Research Article

Ravi Kumar Rachamala*, Narasimhulu Sanke and A. Seshu Kumar

Experimental investigation of Segregated Dry Municipal Solid Waste (SDMSW) and biomass blends in the gasification process

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Abstract: Producing sustainable energy to meet the world's current demands is a major concern. Municipal Solid Waste (MSW) is a good source for producing sustainable energy and currently gets abundantly generated in India. Usually MSW is screened to prepare Segregated Dry Municipal Solid Waste (SDMSW) pellets before subjecting it to gasification to produce producer gas. But, generation of hazardous byproducts is a key issue in the conversion of SDMSW to producer gas. In the present work a multi-purpose downdraft gasifier has been designed and developed that can process biomass and SDMSW pellets blend while reducing undesirable byproducts such as tar and ash. The calorific value, chemical composition and byproduct content of the SDMSW pallets blended with biomass are determined prior to gasification. The feedstock is characterised using ultimate and proximate analysis, and the calorific value is determined using a bomb calorimeter. Gas chromatography is used to assess the quality of the producer gas. The results indicate that adding 50% SDMSW to Biomass results in good efficiency.

Keywords: biomass; gasification; MSW; pyrolysis; SDMSW.

***Corresponding author: Ravi Kumar Rachamala,** Department of Mechanical Engineering, Maturi Venkata Subba Rao (MVSR) Engineering College, Hyderabad 501510, Telangana, India, E-mail: ravirachamala@gmail.com. https://orcid.org/0000-0003-1522-7059
Narasimhulu Sanke, Department of Mechanical Engineering, University College of Engineering (Autonomous), Osmania University, Hyderabad, Telangana, India
A. Seshu Kumar, Indian Institute of Chemical Technology (IICT), Hyderabad, Telangana, India

Introduction

Water and energy are the majour topics towards the growth of a nation which can leads the modern world towards sustainable supply. Throughout the global crisis and access of energy are the major issues faced by human being in 21st century. Due to the unavailability of fossil fuels and growing the population. Researchers need to develop energy efficient methods. Few researchers suggested alternative solutions to generate energy from the alternative fuels, because it is clean energy which is renewable characteristics. Nowadays municipal solid waste is promising and novel source to producing energy by reducing waste. MSW processing is a major issue in developing countries. One of the most cost-effective solutions is to convert MSW into useful producer gas using gasification. Gasification is the process of producing generator gas (producer gas). In the gasification process, biomass is converted into producer gas by partial combustion takes place at temperatures around 1000 °C, and the reactor is known as a gasifier. Nitrogen, water vapor, and carbon dioxide are produced during combustion when there is insufficient oxygen. However, in the gasification process, incomplete combustion of biomass will produce carbon monoxide (CO), hydrogen (H_2), and methane, as well as some byproducts such as tar and dust (Figure 1). These gases are produced during the pyrolysis process when water vapor reacts with carbon dioxide. The key challenge is thus to design a multi-purpose downdraft gasifier to create desirable combustion conditions for biomass/SDMSW blends with higher efficiency while producing fewer byproducts.

Every day, a few tonnes of MSW accumulate in the world. Handling and processing the accumulated MSW has thus become a hassle for developing countries. Turning MSW into useful products wherever they are is a good solution to this problem. It is advisable to use the gasification process to convert MSW into useful producer gas. Limited research has been carried out on the usage of MSW with biomass in downdraft gasifiers.

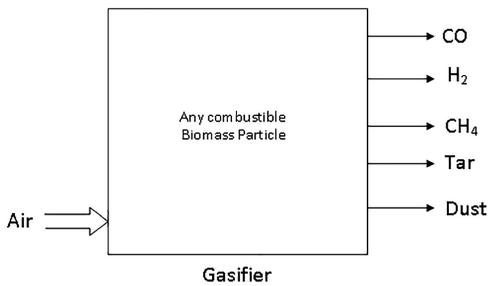

Figure 1: Production of gasification.

