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Study on Potential of Gasification Technology for Municipal Solid Waste (MSW) in Pune City

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Abstract

Solid waste disposal problem is a growing concern of today's world. It creates serious health hazards and environmental issues need to be tackled on urgent basis. Developing economy like India is facing the waste disposal problem due to the rapid industrialization, population growth and changing lifestyle. Like other parts of the country, we have noticed that in Pune City also, per capita waste generation is growing steadily mainly due to the changed lifestyle. The increased volume of waste generation in last 10 years has created stress on the natural resources. If this waste be suitably utilized for energy production instead of incineration or just dumping in the ground, simultaneous reduction in environmental pollution along with proper utilization of waste will be done. Gasification Technology is an efficient one as most of the solid wastes, irrespective of the sources and materials present can be gasified directly to obtain synthesis gas or producer gas having sufficient calorific value. The gas obtained can be used as fuel or can be utilized to generate electricity, even it can produce plethora of various petrochemical products. We have conducted a mathematical modeling and simulation study on a downdraft gasifier to highlight its potential in waste disposal problem for Pune city.

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Keywords: Municipal solid waste; Gasification; Waste to energy; Sustainability; Downdraft gasifier

1. Introduction

Energy crisis is an ever increasing concern across the globe as most of the countries face severe problem of rising energy demands and finding alternatives to meet the same. The conventional energy sources are being exploited on a

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very large scale and it may lead to serious energy crisis in coming fifty years [1]. Hence, there is a dire need of harnessing the potential of renewable energy sources like solar, wind, tidal, geothermal etc. These energy sources are clean, non-depleting and hence termed renewable. Biomass gasification can serve as a feasible alternative of reducing the environmental pollution as well as reducing the gap of the rising energy demands. Biomass being abundantly available in nature as well as being produced by human activities can easily be obtained at sufficiently low cost, even sometimes some initiatives can be received in turn for processing the wastes. A self-sustaining gasification technology for waste material can be devised in conjunction with power generating devices. The quantum of pollution in gasification is much less compared to incineration technique which is generally utilized for speedy waste disposal. The energy produced in gasification process can reduce the dependence on conventional energy sources and hence it can be termed as dual green and environment friendly technology. The municipal solid waste (MSW) produced in urban areas can be utilized as a low-cost or zero cost biomass for gasification. The gasification utilizes thermochemical conversion and hence much faster compared to the microbial process of biogas generation. Biogas digesters are unable to handle solid wastes containing polymeric material, paper, plastic etc. which causes blockage of pores and sometimes toxic to the microbes and hence the rate of digestion of organic fraction is reduced, even can completely be stopped for the extreme conditions. Gasification technology is independent of microbial culture and its sensitive operating parameters. Gas obtained from gasifier have much higher calorific value compared to the biogas plant [2]. Researchers have carried out experimentation to study gasification process [2,3] and also conducted mathematical modeling and simulation studies for better understanding the gasification technique [3,4]. Gasification process was modeled in various ways, namely single stage modeling, sub-zone modeling, kinetic modeling, even artificial neural network [4] was also been used. Due to the complexities of reactions occurring in a gasifier, the exact prediction of all the reactions often difficult and hence modeling of all the zones encompassing all reactions together is still remains a challenge [4].

Nomenclature

$C_{p,x}$	*specific heat capacity*
H	*Enthalpy*
K_{eq}	*Equilibrium constants*
P	*Pressure*
R	*Gas constant*
R_x	*Rate of formation of x species*
T	*Temperature*
h	*mole of hydrogen per mol of carbon*
o	*mole of oxygen per mol of carbon*
$n_{p,x}$	*no. of moles of species x in pyrolysis*
$n_{ox,x}$	*no. of moles of species x in oxidation*
n_x	*concentration of species x*
r_i	*rate of* i^{th} *reaction*
y_x	*mole fraction of species x*
v	*gas velocity*
n	*total molar concentration*
z	*length of reduction zone*
ρ_g	*gas density*
w	*amount of water*
a	*amount of air*

The gasification of MSW will be an effective technique to reduce waste due to following:

- Comparatively fast reduction of waste: Gasification is relatively faster process than conventional processes. Hence, more amount of waste can be treated in minimum time.

