Tar-free Gasification Technology of Municipal Solid Waste-RDF

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ABSTRACT

In India, per capita waste generation is 0.2 – 0.6 kg/day, which is estimated to increase at 1.33% annually. As per estimates, about 115000 tons of Municipal Solid Waste (MSW) is generated per day and this figure could be twice as much by 2020. Estimation exist a potential for generating about 1500 MWe of power from the municipal solid wastes in the country and the potential is likely to increase further with economic development. If we consider about 25% of MSW is converted in to RDF through optimized segregation processes, then about 34500 tonnes per day of RDF is available for converting into energy. This paper elucidates the voyage of an innovative design, development and performance studies of multi-condition acceptability and flexible operatability on tar-free MSW-RDF gasifier. The innovation on the technology and its development is highly emphasized for converting the MSW-RDF into energy through gasification. The designed & fabricated gasifier (100 kg/hr capacity) is a stratified fixed bed down-draft type) gasifier which is square in shape and operates slightly above atmospheric pressure to generate tar free producer gas. This design operates with pellets and fluffy MSW-RDF. The generated producer gas was tested for both thermal and power applications. This designed MSW-RDF gasifier can be scaled up and implemented to suit the requirements of an Industrial energy demand which will have wide ranging applications. The results were found to be satisfactory from the investigations which will be developed for specialized applications in all-scale industrial sectors around the globe. The clean tar-free producer gas which is generated will result in hassle-free and energy efficient operation on 100% gas engine or dual mode engine for the power generation. There would be an entry for this jointly developed MSW-RDF gasification (Indo-Korean) technology which not only solved the role of converting the waste to energy but also on environmental emission control aspects. When compared to landfill disposal, it is found that gasification of MSW-RDF saves 6.5 to 13 million Btu per ton and 0.3 to 0.6 tons of carbon equivalent emissions per ton. The energy generation from the designed MSW-RDF gasifier and process optimization for power generation from gas with enhanced efficiency abets in drastically reducing the cost of factory's energy consumptions. It also tends to achieve reduced environmental emissions with good returns on investments. This voyage is to sprint ahead on the pathway to harness a "Green Power Revolution from Waste" through the developed MSW-RDF gasification device.

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1. Introduction

A critical assessment of municipal solid waste gasification today, starting from basic aspects of the process (process types and steps, operating and performance parameters) and arriving to a comparative analysis of the reactors (fixed bed, fluidized bed, entrained bed, vertical shaft, moving grate furnace, rotary kiln, plasma reactor) as well as of the possible plant configurations (heat gasifier and power gasifier) and the environmental performances of the main commercially available gasifiers for municipal solid wastes. The Solid Waste Management mainly involves not only a reduction in waste generation, but also appropriate treatment and maximum recycling of the waste. Recent policy trends have focused on converting wastes into resources, and these have led to the implementation of ‘‘waste to energy and resources’’ and a ‘‘sustainable and circulation society’’ in the present and future plans for waste management. A new law called ‘‘Promotion Law for Achieving a Resource Circulation Society’’ meant to replace the basic law and to create a platform of resource circulation. This could promote the establishment of a zero waste society and also extend the life of waste landfill facilities in Korea (Won-Seok Yang et al., 2014). With gasification technology, one ton of MSW can be used to produce up to 1,000 kilowatt hours of electricity, a much more efficient and cleaner way to utilize this source of energy. Recovery of energy from MSW by combustion in Waste-to-Energy (WTE) plants reduces land filling and air/water emissions, and also lessens dependence on fossil fuels for power generation. The objective of this study was to assess the potential of gasification processes as an alternative to the combustion and gasification of MSW. The solid waste gasification is a complex process that includes a number of physical and chemical interactions that occur at temperatures generally higher than 600°C, the exact temperature depending on the reactor type and the waste characteristics, in particular the ash softening and melting temperatures (Arena and Mastellone, 2009; Higman and van der Burgt, 2003; E4tech, 2009). The gasification of a solid waste includes a sequence of successive, endothermic and exothermic, steps (Knoef, 2005; de Souza-Santos, 2004), schematically described in Fig. 1 with reference to main reactants and products:

Heating and drying, that occurs at temperatures up to about 160°C: it is a combination of events that involve liquid water, steam and porous solid phase through which liquid and steam migrate.