Simone et al. (2012) conducted experiments on a 200-kW downdraft gasifier with sawdust blended with sunflower seeds. The experimental results show that the generated syngas has the desired compositions and that the gasifier efficiency is close to 70%. Thakare and Nandi (2016) prepared weight-based pallets with various compositions of paper, plastics, ash, and fine earth. The calorific value of generated producer gas is approximately 800–1000 kcal/kg. Seo, Alam, and Yang (2018) characterized and described the properties of MSW. To improve efficiency, a pilot model of a gasifier is being developed to process MSW using advanced technologies. The gasification mechanism is also explained, along with the parameters that affect the quality of producer gas and gasifier efficiency. The developed model reduces emissions by efficient pathways. Rajasekhar et al. (2015) presented the most effective MSW treatment methods that can be used by any municipal corporation. To completely dispose of the residues generated during the pyrolysis process, a plasma gasification method is proposed. Chommontha et al. (2022) used the co-gasification process to investigate the energy potential of coconut petioles with refused-derived fuel (RDF). Gasification of petioles produced producer gas with lower heating values than RDF produced producer gas. Zhao et al. (2016) used MSW blended with wheat straw to make pallets. A laboratory-scale fluidized bed reactor was created to study the gasification characteristics. Pallets can be gasified in an oxygen-rich environment at temperatures ranging from 600 °C to 900 °C. RDF and straw mixture solid fuels were studied by Cai et al. (2021). The research shows that the production of producer gas is temperature-dependent and that if the equivalency ratio is greater than 0.3, the carbon conversion efficiency during co-gasification is higher. Pio, Tarelho, and Matos (2017) developed a pilot-scale biomass gasifier on a bubbling fluidized bed reactor using RDF and biomass. The pyrolysis process is assumed to be steady-state and autothermal, and the effect of process parameters is investigated. Cao, Fu, and Mofrad (2019) performed a series of experiments to investigate the effect of process parameters on the gasification process. The composition of producer gas, and thus its quality, is increasing as the blending ratio varies from 100% SD to 100% MSW. On the other hand, compositions such as H_2 and CO_2 are reduced. Indrawan et al. (2018) patented a gasifier with an integrated IC engine and generator that can process biomass and MSW at various blending ratios. For all blending ratios, the maximum electrical power generated was 5 kW. The gasifier's efficiency decreases as the percentage of MSW increases. Bhoi et al. (2018) investigated the hot and cold gas efficiencies of producer gas generated in a commercial downdraft gasifier by MSW blended with switchgrass (0%, 20%, 40%). The gasifier's performance is satisfactory up to 40% of the MSW blend ratio. Lee, Chung, and Ingley (2014) investigated high-temperature pure-steam gasifiers. The results of the investigation show that it is possible to generate clean producer gas using MSW-biomass-rubber-plastic as feedstock. The maximum calorific value of plastic blends is approximately 810 MJ/Nm^3. Pérez, Melgar, and Benjumea (2012) improve the thermochemical process in downdraft gasifiers by varying reactor geometry, feedstock moisture content, inlet air velocity, and feedstock particle size. The gasifier's efficiency increases with inlet air velocity of 0.06 m/s, the particle size of 2 and 6 mm, and moisture content of 10.62%. Antonopoulos et al. (2011) developed a three gasifier to generate syngas with no byproducts. A producer gas will produce through three stages: pyrolysis, combustion, and gasification. This method can be used to process MSW as well as any biomass, independent of chemical composition. The proposed gasifier has a 30% efficiency with minimal environmental impact. Many researchers proposed various design modifications to gasifiers to process MSW with biomass. There are several methods for gasifying separated MSW and biomass mixtures, as well as syngas cleaning systems, available to limit tar formation and generate high-quality gas with the required compositions. A fixed bed downdraft gasifier, on the other hand, is the simplest to build and operate for co-gasification of MSW and biomass. As a result, it is a more attractive technology for heat and power generation in remote rural communities (Anca-Couce et al. 2021; Hameed et al. 2021; Heberlein et al. 2022; Hu et al. 2017, 2021; Ilyushechkin, He, and Hla 2021; Mednikov 2018; Shahbaz et al. 2020; Soltanian et al. 2022; Wiyono et al. 2020; Xiang et al. 2021). Nevertheless, much research is required to improve the efficiency of MSW handling in biomass gasifiers.

