Modeling of Gasification of Refuse Derived Fuel: Optimizations and Experimental Investigations

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Abstract. Nowadays, renewable energy technologies for decentralized electrification are promising in addressing electrification issues. In this study, gasification of Refuse Derived Fuel is investigated for its potential to generate good quality producer gas for use in internal combustion engines for electricity generation. Representative Municipal Solid Waste is separated, screened, prepared and characterized. Lower heating value of the RDF is 16.63 MJ/kg which is an acceptable yield. The gasification was modeled using non-stoichiometric thermodynamic equilibrium model and implemented on MATLAB for optimization. Optimal values of temperature and equivalent ratios were determined to be 850 °C and 0.2, respectively, at a moisture content of 6%. A downdraft gasifier with the gas cleaning and conditioning system has been designed, manufactured and tested experimentally to validate the model. Based on the result, the producer gas heating value was 8.164 MJ/m^3, which is acceptable for utilization in ICEs. The capacity of the gasifier is 147 kW at feed rate of 46 kg/h and product gas flow rate of 65.14 m^3/h to meet engine requirements. The cold gas efficiency of the gasifier is 70%. In conclusion, a good agreement was observed between experimental and simulation results for gas characterization. Catalytic gasification gives promising results for future investigations on the use of Dolomite as a primary cleaning along with advanced secondary gas cleaning system.

Keywords: Gasification · Modeling · Refuse Derived Fuel · Equivalence ratio (E.R) · Gas cleaning

1 Introduction

Solid Waste Management is becoming a very challenging issue in developing countries due to lack of regulation on solid waste collection, recycling and disposal [1–3]. In Ethiopia, the first waste to energy plant with a capacity of 25 MW$_{el}$ is under construction in its capital city, Addis Ababa. However, Ethiopia is a country with a population of 100 Million people and 80% of the populations live in rural areas [4]. In addition to the waste management problem, 75% of the population is living without access to electricity

[5]. Considering a waste generation rate of 0.25 kg/day/person and the considering the current population of Ethiopia, i.e., 102 Million, potentially 25.5 Million kg of waste is generated daily [4]. Although several waste-to-energy plants exit in most of the developed countries, it is still at its infancy stage in Africa and Ethiopia, in particular.

Municipal Solid waste (MSW) is a good source of energy [10, 11]. The specific energy content of MSW can be enhanced by further processing it into Refuse Derived Fuel (RDF). RDF refers to a separate high calorific fraction of municipal solid waste, solid and dry commercial and/or industrial process wastes [7]. Other terms are also used for MSW derived fuels, such as: Refused Fuel (RF), Packaging Derived Fuels (PDF), and Process Engineered Fuels (PEF) [7]. RDF from MSW can be a good alternative source of energy that can replace fossil fuels [6, 7].

Thermo-chemical conversion of waste is a high temperature process causing modifications on the chemical nature/structure of the feed material. Combustion, gasification and pyrolysis are the three main technological options for thermo–chemical processes [8, 9, 14].Gasification provides good thermo-chemical conversion efficiency by offering high flexibility in terms of various materials as feedstock and due to this, it has an interesting advantage over direct combustion and pyrolysis in some technological applications such as prior gasification of biomass and waste and subsequent utilization of producer gas in ICEs, which is a rational way to use in small scale energy producing units [9, 14, 15]. In gasification, the four important processes that occur inside the reactor are: drying, pyrolysis, oxidation and reduction. Each process inside the gasifier is associated with its certain physical and chemical features in the respective zones. Modeling implies the representation of a chemical or a physical system by a set of equations so that it can represent the system under study [12]. When considering a downdraft gasifier, the modeling of chemical reactions taking place in each zone can be carried out separately as shown in Fig. 1.
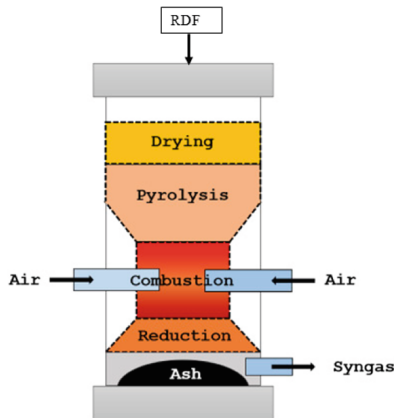

Fig. 1. Schematics of key process zones of downdraft gasifier [16]