Devolatilization for MSW, volatiles represent a significant portion of the carbonaceous fuel that provides an easily ignitable atmosphere of fuel gases around the solid waste as well as part of the produced gases of the gasification process, as schematically described in Fig. 1. The composition, quantities and characteristics of chemical species released from devolatilization (not necessarily in a single stage) depend on several factors, mainly original composition and structure of the waste (Kawaguchi et al. 2002), temperature, pressure and composition of waste-involving atmosphere and heating rate imposed by the particular reactor type (de Souza-Santos, 2004). It should be emphasized that devolatilization releases many components, and hydrogen is required for molecular links in several of them: then devolatilization depletes hydrogen from the original carbonaceous matrix of the waste.

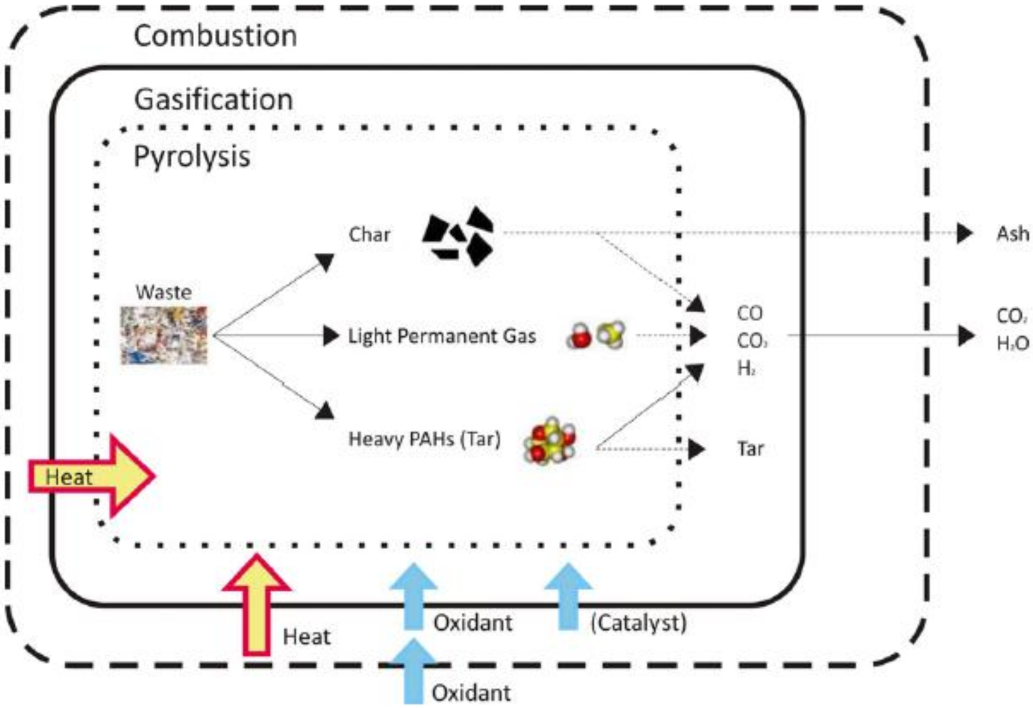

Fig. 1. Schematic representation of pyrolysis, gasification and combustion stages