The main objective of the present research work is to generate a large amount of bio-methane (natural gas) and syngas (SNG) after filtration and purification of producer gas generated by the gasifier. The developed downdraft gasifier was studied to evaluate the performance of the gasifier by the processing of MSW and biomass feedstocks at varying combinations. To process the co-gasification of MSW and Biomass a separate multi-purpose gasifier was designed, fabricated, and tested.

Methodology

The experimental setup is designed and developed for co-gasification of SDMSW and Biomass (Figure 2) at MVSR Engineering College, Hyderabad. It is a new approach to processing dry leaves and carpentry wood waste co-gasification.

A screw conveyor feeds SDMSW and biomass pellets into the gasifier. The gasification process will begin by igniting the pallets in a rich oxygen environment in a Single Thorat Downdraft Gasifier. A blower provides air to enhance the gasification process. Pallets are thermochemically degraded in the gasifier in four stages. In the first stage, pallets are dried, and the pyrolysis process begins in the second stage. During the pyrolysis process, the generated producer gas is cleaned and cooled before being collected in latex gas sample balloons at the outlet vent. The pallet combustion takes place in the next stage, which is at the third level, and their mass is reduced. Tar and ash will be extracted as byproducts in the final stage. The calorific value of the collected producer gas is measured and tested for quality checks. At the outlet, a flow meter is installed to measure the flow rate of producer gas.

Design and fabrication of multi-fuel downdraft gasifier

A downdraft gasifier with multi-fuel processing was designed to process 30 kg/h of Biomass/SDMSW. The schematic layout of the proposed biomass gasifier is shown in Figure 3. The design specifications of modified gasifiers are listed in Table 1.

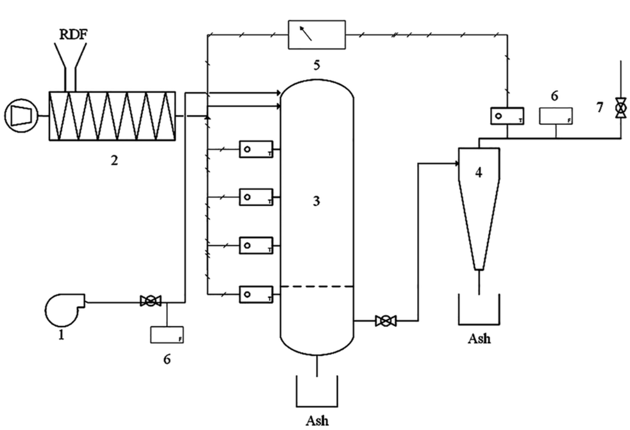

Figure 2: The schematic of the experimental setup. Various parts of the experimental setup are: (1) blower, (2) screw conveyor, (3) Single Thorat Downdraft Gasifier, (4) cyclone, (5) temperature sensors, (6) flowmeter, (7) sampling point.

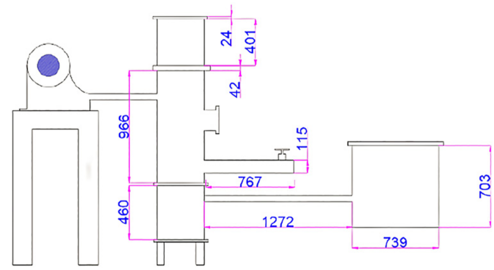

Figure 3: Schematic layout of the experimental setup.

Table 1: Design specifications of gasifier.

Parameter	Dimension
Length (L)	1827 mm
Thickness of gasifier (t)	3 mm
Flang dia (D_0)	342 mm
Shell external dia (D_1)	275.4 mm
Shell internal dia (D_2)	269.4 mm
Volume of gasifier (v)	0.154 m^3

The flow rate of the producer gas is calculated from the flow rate Equation (1).

$$Q_g = AV\ m^3/s \tag{1}$$

where, Q_g = Flow rate of gas, m^3/s.