- Lesser requirement of landfill site: Generally, solid wastes are dumped at landfill sites and it requires large site far from the city. It is impossible to afford such a large landfill sites. If wastes be gasified, landfill site requirement will be lowered.
- Minimization of soil and water pollution: When solid waste dumped at landfill sites, toxic pollutants leached into ground water and pollute water. It may lead to soil infertility as well. MSW gasification serves as a good option to minimize soil and water pollution.
- Replacement of incinerators / combustors: The solid waste portion which is biohazardous like plastics, foam etc. are usually treated at incinerators. Hence, there are possibilities of replacement of incinerators by gasifiers. The incinerators emit dioxin and furan and its concentration often exceeds allowable limits, which calls for alternate mechanism of MSW treatment. The process of integrated gasification and combustion emits dioxin and furan within acceptable limits laws set by national and international agencies [5]. This is possible due to partial oxidation of wastes in presence of limiting oxygen supply.

2. Solid waste generation and collection at Pune

Solid waste generation is directly proportional to urbanization. Change in life style and food habits have an immediate effect on solid waste generation. A recent report indicates that cities like Pune, Mumbai, Ahmedabad, Agra, Bangalore, Bhopal, Chennai, Delhi, Hyderabad, Jaipur, Kanpur, Kolkata, Lucknow, Nagpur, Surat and many more generate more than 500 tonne per day of solid wastes [6]. According to Central Pollution Control Board (CPCB) data, Maharashtra state generates highest amount of solid waste which is about 26,820 tonne per day [7]. This necessitates better collection and waste management systems in the urban areas of the state. Pune being the second largest city and educational and information technology hub, many people migrate from different parts of Maharashtra and even various corners of country as well. A published document in 2014 report puts the Pune city's population at about 3.5 million. Another 0.5 million come into the city every year [8]. This produces around 1600 to 1800 TPD solid wastes as per Pune Municipal Corporation (PMC) data. Of this, 65% comes from residences, hotels and restaurants [9]. Door to door collection of waste system is available at Pune City; around 60% waste is collected efficiently. This system is running under collaboration of Solid Waste Collection and Handling (SWaCH) seva sahakari sanstha maryadit, Pune and Pune Municipal Corporation. Currently 2300 waste Pickers are member of SWaCH [10].

2.1. MSW characterization

The composition of MSW was determined on a wet weight basis. Based on some available data the composition of MSW of Pune is considered as: Organic fraction: 40 – 60% (weight basis), Paper: 5% by weight, Plastics: 5% by weight, ash and fine earth: 15% by weight, Lower calorific value is about 800 – 1000 kcal/kg [1,4].

2.2. Selection of Gasifier for MSW gasification

Gasification can be done in various types of gasifiers namely fixed bed updraft, downdraft gasifier, fluidized bed gasifier and entrained flow gasifier. In this study, fixed bed downdraft gasifier is considered as it can handle high ash feed and it is well known that biomass contain appreciable quantity of ash in it. In addition, maximum tar and char conversion takes place in the fixed bed gasifier, and MSW may contain some material which will leads to more tar/char. Ash produced during gasification will be collected at ash pit (bottom of the gasifier). Clean gas is obtained in downdraft gasifier.

The downdraft gasifier is a co-current gasifier, wherein the fuel and the gasification agent (air in the present case) flow in the same direction (refer to Fig. 1). In the drying zone, moisture is evaporated from biomass as it slowly moves down towards the pyrolysis zone. In the pyrolysis zone, biomass is converted into smaller fractions like char, tars and gas. Some of it undergoes combustion. Due to high temperature, tars are cracked in the oxidation zone and as a result much amount of tar is oxidized. Hence, obtained gas is relatively clean. But this gasifier requires preconditioning of biomass so that it contains lesser amount of moisture [4].

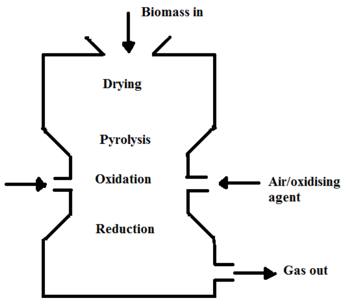

Fig. 1. Schematic diagram of downdraft gasifier

3. Model development of downdraft gasifier

A phenomenological model of downdraft biomass gasifier is developed to study the potential of MSW gasification in Pune city. The model predictions were also compared with the experimental findings reported in open literature. Some researchers have modeled gasification process in one or two stages. Some researchers have done single stage stoichiometric equilibrium modelling for MSW [11,12]. Ratnadhariya and Channiwala (2009) [13] have done three zone equilibrium and kinetic free model. Complexity of reactions in pyrolysis zone and the oxidant present calls for a combined model comprising of equilibrium sub model and the kinetic model for the reduction zone [13,14].