Thermo chemical conversion processes are an essential component of a sustainable integrated municipal solid waste (MSW) management system, as confirmed by several analyses and studies (Brunner et al., 2004; Porteous, 2005; Psomopoulos et al., 2009) and, above all, by waste management systems that are operating successfully worldwide. The gasification-based Waste to Energy technologies can work as standalone applications or as part of integrated or modular systems combining pyrolysis, gasification and/or combustion processes. Their configurations can be sketched as a combination of three sections (Arena et al., 2011): syngas production, syngas utilization and syngas/flue gas cleaning. The first defines the syngas that can be produced and then, for fixed solid waste and gasification technology, the quantity and quality of this syngas. The utilization section indicates the syngas that can be fed in a specific energy conversion device and then, for given machinery (steam turbine, gas engine and gas turbine), its temperature and heating value and cleaning level (i.e. tar and dust content but also that of alkali metals and inorganic contaminants). There are several gasification technologies that in the last two decades have been developed and are now commercially available for WtE plants (Heermann et al., 2001; Malkow, 2004; Arena and Mastellone, 2005; Juniper, 2009). Lower values of ER leave unconverted char and higher tar content while higher values of ER determine the oxidation of part of syngas and the consequent reduction of syngas heating value: this could cause incomplete combustion in the combustion chamber that is usually downstream of the gasifier (Devi et al., 2003; Li et al., 2004; Arena et al., 2010). A possible classification Solid Waste Gasifiers are proposed in Table 1.

Table 1. Classification of Solid Waste Gasifiers

Criteria	**Types**
Heat Supply	Directly heated (auto-thermal) gasifiers Indirectly heated (allo-thermal) gasifiers
Pressure	Atmospheric gasifiers (A) Pressurized gasifiers (P)
Gasification Agent	Air gasifiers (AG) Oxygen enriched-air gasifiers (EAG) Oxygen gasifiers (OG) Steam gasifiers (SG) Plasma gasifiers (PG)
Reactor Design	Fixed bed gasifiers: 1. Up-draft (UD) 2. Down-draft (DD) Fluidized bed gasifiers: 1. Bubbling fluidized bed (BFB) 2. Circulating fluidized bed (CFB) 3. Internally circulating fluidized bed (ICFB) Entrained flow gasifiers (EF) Rotary kiln gasifiers (RK) Moving grate gasifiers (MG) Plasma gasifiers (PG)
Temperature	Low-temperature gasifiers (typically below 900°C) (LT) High-temperature gasifiers (typically above 1200°C) (HT)
Bottom ash Status	Dry bottom ash gasifiers (BA) Vitrified slag gasifiers (VS)
Energy Recovery	Heat gasifiers (dirty syngas is post-combusted in a recovery boiler with heat/electricity production via steam turbine cycle) (HEG) Power gasifiers (syngas is first cooled and cleaned and clean syngas is then burned in an internal combustion engine or a gas turbine) (PWG)

It highlights that the main differences are related to the direct or indirect way of heat supply, to whether the gasifier is operated at above atmospheric pressure (so obtaining higher throughputs, larger hydrogen contents and smaller clean-up units but entailing higher investment and operating costs, that are likely prohibitive for a WtE unit), to the operating temperature range (that can determine the possibility to obtain bottom ash under form of an easy-to-handle molten or vitreous slags), to the way by means of the waste is fed into the gasifier (into the top or into the side) and is moved around within it (by gravity, air flows or mechanical devices); to whether air or oxygen or O2-enriched air is used as oxidant (steam is utilized mainly for coal or biomass gasification). Most of these technologies have been developed and commercialized the cogeneration of heat and power from the syngas of the basis of the above mentioned ‘‘heat gasifier’’ configuration. Only a few, particularly in Japan, utilizes a ‘‘power gasifier’’ configuration or are operated to produce chemicals (in particular, ammonia) (Steiner et al., 2002). A sort of atmospheric moving bed downdraft gasifier is the vertical shaft-furnace proposed by Nippon Steel as ‘‘Direct Melting System’’. It is a high temperature gasification and melting process, with O2-enriched air injection in the melting section (at 36% of O2 concentration), which directly evolved from metallurgical processing technology (Williams et al., 2003; Shibaike et al., 2005). This paper aims to explore the capability of gasification as an environmental-friendly technology by tackling the problem of MSW-RDF through gasification with woody biomass in different proportions, using the different air flow rate as a performance indicator.