Gasifier simulation models are classified into thermodynamic equilibrium model, kinetic model, CFD model and artificial neural network [12, 17]. In thermodynamic equilibrium models, either stoichiometric or non-stoichiometric approaches can be employed. Stoichiometric equilibrium approach includes thermodynamics along with

the chemical equilibrium of chemical reactions. This method can be designed in two ways. It can be used for the global gasification reaction or can be used for each zone of drying, pyrolysis, oxidation and reduction [13]. The non-stoichiometric equilibrium approach is basically designed by minimizing Gibbs free energy of the system [17]. However, elemental composition and moisture content of the fuel is needed. These values can be obtained from ultimate and proximate analysis data of the feed. This approach is typically preferable for feedstocks, like biomass and RDF, as the chemical formula of these feedstocks is not exactly known [18]. Kinetic model is suitable for prediction of product gas composition and gas yield after finite residence time, in a finite volume of reactor at a gasification temperature [17]. Even though kinetic model is computationally intensive, it provides multi-dimensions to investigate the behavior of gasification and gasifier via simulation and it is considered to be the most accurate model [19].

For a product gas to be used in heating/burner applications, with no cleanup, an updraft gasifier can be used. However, if the product fuel gas is to be used in ICEs for an application as that of electricity generation, then a downdraft gasifier is commonly used for its relatively high tar cracking ability among the other gasifier types. In addition, the gas must be cleaned and conditioned before it is fed to the engine [14, 15]. The producer gas exiting the downdraft gasifier is hot and laden with dust, containing up to 1% tars and particulates [27]. If these contaminants are not removed properly, maintenance and reliability problems will occur on engine, heat exchangers and other parts of the system making it more costly and troublesome. In fact, failure of many gasifier-engine systems have been attributed due to the problem of improper cleanup systems alone [20]. The gas cleaning and conditioning system also plays important role in controlling hazardous emissions. In order to design effective gas clean up systems, nature of contaminants with the magnitude of potential problem has to be determined.

Well-carried out design of an economical gas cleaning and conditioning system was performed to achieve conditions demanded by the internal combustion engines (Table 1).

Table 1. Gas quality requirements for power generation applications in ICEs [27]

| Major contaminants	Level of purification demanded by IC engine
Particle concentration	<50 mg/Nm^3
Particle size	<10 μm
Tar	<100 mg/Nm^3

The recommended procedure is as follows [28]:

1. Particulates are first removed at temperature below dew point of tar ($\approx 300\,°C$)
2. Next, tar is removed at intermediate temperatures ($\approx 100\,°C$)
3. Finally, water is removed at 30 °C to 60 °C, and each separate contaminant will be handled more easily.

The cleaning subsystem is designed with properly-sized components of the following selected methods (Table 2).

Table 2. Gas contaminants cleaning methods selection

	Contaminants	Available cleaning/filtering methods [25, 29–31]	Methods employed on this study
1	Particulates	• Cyclone separator • Barrier filter • Electrostatic precipitator • Wet scrubber	• Cyclone separator (**Justification**: easy design and uses gravity for settling of particles out of gas line. A cyclone of high efficiency can be fabricated a low effort and cost)
2	Alkali Compounds	• Cooling below 600 °C + electrostatic precipitator • Cooling below 600 °C + fabric filter • Cooling below 600 °C + bag filter	• Cooling below 600 °C + fabric filter (**Justification**: has good efficiency, ease of manufacturing and cost-effective)
3	Nitrogen Compounds	• Standard Catalytic Methods	• Catalytic distraction
4	Sulfur and Chlorine	• Wet scrubbing • Additives	• Additives (**Justification**: Abundant availability of Dolomite catalyst in Ethiopia for a primary cleaning (cleaning performed inside the gasifier) than wet scrubber)
6	Tar	• Thermal destruction • Catalytic destruction • Barrier filters • Wet scrubbers	• Catalytic destruction + Barrier filters (**Justification**: use of barrier filters of high efficiency and the inexpensive dolomite catalyst that will affect heating value of the gas positively along with the primary cleaning advantage)

The schematic of the pilot setup is shown below (Fig. 2).
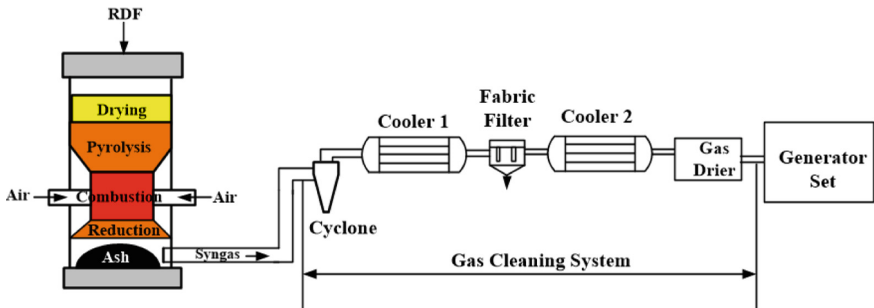
Fig. 2. Schematics of the pilot setup