A = Cross sectional area of outlet pipe, m^2.

V = velocity of producer gas, m/s.

Mass of biomass/SDMSW pallet, M = Density of pallet × Volume of pallet, kg.

Mass of the gas = Density of the gas × volume of the gas, kg.

The Efficiency of the gasifier can be calculated from Equation (2).

$$\eta = \frac{\text{mass of gas} \times \text{calorific value of gas}}{\text{mass of pallet} \times \text{calorific value of pallet}} \tag{2}$$

Preparation and characterization of biomass/SDMSW pallets

The preparation of biomass/SDMSW pallets is crucially important in producing high-quality producer gas. Carpentry waste wood is collected for biomass, and pallets are prepared. Dry organic MSW is collected from various locations on the college campus. Desired raw materials are segregated from collected MSW and sun-dried for 3–4 h. As shown in Table 5, biomass and SDMSW pallets are prepared as per ASTM D5231, with 11 different compositions. These pallets are fed into the gasifier as shown in Figure 4.

Characterization of biomass/SDMSW pallets

Ultimate analysis was performed to determine the useful combustible compositions of the pallets. For accurate results, samples are collected from pallets, three trails are made, and an average is taken (Table 2).

Figure 4: Combination of SDMSW and wood.

Table 2: Ultimate analysis.

(wt%)	Trail-1	Trail-2	Trail-3	Average
Carbon	35.06	36.01	35.23	35.43
Nitrogen	0.28	0.29	0.28	0.28
Hydrogen	5.44	5.46	5.45	5.45
Sulfur	0.11	0.12	0.11	0.11

Proximate analysis was performed to determine the amount of unusable byproducts, and the results are tabulated in Table 3. A calorimeter is used to determine the calorific values of the designed pallets (Table 4).

Table 3: Proximate analysis.

(wt%)	Trail-1	Trail-2	Trail-3	Average
Moisture	7.80	7.81	7.82	7.81
Volatile	57.59	57.60	57.60	57.60
Fixed carbon	13.90	13.91	13.91	13.91
Ash	20.50	20.59	20.60	20.56

Table 4: Calorific value of SDMSW.

(kcal/kg)		Trail-1	Trail-2	Trail-3	Average
Calorific value	SDMSW	3300	3300.5	3300.1	3300.5
	Biomass	3501	3494	3504	3499.66

Figure 5: Photograph of the experimental setup.

Experimentation

Prepared pallets of different compositions are fed into the gasifier individually and allowed for the gasification process. The photograph of the experimental setup is shown in Figure 5.

Producer gas is collected at stage three, it is cooled and cleaned before testing. The quantity of producer gas generated for each sample composition is measured by using a venturi meter. The velocity of the producer gas is measured by using an anemometer. The efficiency of the gasifier is calculated from Equation (2) and the values are tabulated in Table 5.

Results and discussions

The effect of blending ratios on producer gas generation is investigated. The amount of producer gas produced during the pyrolysis process is greatly influenced by the blending ratio. The volume and mass of producer gas decrease as the SDMSW ratio rises. The blending ratio has a significant impact on the quality of producer gas, i.e. the calorific value of producer gas. Figures 6 and 7 depict the variation in volume and quality of producer gas generated with blending ratio. These findings support trends reported by other authors (Bhoi et al. 2018; Cao, Fu, and Mofrad 2019); however, these tendencies are not always consistent; it is dependent on the quality of SDMSW and the calorific value of biomass and SDMSW. Figure 8 shows the variation of calorific value of producer gas with blending ratios. With increase in amount of SDMSW from 0% to 100%, the volume of producer gas decreases from 7.48 m^3 to 2.70 m^3, and the mass of the gas decreases from 6.88 kg to 2.48 kg.

Table 5: Experimental results for combinations of SDMSW and biomass.