2. Materials and Methods

2.1. Pre-treatment and sorting of MSW-RDF waste

MSW-RDF waste was collected from the districts of Hyderabad, India. The composition of RDF waste is paper, card board, plastics, textiles waste, rubber waste, leather waste, wood waste and other in-organic combustible waste. The first few sample batches of MSW-RDF waste were sorted into categories including category A (paper, card board), category B (plastic), category C (textile and rubber waste), and category D (wood waste and other in-organic wastes) in order to determine their overall average composition. Plastics were eliminated as they were typically beyond the gasification feedstock upper size limit of 4 cm and tended to cause blockage in the feeding system and reactor. Each sample of the remaining categories was taken as 25 to 100kg and sun dried for 12 h before gasification. Moisture content and dry weight of each category was calculated through the weight difference before and after the 12- days drying process.

2.2. Feedstock characterization

The gasification feedstock in this study consisted of Tamarind wood chips (Suriyapet, India) with a particle size range of 10cm length and 6 cm diameter, and RDF waste with a wide size range (as small as 0.5 cm to 3cm). Due to its high moisture level (in the range from 60 to 70%), RDF waste was pre-dried (maximum allowable moisture level of 35% for transient state gasifier operation) as outlined in section2.3. Thermal gravimetric analysis (TGA) was performed using a thermal analyzer to do a proximate analysis of moisture, volatile, fixed carbon and ash contents of the feedstock. Briefly, the feedstock was heated from 25 to 950^{O}C at a rate of 20^{O}C /min under air atmospheres. The proximate and ultimate analysis of MSW-RDF waste is presented in the Table 2.

Table 2. Proximate and ultimate analysis of MSW-RDF waste

Proximate Analysis			Ultimate Analysis		
Moisture	:	5.33%	Moisture	:	5.33%
Volatile Matter	:	86.75%	Carbon	:	57.45%
Ash	:	3.10%	Hydrogen	:	7.70%
Fixed Carbon	:	4.82%	Oxygen	:	24.96%

2.3. Gasifier design

The down draft gasification design is a multi-condition flexible operation on high temperature which is a rectangular shaped operated on all types of firewood and MSW-RDF that produces tar free gas while removing ash and particulate in the proficient manner. This system can handle high bulk density biomass and MSW-RDF waste which operates on stratified downdraft mode under slightly above atmospheric pressure for flexible rating (Fig. 4). The gasification zone temperature is maintained 1200°C and above at very high temperatures to achieve tar-free gas. This reactor can accommodate any type of biomass feed and RDF waste even with higher bulk density 1000 kg/m^3 and 800kg/m^3 respectively. And also comparable to woody biomass such as large wood blocks up to 300 mm length and 100 mm diameter even on higher moisture biomass up to 40%. It works under pressure below 30 cm of water column.