This study aims to build a realistic model for gasification of RDF in a fixed bed downdraft gasifier, to estimate species concentration in the producer gas and the heating

value for wide range of gasification temperatures. The optimal equivalence ratio and operating temperature will be computationally estimated at a moisture content of 6%. Equivalence ratio (E.R) is the ratio of actual air fuel ratio to stoichiometric air fuel ratio and provides the basis for evaluating the amount of air supplied for gasification with respect to the amount of air required for complete combustion or stoichiometric oxidation of the feedstock. It also involves performing process design of the gasifier and a gas cleaning and conditioning system with proper sizing, and fabrication of the pilot set up that can produce a producer gas that meets the minimum requirements of ICEs. Further, experimental investigations on the pilot setup will be carried out to draw valid conclusions on the characterization of the product gas by validating with model outputs and a preliminary investigation on catalytic gasification will be done by the use of Dolomite mineral for primary gas cleaning.

2   Methodology

2.1   Characterization of RDF Sample

The ultimate and proximate analysis results for the RDF sample are depicted as shown in Table 3. The moisture content, ash content, volatile matter and fixed carbon were determined by standard procedures [21]. The moisture content is determined by the loss in weight that occurs when a sample is dried in a laboratory oven at 105 °C for 1 h. The volatile matter is determined by measurement of weight loss following combustion of about 1 g RDF sample in a furnace at 950 °C for 6 min. To determine the ash content, the samples were heated in a laboratory ash furnace at 750 °C for at least 3 h. The ultimate analysis of the sample was determined using ultimate analyzer. Thus, based on the elemental analysis, the chemical formula of the RDF sample is determined and normalized with respect to Carbon. The chemical formula of the RDF sample is $CH_{1.7155}O_{0.6510}N_{0.01172}$.
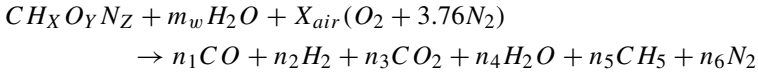
Table 3. Characterization of the RDF

Ultimate analysis (w/w %)	
Carbon	41.7241
Hydrogen	5.9648
Oxygen	36.2183
Nitrogen	0.5703
Sulfur	0
Proximate analysis (w/w %)	
Moisture content	6.56
Volatile matter	7.12
Fixed carbon	11.36
Ash content	8.96
LHV [MJ/kg]	16.63

2.2 Mathematical Model

The non-stoichiometric equilibrium model for gasification of the RDF was formulated by developing empirical relations for predicting the individual fraction of major combustible constituents of the producer gas. These relations can be used for any gasifier and are more accurate and realistic for downdraft gasifier due to its relatively higher tar cracking ability. In this work, the following assumptions were made [22–24]: The species considered to appear in the producer gas are: CO, CO_2, H_2, CH_4, N_2 and water; 100% carbon conversion efficiency; the residence time is high enough to achieve thermodynamic equilibrium; ash in feedstock is inert in all gasification reactions (although this hold true only for reaction temperatures below 700 °C); the pressure drop inside gasifier is negligible and all gaseous products behave as ideal gases, the process is adiabatic, Sulfur and Chlorine content in RDF is negligible (they have a very small share (<0.6%) in the total feedstock).

The chemical composition of RDF is taken to be in the form $CH_X O_Y N_Z$ and the global gasification reaction can be written as:

$$CH_X O_Y N_Z + m_w H_2O + X_{air}(O_2 + 3.76N_2)$$
$$\rightarrow n_1 CO + n_2 H_2 + n_3 CO_2 + n_4 H_2O + n_5 CH_5 + n_6 N_2$$

m_w is calculated from:

$$M_{RDF} \times m = m_w[18(1-m)] \rightarrow m_w = \frac{M_{RDF} \times m}{[18(1-m)]}$$

Mass Balance

$$\text{Carbon Balance: } n_1 + n_3 + n_5 = 1 \tag{1}$$

$$\text{Hydrogen Balance: } x + 2m_w = 2n_2 + 2n_4 + 4n_5 \tag{2}$$

$$\text{Oxygen Balance: } y + m_w + 2X_{air} = n_1 + 2n_3 + n_4 \tag{3}$$

$$\text{Nitrogen Balance: } n_6 = 0.5Z + 3.76X_{air} \tag{4}$$

Basic Chemical Equilibrium Reactions and Equilibrium Constants
The major reactions that occur inside downdraft gasifier are [14]:

$$C + CO_2 \rightarrow 2CO \tag{5}$$

$$C + H_2O \rightarrow H_2 + CO \tag{6}$$

The two reactions shown above can be combined into one single reaction known as water-gas shift reaction.

