages and disadvantages of downdraft gasifier design (Mangre *et al.*, 2017; DALMIŞ *et al.*, 2018)

Downdraft gasifier design	Advantages	Disadvantages
Imbert	-Has uniform temperature distribution -Better tar conversion efficiency as pyrolyized fuel pass through narrowed CSA	-Manufacturing is costly due to throat design -Bridging and channeling is commonly experienced.
Stratified	-Easy to manufacture -Bridging and channeling is less encountered -Best for fuel with low density	-Temperature distribution is not uniform -Less tar conversion efficiency

Generally, several advantages are associated with downdraft gasifier design. It produces gases fuel with low tar; this makes it more superior to updraft gasifier for clean producer gases. Tar is an aromatic condensable hydrocarbon which causes fouling on pipes and equipment where producer gas is being used if not cracked into combustible particles. In downdraft gasifier tar produced in the pyrolysis zone is carried along with incoming air through hot oxidation zone where tar cracking occurs, however, complete tar separation is not well achieved. The feedstock moisture content is limited at 25 % hence can not handle biomass with high moisture content.

Rajvanshi (1986) reported that chemical reaction at the downdraft gasifier throat do not allow complete separation of tar from producer gas. It was also reported that there have been several methods for producer gas cleaning including filtration, catalytic and thermal cracking (Asadullah, 2013b). However, the use of filtration and catalytic conversion methods requires addition cost to the gasification system.

Cross flow gasifier (Figure 1 c) is named since the gasifying media enters at one side and flow across the gasifier. This type is commonly used in small scale range contrary to updraft type. The type is not affected by the feedstock moisture content as it can handle biomass with considerable moisture content, especially when the top of the gasifier is open for moisture to escape. However, the fuel particle size is considered to be small about 20 mm while the maximum size that can be handled by updraft as well as downdraft is about 70 mm respectively. Apart from being economically feasible at small scale range, cross draft gasifier produces much more purer syngas as compared the other two fixed bed gasifier previously mentioned (Giouzelis *et al.*, 2016).

MSW Gasification in a fixed bed gasifier

Gasification of biomass is becoming of great important due to the increase of energy demand as a result of population growth, urbanization and industrialization. Fixed bed gasification systems have been in use for some number of decades for biomass gasification. Some commercial downdraft and cross draft gasification systems have been developed in some countries. These include downdraft gasifier developed by a company Xylowatt in Belgium for wood chips gasification and a cross draft system developed by ITI Energy Ltd in UK for solid waste gasification. Recently, there has been an interest on MSW gasification due to the increase in MSW generation as well as the increase in energy demand. It is for this reason this review aims at discussing the MSW gasification in a fixed bed gasifier for possible hybridization.

Thakare and Nandi (2016) develop and simulate mathematical model for MSW gasification in a fixed bed gasifier. They considered fixed bed downdraft gasifier since it can handle feedstock with high ash content despite that it requires low moisture content (MC) feed. The results were highly affected by the amount of feed stock moisture content such that only nitrogen increases with increase of MC while other gases were decreasing. Due to the high MC of MSW the feedstock requires extra reprocessing into refuse derived fuel (RDF) compacted into small sizes that can be gasified in downdraft gasifier (Etutu *et al.*, 2016).

Despite that, downdraft gasifier has become a potential fixed bed gasifier for MSW it faces some challenges. Rajvanshi (1986) reported that chemical reaction at the downdraft gasifier throat does not allow complete separation of tar from producer gas. Asadullah (2013a) reported several methods for producer gas cleaning including filtration, catalytic, and thermal cracking. However, the use of filtration and catalytic conversion methods require addition cost to the gasification system. The best option would be to develop a design model which can deliver optimal operating temperature and longer residence time hence increase thermal energy for tar cracking.

Therefore, further minimization of tar in DDG can be attained through improving thermal cracking technique to achieve temperature higher than the downdraft gasifier combustion zone temperature which range between 800 ºC to 1000 ºC (Shelke *et al.*, 2014). The recommended temperature at which tar cracking occurs is about 1000 ºC (Fjellerup *et al.*, 2005; Njikam *et al.*, 2006). In some cases double air supply in downdraft gasifier has shown effects on reducing tar content in the producer gas (Martínez *et al.*, 2012). In this gasifier design, the first air supply is injected near the top where pyrolysis zone occurs whereas the second air supply is injected at the oxidation zone.