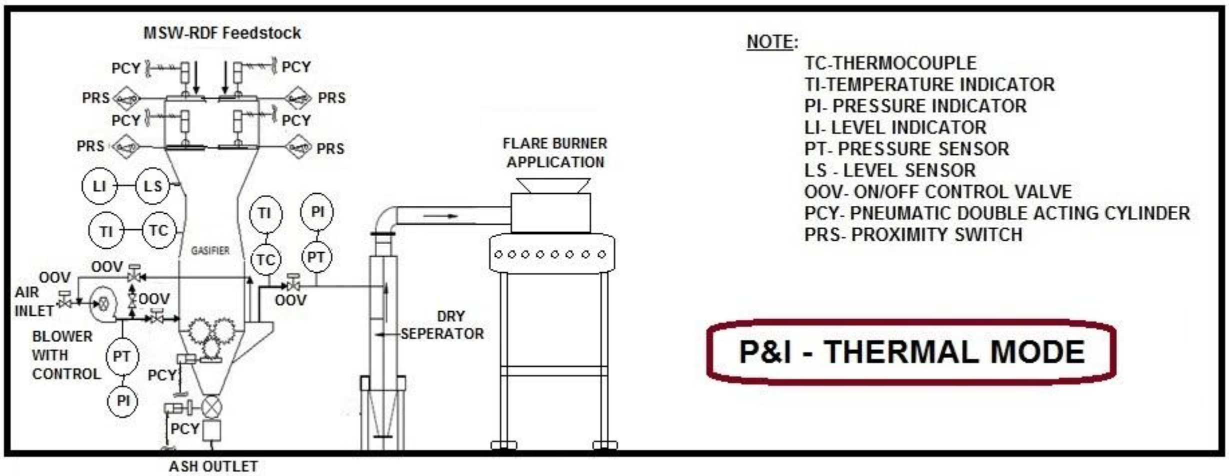

Fig.2. MSW-RDF Waste stratified down draft gasifier

The maintenance of char bed porosity, prevention of load to the char bed, uniform distribution of air for partial combustion and augmented performance is achieved adopting air nozzle duct at the centre of the gasifier and rotating grate mechanism. The grate is rotary mechanism which is designed to minimize char ash generation and thus achieving very high gasification efficiency. This system is fully insulated to achieve maximum thermal efficiency as well as cold gas efficiency with tar-free gas. The pressure drop across grate can be uniformly maintained which will make possible to gasify smaller particles of biomass. The load above the reduction zone is totally minimized that helps in efficient agitation of char bed avoiding clinker formation. The design claims are intended for very high temperature reactions inside the gasification zone of the solid waste gasifier. The approach of this work was purely adopted on the basis of engineering calculations. The pilot model gasifier (Fig. 4) was designed for 300 kWth stratified downdraft mode operating with air at around 35°C as gasifying agent.

2.4. Gasification of Wood waste and MSW-RDF waste

The feedstock was prepared in five categories including pure wood waste (100% wood waste), 75:25 mixture (75% wood waste mixed with 25% MSW-RDF waste), 50:50 mixture (50% wood waste mixed with 50% MSW-RDF waste), 25:75 mixture (25% wood waste mixed with 75% MSW-RDF waste) and (100% MSW-RDF waste), all by weight.

A 300-kWth, fixed-bed stratified downdraft gasifier with feedstock consumption rate of 100 kg/h was investigated. The feeding mechanism of the gasifier was a batch hopper with feedstock auger. The reactor was first started up to increase the temperature on the charcoal for initial ignition under suction mode of operation and later converted into pressure mode of its continuous operation. The feedstock was filled on batch wise into the hopper, and the pneumatic valve fed the feedstock into the reactor at a rate of 100 kg/h. Feedstock entered into the reactor undergoes gasification reaction in different zones of drying, pyrolysis, gasification, and reduction in the reactor. Air flow into the reactor (gasification zone) was controlled through a nozzle with a check valve. The residence time of each sample proposition in the reactor was approximately 1 hour. The temperature is measured by mean of eight thermocouples (type K) located at different zones of the reactor bed. Air and gas flow rates were measured with an orifice and differential manometer. All the trials (Trial-1 to Trial-5) were experimented for 10 days each and averaged. Among the different composition trials performed, five trial averaged data have been tabulated and discussed as shown in Table 3. During all the trials, the gasifier was continuously operated for 8 hours per day from one single fixed bed batch trials under different combinations of MSW-RDF and wood wastes. This method will suitable for developing countries with cheap manpower and for batch operation. The gas outlet flame is shown in Fig 3. The better operation performance of the gasifier was observed in the category 3, where was obtained the higher flow rate of the gas and all zone temperatures were high for other experiments.