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{7}$$

The other reaction that is important in the gasification process is the methane formation reaction.

$$C + 2H_2 \leftrightarrow CH_4 \tag{8}$$

Now, Eqs. 7 and 8 are the two major reactions in the gasification process. The equilibrium constants for the above two major reactions as a function of their molar composition are as follows:

$$K_1 = \frac{n_{CO_2} * n_{H_2}}{n_{CO} * n_{H_2O}} = \frac{n_3 \, n_2}{n_1 \, n_4} \tag{9}$$

$$K_2 = \frac{n_{CH_4} * n_{tot}}{\left(n_{H_2}\right)^2} = \frac{n_5 \, n_{tot}}{n_2 \, n_2} \tag{10}$$

Gibbs free energy is used in determining the values of K_1 and K_2. For the given ideal gases, the Gibbs free energy is a strong function of temperature.

$$\ln K(T) = \frac{-G(T)}{RT} \tag{11}$$

$$\Delta G \, (T) = \sum_i n_i \Delta g^o_{f,i}(T) \tag{12}$$

The change in Gibbs free energy for each individual gas is empirically given by (Table 4):

$$\Delta g^o_{f,i}(T) = H^o_{f,i} + aT\ln T - bT^2 - 0.5cT^3 - (d/3)T^4 + (e/2T) + f \tag{13}$$

Table 4. Enthalpy of formation and constants for Eq. 13 [14]

Species	$\bar{H}^o_{f,298}$	$a \times 10^2$	$b \times 10^5$	$c \times 10^8$	$d \times 10^{12}$	$e \times 10^{-2}$	f	g
CH$_4$	−74.8	−4.62	1.13	1.32	−6.65	−4.89	14.1	−0.223
CO	−110.5	0.562	−1.19	0.638	−1.85	−4.89	0.868	−0.0613
CO$_2$	−393.5	−1.95	3.12	−2.45	6.95	−4.89	5.27	−0.121
H$_2$O	−241.8	−0.895	−0.367	0.521	−1.48	0	2.87	−0.0172

Energy Balance inside the Gasifier

The total energy content in any chemical species is the sum of its chemical enthalpy and sensible enthalpy, which can be written as:

$$H^O_{f,RDF} + m_w \left(H^O_{f,H_2O(l)} + H_{vap}\right) + X_{air}\left(H^O_{f,O_2} + 3.76H^O_{f,N_2}\right)$$

$$= n_1\left[H^O_{f,CO} + \int_{298\,K}^{T_g} (C_{p,CO}dT)\right] + n_2\left[H^O_{f,H_2} + \int_{298\,K}^{T_g} (C_{p,H_2}dT)\right]$$

$$+ n_3 \left[H^O_{f,CO_2} + \int\limits_{298\,K}^{T_g} (C_{p,CO_2} dT) \right] + n_4 \left[H^O_{f,H_2O} + \int\limits_{298\,K}^{T_g} (C_{p,H_2O} dT) \right]$$

$$+ n_5 \left[H^O_{f,CH_4} + \int\limits_{298\,K}^{T_g} (C_{p,CH_4} dT) \right] + (0.5z + 3.76 X_{air}) \int\limits_{298\,K}^{T_g} (C_{p,N_2} dT) \qquad (14)$$

Since heat of formation of all diatomic molecules ($H^O_{f,N_2}, H^O_{f,O_2}, H^O_{f,H_2}$) is zero at reference temperature and pressure of 298 K and 1 atm, Eq. 13 reduces to:

$$H^O_{f,RDF} + m_w \left(H^O_{f,H_2O(l)} + H_{vap} \right) = n_1 \left[H^O_{f,CO} + \int\limits_{298\,K}^{T_g} (C_{p,CO} dT) \right]$$

$$+ n_2 \left[H^O_{f,H_2} + \int\limits_{298\,K}^{T_g} (C_{p,H_2} dT) \right] + n_3 \left[H^O_{f,CO_2} + \int\limits_{298\,K}^{T_g} (C_{p,CO_2} dT) \right]$$

$$+ n_4 \left[H^O_{f,H_2O} + \int\limits_{298\,K}^{T_g} (C_{p,H_2O} dT) \right] + n_5 \left[H^O_{f,CH_4} + \int\limits_{298\,K}^{T_g} (C_{p,CH_4} dT) \right]$$

$$+ (0.5z + 3.76 X_{air}) \int\limits_{298\,K}^{T_g} (C_{p,N_2} dT) \qquad (15)$$