S. no.	Blending ratio biomass/SDMSW (w/w%)	Calorific value of pallets, kcal/kg	Velocity, m/s	Flow rate, 10^{-3} m^3/s	Time, s	Volume of gas, m^3	Mass of gas, kg	Calorific value of producer gas, kcal/kg	Efficiency %
1	100% biomass	3499.67	2.05	4.15	1800	7.48	6.88	3498.65	68.78
2	90:10	3479.72	2.22	4.51	1620	7.30	6.72	3478.68	67.18
3	80:20	3459.77	2.40	4.86	1400	6.81	6.26	3461.43	62.63
4	70:30	3439.83	2.57	5.22	1230	6.42	5.90	3442.16	59.04
5	60:40	3419.88	2.80	5.67	1040	5.90	5.43	3418.62	54.28
6	50:50	3399.93	3.00	6.08	860	5.23	4.81	3399.23	48.09
7	40:60	3379.99	3.10	6.28	720	4.52	4.16	3379.99	41.60
8	30:70	3360.04	3.30	6.69	640	4.28	3.94	3357.48	39.37
9	20:80	3340.09	3.40	6.89	530	3.65	3.36	3339.10	33.59
10	10:90	3320.15	3.50	7.09	445	3.16	2.90	3323.58	29.03
11	100% SDMSW	3300.20	3.70	7.50	360	2.70	2.48	3304.19	24.83

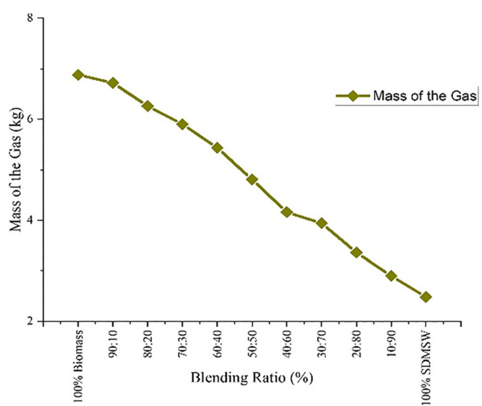

Figure 6: Volume of producer gas versus blending ratio.

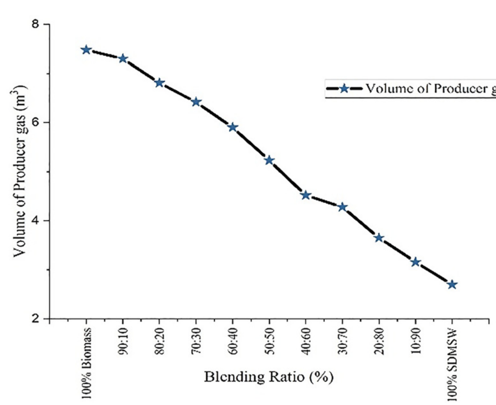

Figure 7: Mass of producer gas versus blending ratio.

Due to the low density of SDMSW, the time required to complete the gasification process for 100% biomass blending ratio is around 1800 s, whereas for 100% SDMSW the time required to complete the gasification process is

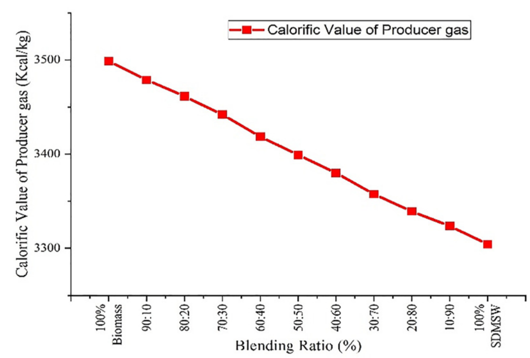

Figure 8: Calorific value of producer gas versus blending ratio.

360 s. The amount of combustible components in biomass is greater than in SDMSW, which plays an important role in the production of producer gas during the pyrolysis process.

The mass of the producer gas decreases as the percentage of SDMSW increases, owing to lower density when compared to biomass. Thermochemical conversion of pallets occurs during the pyrolysis process, which is dependent on the density and combustible parameters of the feedstock. As a result, as the SDMSW percentage increases, the volume and mass of the producer gas, as well as the calorific value, decrease. The velocity and flow rate of the producer gas, on the other hand, increases as the percentage of SDMSW increases. This is due to the low density of SDMSW in comparison to biomass. Because of the lower density, the pyrolysis process accelerates and takes less time to complete the gasification of solid mass, increasing the flow rate and velocity of the producer gas.