Following assumptions were considered while developing the model

- Gasifier is sub divided in three zones viz. drying-pyrolysis, oxidation and reduction zone.
- Adiabatic condition of the gasifier is considered.
- Nitrogen is taken as an inert component of air.
- Char is modelled as a carbon.
- One dimensional steady state flow model is developed without any radial distribution.

The ultimate analysis values of MSW are considered as identical to earlier published data [11] as given in Table 1

Table 1: Ultimate analysis of wastes (% dry basis)

Component	%
C	30.3
H	3.4
N	1.4
O	35.8
Ash content (A)	29.1

3.1. Development of sub model drying and pyrolysis zone

This modeling has been done on thermodynamic stoichiometric equilibrium for 85 kg biomass and air to fuel ratio is taken as 0.325. This development is done by following the mass balance equation mentioned below.

$$C_1H_hO_o + \omega\, H_2O = n_{p,C}C + n_{p,CO2}CO_2 + n_{p,CO}CO + n_{p,CH4}CH_4 + n_{p,H2}H_2 + n_{p,H2O}H_2O + n_{p,C2H2}C_2H_2 \quad (1)$$

Carbon balance: $n_{p,C} + n_{p,CO2} + n_{p,CO} + n_{p,CH4} + 2n_{p,C2H2} = 1$ (2)

Hydrogen balance: $2n_{p,H2} + 2n_{p,H2O} + 2n_{p,C2H2} + 4n_{p,CH4} = h + 2w$ (3)

Oxygen balance: $2n_{p,CO2} + n_{p,CO} + n_{p,H2O} = w + o$ (4)

The key assumptions for developing this zone which are as discussed below.

- 40% of oxygen of biomass reacts with carbon to form CO and CO_2.
- The ratio of moles of CO and CO_2 is inversely proportional to their molecular masses. i.e. $\frac{n_{p,co}}{n_{p,co2}} = \frac{44}{28}$
- 40% available hydrogen is released as H_2.
- Remaining 60% reacts with carbon to form methane and acetylene.
- The ratio of moles of CH_4 and C_2H_2 is inversely proportional to their molecular masses. i.e. $\frac{n_{p,CH4}}{n_{p,C2H2}} = \frac{26}{16}$

3.2. Development of sub model oxidation zone

The output of the drying pyrolysis zone will be input for the oxidation zone. Therefore, unreacted char will oxidise to form CO and CO_2 and also oxidation of combustible gases will undergo into combustion.
The mass balance equation is given as follows:

$$n_{p,C}C + n_{p,CO2}CO_2 + n_{p,CO}CO + n_{p,CH4}CH_4 + n_{p,H2}H_2 + n_{p,H2O}H_2O + n_{p,C2H2}C_2H_2 + \alpha(O_2 + 3.76N_2) = n_{ox,C}C + n_{ox,CO2}CO_2 + n_{ox,CO}CO + n_{ox,CH4}CH_4 + n_{ox,H2}H_2 + n_{ox,H2O}H_2O + 3.76\alpha N_2 \quad (5)$$

Mathematical model developed based on following assumptions:

- H_2 formed in pyrolysis zone will be fully oxidised in this zone to form H_2O.
- The C_2H_2 undergoes oxidation to form CO_2 and H_2O.
- The remaining O_2 will be used in char combustion.
- The ratio of formation of CO and CO_2 is inversely proportional to their exothermicity of the reaction.
- CH_4 formed in pyrolysis is taken as it is in this zone.
- N_2 is considered as an inert.

3.3. Development of sub model of reduction zone

This kinetic model is based on model proposed by Centeno et. al. (2012) [14], some modifications have been done in this model. The four equilibrium reactions are considered in this zone as discussed below. The output of the oxidation zone is taken as input for simulation of this zone.

Boudouard reaction: $C + CO_2 \rightarrow 2CO,\ \Delta H^0_{f,298} = 172.61\ kJ/mol$

Water gas reaction: $C + H_2O \rightarrow CO + H_2,\ \Delta H^0_{f,298} = 131.4\ kJ/mol$

Methanation reaction: $C + 2H_2 \rightarrow CH_4,\ \Delta H^0_{f,298} = 75\ kJ/mol$

Steam reforming reaction: $CH_4 + H_2O \rightarrow CO + 3H_2,\ \Delta H^0_{f,298} = 206\ kJ/mol$