C_p can be determined from an empirical correlation given by [14] (Table 5):

$$C_p(T) = C_1 + C_2 T + C_3 T^2 + C_4 T^4 \qquad (16)$$

Table 5. Coefficients of specific heat capacity for various gases [14]

Species	C_1	C_2	C_3	C_4
N_2	31.2	$-1.36\,(10)^{-2}$	$2.68\,(10)^{-5}$	$-1.17\,(10)^{-8}$
CO_2	19.8	$7.34\,(10)^{-2}$	$-5.60(10)^{-5}$	$1.72\,(10)^{-8}$
H_2	29.1	$-1.92\,(10)^{-2}$	$4.00\,(10)^{-6}$	$-8.70\,(10)^{-10}$
CO	30.9	$-1.29\,(10)^{-2}$	$2.79\,(10)^{-5}$	$-1.23\,(10)^{-8}$
CH_4	19.3	$5.21\,(10)^{-2}$	$1.20\,(10)^{-5}$	$-1.13\,(10)^{-8}$
H_2O (g)	32.2	$1.92\,(10)^{-2}$	$1.06\,(10)^{-5}$	$-3.60\,(10)^{-9}$

Model Implementation

The equilibrium constants of gasification reactions (Eqs. 9 and 10) and the elemental composition of the fuel (RDF) from ultimate analysis data are input to the model to obtain producer gas composition. It involves solving the system of equations in MATLAB using Newton–Jacob Iteration. Once the producer gas composition is determined from the feedstock, a linear equation is developed to calculate the concentration of each gas species in the producer gas.

Experimental Setup

The pilot set up used for experiment is shown in Fig. 3 with gasifier dimensions in Table 6.

Table 6. Design parameters of the gasifier

Gasifier design parameter	Value
The throat diameter, d_t	10 cm
The superficial velocity of the gas, v_g,	2.5 m/s
Throat Inclination, θ	45°
Height of Nozzle Plane above the Throat, h	9.79 cm
Height of Oxidation Zone, h_{oxd}	19.58 cm
The nozzle inner diameter, d_m	1.043 cm
Number of nozzles, N	5
Top Nozzle Ring Diameter, d_n	22.08 cm
Height of the Reduction Zone, h_r	18.72 cm
Height of the Pyrolysis Zone, h_p	130 cm
Total Height of the Reactor, H	180 cm

Fig. 3. The fabricated experimental setup

3   Result and Discussion

Molar fractions of compositions of the producer gas for gasification temperatures ranging from 573.15 K to 1523.15 K (300 °C to 1250 °C) and for equivalence ratios ranging from 0.2 to 0.35 are simulated. Model results are shown in Figs. 4, 5, 6, 7 and 8. The variation of LHV at different temperatures and equivalence ratios at a moisture content of 6%, are estimated using the following formula and is shown in Fig. 8. LHV of the producer gas (LHV_g) is calculated from the gas analysis data of the producer gas. Lower heating value of different constituent of the producer gas at STP (20 °C and 1 atm) is

used in the calculation. The following expression is used for calculation of lower heating value of the producer gas.

$$LHV_g = \sum X_i H_i$$

Where, X_i = Volume fraction of producer gas constituent and H_i = Heating value of constituent gases. Heating values of constituent gases are referred from Table C.2 of [14]. E.R is the most influential parameter in any gasification process and often has significant impact on product gas composition. The theoretical gasification occurs between E.R values of 0.19–0.43 and the optimum point is near to 0.25 [14].
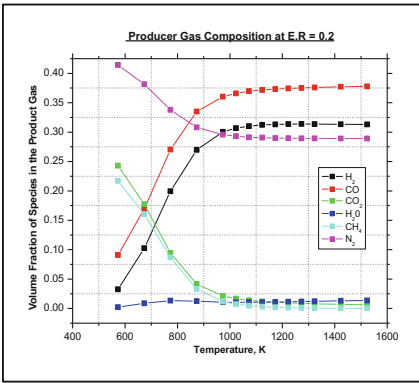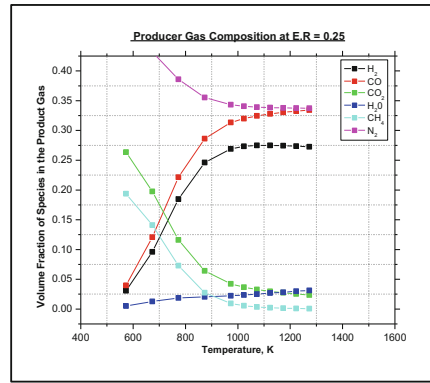