Table 3. Average operation parameters of the stratified down draft gasifier system

Category	Particulars	Total Average Values						
		Total Operating Hours	Temperature Deg C Combustion T 4	Reduction T 3	Pyrolysis T 2	Drying T 1	Air flow rate m^3/hr	Gas flow rate Nm^3/hr
A	Trail 1 100% Wood	8:18	871.95	744.53	641.8	514.26	148.68	249.2
B	Trail 2 75% Wood + 25% RDF	8:32	847.05	723.64	563.4	463.28	148.53	248.9
C	Trail 3 50% Wood+ 50% RDF	8:16	883.57	757.1	659.14	558.88	149.37	249.7
D	Trail 4 25% Wood + 75% RDF	8:29	724.79	657.10	486.26	439.28	147.9	248.6
E	Trail 5 100% RDF	8:19	717.11	601.79	397.6	331.94	147.47	247.9

Initial stage at 1st hour   Final stage at 8th hour

Fig. 3. MSW-RDF Waste producer gas flame at various stages

3. Results and discussion

3.1. Pre-treatment and sorting of MSW-RDF waste

Table 4 shows that every 100 kg of MSW-RDF waste in this study contained 50.0 kg of category A, 12.5 kg of category B, 10.0 kg of category C, 8.0 kg of category D, and 19.5 kg of category E by fresh weight. The moisture contents of each category were 55.0, 52.0, 73.2, 69.5 and 75.5%, respectively. The whole category was sun dried between 10 to 12 days for pre drying process. The RDF waste as a whole had a average moisture content of 65.04% and 5.3% before and after pre-drying, respectively. This is translated to a 91.85% reduction in moisture level.

Table 4. Drying weight analysis of wood waste and MSW RDF waste

Parameters	Wood Waste	MSW RDF Waste				Total	Average
Categories	Cat A	Cat B	Cat C	Cat D	Cat E	Cat A+(B+C+D+E)	
Fresh Weight (kg)	50	12.5	10	8	19.5	100	
Moisture content, wet basis (wt %)	55.0	52.0	73.2	69.5	75.5	352.2	65.04
Dry weight (kg)	5	5.8	4.8	4	7.3	26.9	5.38

3.2. Temperature distribution inside gasifier

The temperature distributions in gasifier's bed during the different categories run are indicated in Fig. 4. The temperature of the bed in the reactor ranges from 883^{O}C in the combustion zone to 331^{O}C in the drying zone after the stabilization. As it is observed, there is an oscillation of the temperature value in all the bed section during all the experiments, with the exception of the temperature in the bottom of the reactor, where is located at the entrance of the air and the temperature remains more transient. The principal reason of this variation is that the feeder system is activated discontinuously when the RDF waste level in the reactor is decreased during the gasification process, the introduction of the RDF waste at the top of the bed induces an downward movement of the bed causing a high displacement of all the section of the bed, garnering a variation in the temperature profile as is observed. As shown in the fig 4 Category C operation (Wood waste 50 kg, MSW-RDF waste 50 kg), the gasifier is continuously run for 8 h from one single fixed bed batch wastes was obtained into higher temperatures for all zones compared to other experiments.