The rates of reaction of the above described equations are mentioned below:

$$r_1 = CRF * A_1 * exp^{\left(-\frac{E_1}{RT}\right)} * (y_{CO2} - \frac{y_{CO}^2}{K_{eq,1}}) \quad (6)$$

$$r_2 = CRF * A_2 * exp^{\left(-\frac{E_2}{RT}\right)} * (y_{H2O} - \frac{y_{CO}y_{H2}}{K_{eq,2}}) \quad (7)$$

$$r_3 = CRF * A_3 * exp^{\left(-\frac{E_3}{RT}\right)} * (y_{H2}^2 - \frac{y_{CH4}}{K_{eq,3}}) \quad (8)$$

$$r_4 = CRF * A_4 * exp^{\left(-\frac{E_4}{RT}\right)} * (y_{CH4}y_{H2O} - \frac{y_{CO}y_{H2}^3}{K_{eq,4}}) \quad (9)$$

Here, *CRF* is char reactivity factor which is taken as 100. The pre-exponential factors of above reactions and their activation energies are provided in following Table 2.

Table 2: Kinetic parameters of reduction zone gasification reactions [14]

Reaction	Pre-exponential factor(A, sec^{-1})	Activation energy (E, kJ/mol)
1	36.16	77.39
2	1.517×10^{4}	121.62
3	4.189×10^{-3}	19.21
4	7.301×10^{-2}	36.15

The model equations are given as follows:

$$\frac{dn_x}{dz} = \frac{1}{v}(R_x) \tag{10}$$

$$\frac{dv}{dz} = \frac{1}{\sum_x n_x C_x}\left(\frac{\sum_x n_x C_x \sum_x R_x}{n} - \frac{\sum_i ri\Delta Hi}{T} - \frac{dP}{dz}\left(\frac{v}{T} + \frac{v\sum_x n_x C_x}{P}\right) - \sum_x R_x C_x\right) \tag{11}$$

$$\frac{dT}{dz} = \frac{1}{v\sum_x n_x C_x}\left(-\frac{\sum_i ri\Delta Hi}{T}\right) \tag{12}$$

$$\frac{dP}{dz} = 1183\left(\rho_{gas} - \frac{v^2}{\rho_{air}}\right) + (388.19v) - 79.896 \tag{13}$$

The initial pressure (*P*) is considered higher than atmospheric pressure for steady flow. In oxidation zone, exothermic reactions take place and hence the temperature will further increase. Also, ρ_{gas} and ρ_{air} are the densities of the gas and air respectively. The initial gas velocity v is assumed to be 0.4 m/s.

4. Results and discussion

The final output of the reduction zone is done in Matlab by RungeKutta 4th order method. The developed model is simulated to study the effect of various operating parameters. The simulated results of effect of moisture content is represented in graph (Fig. 2) for the downdraft gasifier.

The figure 2 indicates that increasing moisture content of MSW, % composition of N_2 increases while all other gases composition is decreasing. As the moisture content of MSW is increasing, more quantity of water vapor will be evaporated and hence lesser will be the gasification reaction causing decrease in percentage composition of the other gases, this will cause increment of % N_2 at the exit (on dry basis).

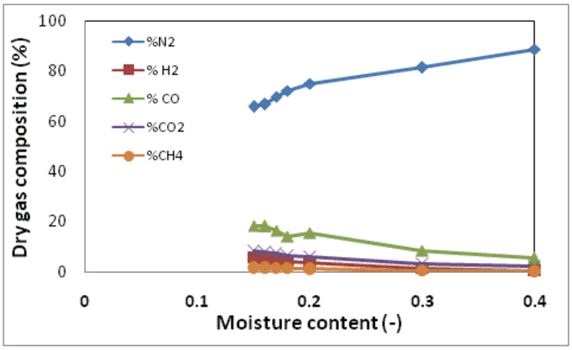

Fig. 2. Effect of moisture content

The proposed model was compared with the published results to study the efficiency of the model. The model was validated against a single stage equilibrium model and experimental data.

4.1 Performance of proposed model vis-à-vis Bhavanam and Sastry (2013) [11] equilibrium model:

The Bhavanam and Sastry's model suggests single stage mathematical model to determine product gas composition. Single stage thermodynamic model is studied for three types of biomass namely. Animal waste, MSW and Groundnut Shell. They have simulated it in MATLAB by Newton Jacobi iteration method. Here Bhavanam and Sastry (2013) [11] model's output for MSW gasification has been compared at 800 ^{0}C and 16% moisture with proposed model.

Table 3: Proposed model's output at 800^0 C and at 16% moisture

Composition	n_{CO}	n_{H2}	n_{CO2}	n_{CH4}	n_{H2O}	n_{N2}
% $y_{x,db}$	20.228	7.5	7.9	1.55	-	62.72

The proposed model and Bhavanam and Sastry model has been compared in following graph (Fig. 3).