Fig. 4. Producer gas composition at E.R = 0.2   **Fig. 5.** Producer gas composition at E.R = 0.25
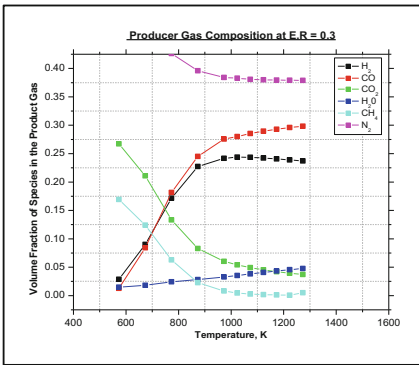

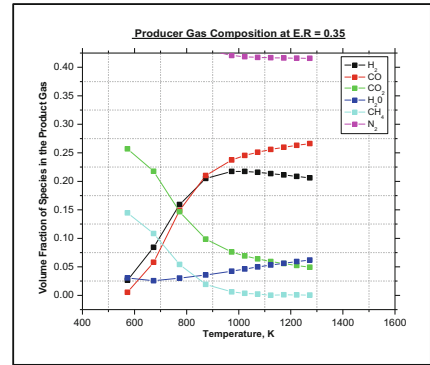**Fig. 6.** Producer gas composition at E.R = 0.3   **Fig. 7.** Producer gas composition at E.R = 0.35

From the above results, it can be seen that concentrations of H_2 and CO increase in a similar trend towards higher temperature values. This is attributed to the fact that the water-gas shift reaction (Eq. 7) and the methane formation reaction (Eq. 8) favor

backward reactions at higher temperatures (800 °C and 700 °C, respectively) to give more CO and H_2 at the expense of CO_2 and CH_4, respectively. This agrees with the points discussed in [14]. Additionally, it can be observed that molar concentrations of H_2 and CO decrease at higher E.R values. This results in decreased heating value of the product gas at higher E.Rs. The concentrations of H_2 and CO increase for temperatures above 800 °C and slightly decrease as E.R increases. This is because, as E.R increases, more air/oxygen is supplied to the process. Oxidation will dominate the reduction reaction and, thus, reducing the heating value by providing less room for the most important process of reduction where chemical energy is bonded in the constituents of the producer gas. If E.R is kept on increasing, finally, when E.R = 1, the gas will be of no heating value and, hence, a flue gas. It can also be observed from Fig. 8 that, heating value of the gas will decrease at higher temperatures for a given equivalence ratio. This is due to a decrease in the concentration of CH_4 at higher temperatures of thermo-chemical conversion. As seen from the results, as the methane formation reaction tends to a backward reaction at higher temperatures to give more H_2 than CH_4. Methane has the highest LHV among all the other gases according to Table C.2 of [14] and, thus, decline of its concentration will significantly affect the total LHV value of the gas. Another option to maximize the LHV of the gas is to maximize production of species with relatively higher LHV next to CH_4 (CO and H_2) at higher temperatures. However, the LHV value at higher temperatures will be lesser than that of the LHV at lower temperatures. This shows that the LHV of Methane significantly affects the LHV of the producer gas. In fact, this is one of the rationales behind the need for optimization.
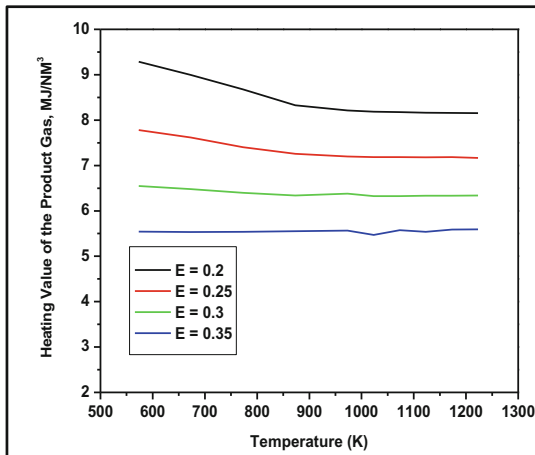

Fig. 8. Heating value of the product gas at different E.Rs

The computation results indicate that in each cases carbon monoxide is the most dominant component in the product gas, followed by hydrogen and carbon dioxide, at higher temperatures. This is due to the water-gas reduction and partial combustion of carbonaceous char materials at the bed. Hydrogen is formed in the bed due to gasification reactions involving water with further release of carbon monoxide and carbon dioxide.