Tar could also be reduce in the producer gas through the following: increasing residence time, operating with high air concentration, operate the reactor at higher temperature above 750 ˚C and gasifier design including increasing bed height (Ghaly and MacDonald, 2012; Klinghoffer and Castaldi, 2013). Some designs modification done by the combination of gasifier features have shown better results. Kramreiter *et al.* (2008) combined updraft and downdraft design features to harvest the advantages of both. This combination has better output results in terms of low tar content.

Gasifying agent

Biomass gasification system output depends on the type of feedstock, although gasifying agent plays an important role. In a fixed bed gasification the common gasifying agent used includes air, pure oxygen, steam and in some cases carbon dioxide (Oyugi *et al.*, 2018). Air is used when the quality of producer gas is not taken into consideration where as pure oxygen; carbon dioxide and steam are used when the quality of producer gas is considered. Energy content in terms of HHV for the mentioned gasifying media is indicated in Table 2.

Table 2: syngas HHV for different gasifying media (Latif, 1999; Sadhwani *et al.*, 2016)

	Gasifying media	Producer gas HHV (MJm^{-3})
1	Air	4-7
2	Steam	10-18
3	Pure oxygen	10-18
4	Carbon dioxide	7.22-8.64

Chemistry of gasification process

Several chemical reactions take place in the gasifier in four stages: drying, pyrolysis, combustion and gasification. The endothermic reaction is experienced in drying and pyrolysis stages to evaporate water and release volatile matters respectively. The solid char remains for further reaction in the combustion and gasification stages as elaborated in Table 3.

Table 3: Combustion and Gasification reactions

S/N	Reaction identification number	Reaction	Reaction name	Gasifier Section
(1)	R1	$C + 0.5O_2 = CO$	Carbon partial combustion	Combustion
(2)	R2	$C + O_2 = CO_2$	Carbon complete combustion	Combustion
(3)	R3	$C + CO_2 = 2CO$	Boudouard	Gasification
(4)	R4	$C + 2H_2 = CH_4$	Methanation	Gasification
(5)	R5	$C + H_2O = CO + H_2$	Water gas	Gasification
(6)	R6	$CO + 0.5O_2 = CO_2$	CO oxidation	Combustion
(7)	R7	$H_2 + 0.5O_2 = H_2O$	Hydrogen oxidation	Combustion
(8)	R8	$CH_4 + H_2O = CO + 3H_2$	Steam Methane reforming	Gasification
(9)	R9	$CO + H_2O = CO_2 + H_2$	Water gas shift	Gasification
(10)	R10	$CH_4 + 0.5O_2 = CO + 2H_2$	Methane oxidation	Gasification

These reactions take place in the four stages in different arrangements depend on the gasifier design. For example in downdraft gasifier, the feedstock flows down past drying, pyrolysis, combustion and gasification, while in the cross draft biomass flows down while all four stages are concentrated nearly in the same area as shown in Figure 2.

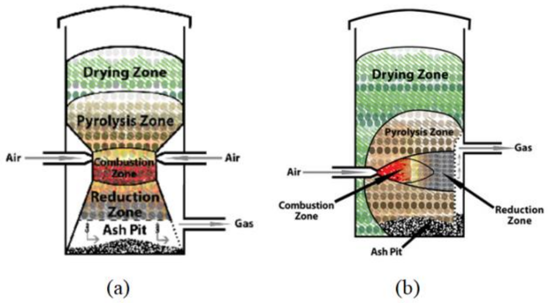


Figure 2: Stages of reaction in (a) downdraft and (b) Cross draft gasifier (EnggCyclopedia, 2019)

2. Conclusions

The international agreement upon climate changes including Kyoto protocol and European Landfill Directives has influenced the use of alternative methods for MSW management other than landfill. Gasification system complies with these agreements hence is a most promising technology for energy recovering from MSW and enhance MSWM process.

However, syngas produced through gasification process contain tar which limits its application. In up draft gasification system is even much worse such that extra cleanup is required. Although downdraft and cross draft have shown advantages on having less tar content it still require to be further reduced. This can be full filled in several ways, including increasing residence time through design modification hence increasing bed height as well as gasifier temperature. Several designs feature have been achieved to improve fixed bed gasifier performance including, combination between updraft and downdraft features. Hence therefore further design modification is required for better gasifier output results.

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