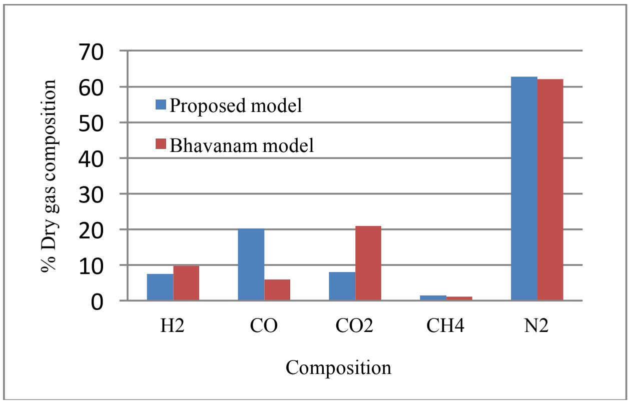

Fig. 3. Comparison of the proposed model with Bhavanam and Sastry model

From the diagram (Fig 3) it is evident that % H_2 in proposed model is comparable with that of the earlier published model. The produced CO is a bit higher than Bhavanam and Sastry model which is compensated by less % CO_2 as in our model more CO is being produced. It can be noted that composition of other gases namely % CH_4 and % N_2 are in good agreement.

4.2 Comparison with experimental data (Kumararaja et.al. 2010 [15])

The performance of the proposed model is compared with the experimental data published by Kumararaja et. al. 2010 [15]. We have simulated the performance of downdraft gasifier operating on MSW and compared the result with earlier published result of experimental study conducted by Kumararaja et. al. 2010 [15] on woody biomass. As evident from the data provided in Table 4, most of the results are in good agreement. This clearly indicates that the assumptions considered for the development of model of the gasifier is a reasonable one and valid for most of the practical operations.

Table 4: Performance of the proposed model with published experimental data

Operating parameters	Experimental data of Kumararaja et.al. [15]	Prediction of the model developed in present study
Biomass	Wood	MSW
Duration(hour)	4	4
Biomass feed rate(kg/hr)	6	6
Gasification air flow rate(kg/hr)	8.95	8.95
Producer gas flow rate(kg/hr)	11.95	12.45
Total biomass fed(kg)	24	24
Total air fed(kg)	35.80	35.80
Total Producer gas composition(kg)	47.80	49.95
Input stream	59.8	59.8
Residual in output stream	12	10

The output of product gas is higher than experimental output due to consideration of thermodynamic equilibrium behaviour for two zones. If equilibrium condition be considered, maximum possible conversion will be obtained. It is required to calculate error for prediction of gas behaviour for validation. Thus it is calculated as shown below,

$$\%error = \frac{|(output\ of\ model - output\ of\ experimental\ data)|}{output\ of\ experimental\ data} \times 100 \tag{14}$$

Above formulae are calculated for validation of proposed model with experimental results. The average error prediction range is in between 10% to maximum 17%.

Table 5: Error and accuracy of the simulated results with the experimental values

Output	Producer gas	Residue	% Average Error	% Average Accuracy
%Error	4.498	$\|-17.91\|$=17.91	11.204	-
% Accuracy	95.502	82.09	-	88.796

The Table 5 provides percentage error and accuracy for the validation purpose of the proposed model. It depicts that proposed model's producer gas composition is 95.5 % accurate with experimental data published by Kumararaja et.al. (2010) [15]. The % average error calculated in table shows 11.2 % which is in reasonable agreement with the experimental data.

5. Conclusion

The main objective of the study is to utilize municipal solid wastes (MSW) in energy recovery via gasification methodology. The producer gas obtained can be utilized as source of energy, in addition incineration operation and / or landfilling with the waste can be minimized. Hence the process outlined here is two way sustainable, (i) it can reduce load on fossil fuel being an alternative energy source, (ii) by providing a better and greener alternative to process the waste generated in various cities across the globe. Studies have been carried out to determine the potential of MSW as usable energy. This technology can be termed as wastes to energy. To study the potential of MSW, mathematical model for two zones (drying-pyrolysis and oxidation) and kinetic model for reduction zone have been utilized to determine dry gas composition at exit temperature. The gas produced can either be used as a source of energy or can be utilized for synthesis of various petrochemicals as its major components are carbon monoxide, methane and hydrogen. The simulated results are validated with a single stage equilibrium model [11] and experimental results of a downdraft gasifier [15].

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