Methane formation is favored at temperatures less than 700 °C as postulated from its reaction thermodynamics and at temperatures above 900 °C, production of methane is almost negligible (Figs. 4, 5, 6 and 7).

Fig. 9. The produced producer gas

Fig. 10. Experimental apparatus

Molar concentrations of carbon monoxide and hydrogen reach peaks at temperatures above 800 °C with no or slight variation after the peak value. This makes LHV of the producer gas to be constant after 800 °C for each equivalence ratio. The LHV of species concentration gives the maximum value of 8.164 MJ/m^3, which is a well-accepted yield as recommended by [26, 27]. The optimal parameters for this maximum LHV value are a gasification temperature of 850 °C and an equivalence ratio of 0.2. This temperature is a point at which more carbon monoxide and hydrogen gas discovered in the product gas at equivalence ratio of 0.2, with a remarkable contribution to the maximization of the gas heating value. At these optimal operating conditions, the gasifier power will be 147 kW at cold gas efficiency of 70% and at feed rate of 46 kg/h to produce gas flow rate of 65.14 m^3/h, which is fit for engine operational requirements.

The results obtained with the model implementation in this work have been validated with experimental results from the test runs conducted on the pilot setup (Figs. 9 and 10). During the first test, experimental characterization of the producer gas was performed and results were compared with model output at optimal operating conditions for validation, shown on Fig. 11. Very similar results are achieved for CO and CH$_4$ concentrations in the product gas. Both approaches estimate very small production of CH$_4$ and relatively higher CO. The very small concentration of methane in the product gas confirms the fact that no chemical equilibrium can be achieved in reality, especially below 800 °C. The methane formation reaction favors backward reaction and production of carbon and hydrogen gas is facilitated at higher temperatures, which is expected to have major share in other gases (collective gases remained in ppm). As a result, insignificant amount of methane is predicted and obtained in both cases. Therefore, carbon is the most dominant in the product gas in the form of CO, CO$_2$ and CH$_4$. The experimental and modeling results show a very good agreement on the contents of CO, CH$_4$ and other collective gases with unexpected deviation on CO$_2$ content as shown on Fig. 11. The CO$_2$ content, which is estimated to have fewer shares in the product gas in both approaches, has shown significant deviation one from the other, experimental result has overestimated the CO$_2$ content as the following gaps were identified on the experiment to attribute to the deviation.

- The control of the gasification temperature exactly at 850 °C is difficult. The experiments were conducted at various temperature ranges and sampling was taken only at temperatures near to the optimal value. With slight difference on the gasification temperature, exaggerated deviation on CO_2 yield is observed. The water gas shift reaction is a reversible reaction more active at temperatures above 800 °C. The reaction is forward reaction in the instantaneous temperatures of sampling and is characterized by increased mole fractions of CO_2.
- The air flow rate was measured well to meet the condition (E.R = 0.2), but to make continued tests, two air compressors was used interchangeably with repeated calibrations in the middle of the test each time air lines are changed. There is a possibility for the combustion zone to be air-rich contributing for the increase in CO_2 content.

On the second test, catalytic gas purification was evaluated by comparing the results with that of the gasification without catalyst from test 1 as shown in Fig. 12. Using the above measured species, the tar cracking performance of the catalyst was preliminarily examined. The catalytic gasification is observed to yield more CO and reduce CO_2 content. This effective reduction process has come to effect by tar cracking action imposed by the Dolomite catalyst. Experiment reveals slightly overestimated values for the other gases and the best analysis referred to this case is increase of contents from broken compounds like NO_X to which the catalyst is sensitive to. The experiment gives well agreed results for CO, CO_2 and CH_4 expected variations before and after the cleaning process. This can be clearly seen that these species are more of sensitive to the methane formation and water gas shift reduction process in the bed of the gasifier than other thermal and filtration processes outside the gasifier. The oxygen content in both samples (before and after) is quiet low and yet much underestimated result was obtained from the sample after the clean-up. This might be attributed to favored oxidation of SO_X and other compounds at lower temperature after cooling stages, increases the parts of other gases per millions at the expense of used up oxygen gas.
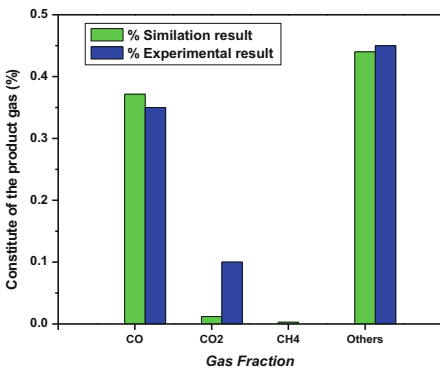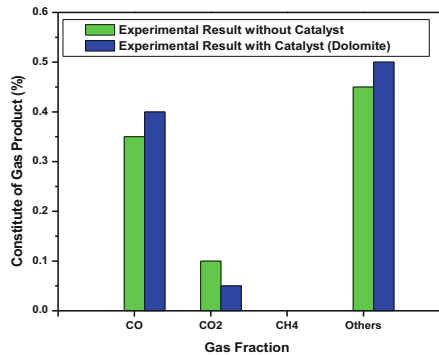