The variation of calorific value of producer gas with blending ratios is shown in Figure 7. With increase in the percentage of SDMSW the calorific value decreases significantly. The amount of combustible components decreases as the percentage of biomass decreases, as does the calorific value. The calorific value of feedstock for 100% biomass is 3499.67 kcal/kg, and when the blending ratio is changed to 100% SDMSW, the calorific value of feedstock is 3300.20 kcal/kg. The calorific value of 100% biomass generated producer gas is 3498.65 kcal/kg and 100% SDMSW generated producer gas is 3304.19 kcal/kg. The gasifier's effective efficiency is calculated using Equation (2), and it is found to be significantly affected by the blending ratio. Figure 8 shows how the efficiency of the gasifier decreases as the percentage of SDMSW increases. Up to 50% blending ratio, the efficiency of the gasifier reduced from 68.78% to 48.09% i.e. 20% reduction, whereas the portion of the SDMSW increases more than 50% the efficiency drops from 48.09% to 24.83% i.e. 24%, shown in Figure 9. For 100% SDMSW the gasification time is less compared to 100% biomass which has shown in Figure 10. From the results, it can be presumed that SDMSW can be processed in a gasification plant. The developed multi-purpose downdraft gasifier can process SDMSW into producer gas, which may be used in domestic and industrial applications. The results also indicate that adding 50% SDMSW to Biomass results in relatively good efficiency to process SDMSW (Bhoi et al. 2018; Cao, Fu, and Mofrad 2019).

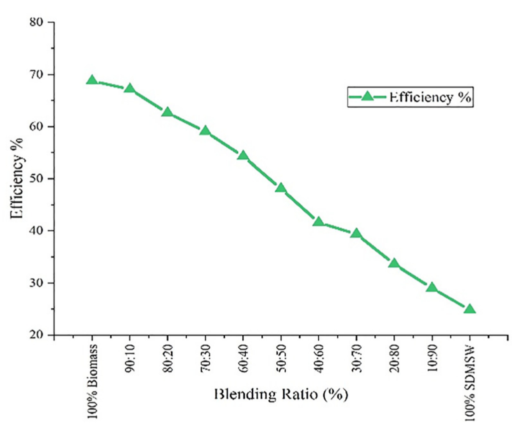

Figure 9: Efficiency of the gasifier versus blending ratio.

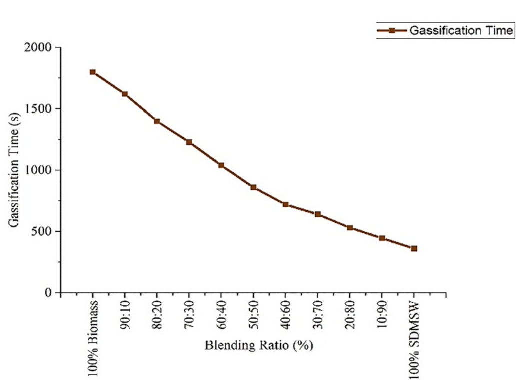

Figure 10: Gassification time versus blending ratio.

Conclusions

The redesigned gasification plant is used to process SDMSW and generate producer gas in this study. The efficiency of the gasifier varies from 68.78% to 24.83% depending on the percentage blend of SDMSW and biomass used. Because SDMSW has a lower density than biomass, the gasification time is lowered from 1800 s to 360 s. As the SDMSW ratio rises, the volume of producer gas drops. The 50% blending ratio of SDMSW and biomass provided a fairly good efficiency of 48.09%. The amount of SDMSW and biomass in the gasifier has a big influence on its efficiency. The blending ratio has little effect on the variation in calorific values of producer gas. As a result, the producer gas quality is unaffected by the blending ratio. The proposed gasification plant can be used to process SDMSW with biomass to generate producer gas with reasonable efficiency.

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