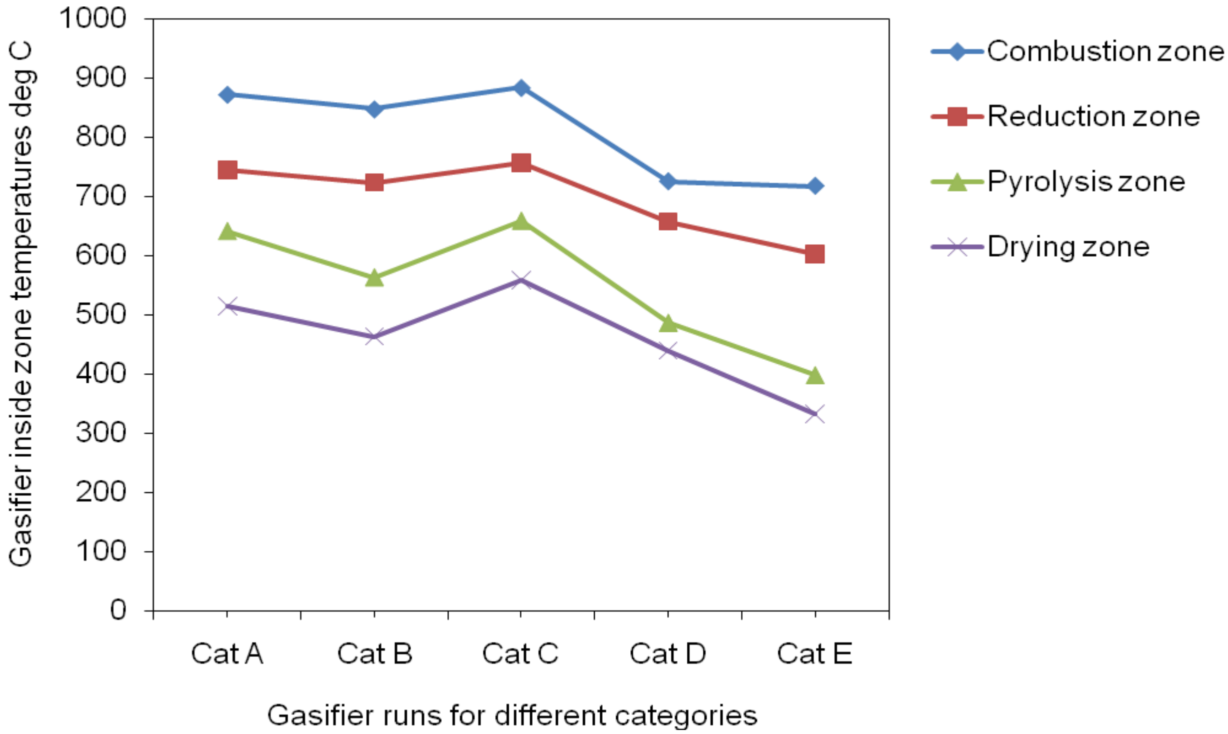

Fig. 4. Gasifier zone temperatures at different runs

3.3. Technology implementation

This MSW-RDF gasifier model may be suitable for implementation in cities like Hyderabad and Chennai which is a big city state having a land area of around 750 km^2. Construction wood and horticultural wastes are easily available from wood waste collectors concentrated in the northern or western regions of Hyderabad. These waste collectors typically provide disposal services that collect wood and horticultural waste from construction and other work sites. Meanwhile, since the northern and western parts of Hyderabad are considered industrial areas with various companies setting up their factories, food waste can be obtained from canteens in these factories, while the setting up of a gasification plant within these regions for the processing of such waste is convenient. Besides supplementing producer gas as a thermal and electrical power source to run the plant, final char ash produced can be applied to cement plant sites in these areas were used.

4. Conclusions

In this work, the gasification of MSW-RDF waste and woody biomass in different proportions was carried out to evaluate the compatibility of MSW waste as a gasification feedstock, as well as the potential of MSW waste as an alternative source for sustainable energy production. The gasification experiment in a fixed bed stratified downdraft gasifier was successfully carried out up to 40% MSW waste before bridging in the hopper occurred owing to the fine particle size of RDF waste. Nevertheless, it was found that increasing MSW waste proportions in gasification increased the quality of producer gas (CO and H_2) produced, with the highest gas flow rate of 249.7 Nm^3/hr achieved with a 50:50 wood waste-MSW RDF waste mixture (w/w). This suggests that gasification may be a green technology that can provide an alternative route to dispose MSW waste by harnessing clean energy in the form of Producer gas. The experience of gasifier users with regard to the difficulty to use the gas produced in a typical down draft fixed bed gasifier has led us to the development a gasifier capable of generating producer gas with a significant reduction in the tar content, respect to the typical values of this parameter; from the modification of the typical design of the stratified down draft fixed bed gasifier. With this concept, a stratified down draft gasifier was designed and constructed. The reactor produced MSW waste producer gas continuously for 8 hours and worked stably during all the experiments. The quality of the gas obtained was better in this design; because was possible to generate producer gas with no tar content with maximum operation efficiency.

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