Fig. 11. Simulation vs experimental result

Fig. 12. Comparision of gasification with and without catalyst

The model used an assumption of 1 bar pressure in the gasifier and the pressure gauge at the outlet of the gasifier gave a reading close to 0.82 bar, which makes the assumption valid as the amount of pressure drop observed supports the fact that downdraft gasifier have relatively lower pressure drop.

4   Conclusion

In use of producer gas for IC engines, the most important objective is to produce a cleaner (low tar) gas with high heating value. To achieve the production of gas with relatively high heating value, it is important to convert carbon dioxide and water to as much carbon monoxide, hydrogen and methane as possible, as these constituents contribute relatively high heating values for the gas. Therefore, it can be seen that it is desirable to give emphasis and encourage the two main reduction reactions (Methane formation reaction and Water Gas shift reaction). The optimum LHV of the product gas (8.164 MJ/m^3) is high enough for downdraft gasification as recommended by [26, 27] and is a good yield from downdraft for applications such as utilization of the gas in IC engines for electricity generation. Operating conditions of the gasifier for this best operating condition are at 850 °C and equivalence ratio of 0.2. Tar is observed in the producer gas in lower equivalence ratios and further gas cleaning and conditioning system has to be considered. Non-stoichiometric models give reliable results for producer gas characterization from simple input that can be determined from elemental composition and proximate analysis data. The lower heating value (LHV) of a typical RDF lie in the range 15 MJ/kg to 18 MJ/kg according to the selection process and amount high LHV constituents present [7]. The LHV value of the prepared RDF is 16.63 MJ/kg, which is in the suitable range. A good agreement between modeling and simulation results was achieved for gas characterization at the gasifier outlet, which supports the fact that non–stoichiometric thermodynamic equilibrium model can adequately simplify the computation. Catalytic gasification and the gas cleaning system gives promising results for future advanced investigations on the use of Dolomite as a primary cleaning and more advanced secondary gas cleaning techniques. Generally, the pilot plant is of easy configuration as shown on Fig. 3, which can produce 147 kW of power in an area of less than 3 m^2 and is user-friendly operation, that is, control of the system require only control adequate feed rate than any other technical adjustments on the system.

Acronyms

E.R	Equivalence Ratio
CFD	Computational Fluid Dynamics
ICEs	Internal Combustion Engines
MW$_{el}$	Mega Watts of electricity

μm	Micro Meter
kW	Kilo Watts
LHV	Lower Heating Value
MSW	Municipal Solid Waste
PDF	Packaging Derived Fuels
PEF	Process Engineered Fuels
ppm	Parts Per Million
RDF	Refuse Derived Fuels
RF	Refused Fuels
WTE	Waste – to – Energy
C, H, O, N	Carbon, Hydrogen, Oxygen, Nitrogen
M_{RDF}	Molecular weight of the RDF
m	Moisture content of the RDF
m_w	Number of moles of water vapor in dry basis
n_i	Number of moles of species 'I' in the producer gas.
n_{tot}	Total number of moles of gases
x, y, z	Normalized coefficient of atomic Hydrogen, Oxygen and Nitrogen for RDF molecule.
X_{air}	Number of moles of air
K_1	Equilibrium Constant for Water – Gas Shift Reaction
K_2	Equilibrium Constant for Methane Formation Reaction
$\Delta G\,(T)$	Gibbs free energy [KJ/Kmol]
$\Delta g^o_{f,i}(T)$	Change in Gibbs free energy for individual gas, i at a given temperature.
$H^O_{f,i}$	Enthalpy of formation for spices i
a, b, c, d, e, f	Coefficients for Gibbs free energy empirical correlation.
$C_{p,i}$	Specific heat capacity for species i

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