Design and Performance Analysis of a Producer Gas Cleaning System for a Downdraft Gasifier Processing Segregated Dry Municipal Solid Waste and Biomass

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Abstract. This study presents the design and performance analysis of a producer gas cleaning system for a downdraft gasifier used to process Segregated Dry Municipal Solid Waste (SDMSW) and biomass. The cleaning system is critical to remove impurities such as particulate matter, tars, and other pollutants from the producer gas, which can negatively impact the efficiency and longevity of the gasifier, as well as damage downstream equipment. The cleaning system was designed to include several stages, such as mechanical filtration, adsorption, and catalytic oxidation. The performance of the cleaning system was evaluated using a combination of SDMSW and biomass as feedstock, and the results showed that the cleaning system was able to effectively remove impurities from the producer gas, resulting in an improvement in the efficiency and longevity of the downdraft gasifier. This study provides valuable insights for the optimization of downdraft gasifier systems using SDMSW and biomass as feedstock, and highlights the importance of an effective producer gas cleaning system in the overall performance and cost-effectiveness of this technology. The gas cleaning system was utilized to test the producer gas by gas chromatography. Results from the analysis show a mass flow of 783 kg/hr, a lower heating value of 4.58 MJ/Nm^3, a specific heat of 1.11 kJ/kg K, and a cold gas efficiency of 79.7%. Additionally, the system was able to reduce tar and ash by 50 kg/hr and 5.5 kg/hr respectively.

Keywords: Downdraft gasifier · producer gas cleaning · impurities · mechanical filtration · Syngas

1 Introduction:

In a downdraft gasifier, fuel (such as biomass, coal, or municipal solid waste) is fed into the top of the gasifier, and the air is introduced through the bottom [1]. The fuel and air are mixed and then undergo a series of chemical reactions that result in the production of

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B. Raj et al. (Eds.): ICETE 2023, AER 223, pp. 970–984, 2023.
https://doi.org/10.2991/978-94-6463-252-1_98

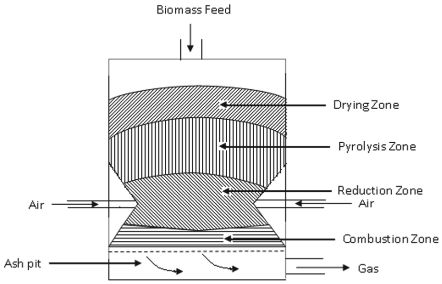

Fig. 1. Downdraft gasifier with various zones

producer gas. The producer gas is composed mainly of carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2), as well as small amounts of methane (CH_4) and other gases [2]. The downdraft gasifier operates at relatively low temperatures (around 600–800 °C) and pressures (around 1–10 atmospheres). The fuel is first heated and dried, then pyrolysis takes place where the organic matter is broken down by heat into volatile gases, fixed carbon, and ash [3, 4]. This volatile gas then moves into the reduction zone, where the volatile gas is mixed with the air stream as shown in Fig. 1, and due to the high oxygen concentration, the volatile gas is reacted with the air, to form CO and H_2 [5]. The producer gas is then cooled and cleaned before it is sent to the end-use application.

A producer gas cleaning system is an essential component of a downdraft gasification process used to produce clean and high-quality fuel gas. In the case of processing segregated dry municipal solid waste (SDMSW) and biomass blends in a downdraft gasifier, the produced fuel gas is expected to be contaminated with particulate matter, tars, and other pollutants that can significantly reduce the efficiency of downstream equipment and negatively impact the environment [6, 7]. Therefore, the design and performance of the producer gas cleaning system are crucial to ensure reliable and efficient gasification [8, 9]. The design of the producer gas cleaning system typically involves the integration of various gas cleaning stages that are selected based on the characteristics of the raw gas and the desired gas quality [10]. These stages may include cyclones, scrubbers, condensers, filters, and other gas-cleaning devices [11]. The selection of gas cleaning stages, their sizing, and operating conditions are critical to ensure the effective removal of pollutants while minimizing energy consumption and operating costs [12, 13]. The performance of the producer gas cleaning system is evaluated based on the efficiency of pollutant removal, the quality of the cleaned gas, and the overall energy balance of the gasification process [14, 15].

The focus of this study was to create a combined downdraft gasifier and producer gas cleaning system capable of handling both SDMSW and biomass. By incorporating mechanical filtration, adsorption, and catalytic oxidation, impurities were removed from the producer gas. The cleaning system's effectiveness was tested using a blend of SDMSW and biomass as feedstock and was found to enhance the gasifier's efficiency and longevity. This research provides valuable insights into optimizing downdraft gasifier systems that use SDMSW and biomass, emphasizing the importance of an effective producer gas cleaning system in achieving better performance and cost-effectiveness of this technology.

2 Materials and Methods

An experimental setup for co-gasification of SDMSW and biomass was developed at MVSR Engineering College, Hyderabad as shown in Fig. 2. Using a unique approach to process carpentry wood waste and dry leaves. The downdraft gasifier's cleaning system involves a cyclone separator that eliminates particulate matter from the producer gas. The design of the cyclone separator is a crucial factor that necessitates thorough consideration of various factors to guarantee its efficiency and effectiveness.

Various components of the experimental arrangement are: (1) a support stand for the air blower, (2) the air blower, (3) the airflow regulator, (4) the gasifier, (5) feedstock, (6) the fire door, (7) gas blow-off pipe, (8) gas outlet pipe, (9) ash collection unit, (10) cyclone separator, (11) wet scrubber, (12) gas flow meter, (13) manometer, (14) gas burner, (15) tar collection.

2.1 Preparation and Characterization of Biomass/SDMSW Pallets

The production of high-quality producer gas in a gasification system is highly dependent on the proper preparation of biomass/SDMSW pallets. This process involves the collection of carpentry waste wood and its conversion into pallets that can be used as biomass fuel. Dry organic Municipal Solid Waste (SDMSW) is also collected and sun-dried for several hours before being combined with the biomass as shown in Fig. 3. To ensure consistency and accuracy in the experimentation process, eleven different compositions of biomass and SDMSW pallets are created according to ASTM D5231 standards, listed in Table 6. These compositions are fed into the gasifier for testing. The moisture content of the feedstock is carefully controlled to ensure optimal gasification results.

The moisture content present in the feedstock can negatively impact the efficiency of the gasification process. The size and shape of the biomass/SDMSW pellets also play a critical role in the gasification process. Pallets that are too large can cause blockages in the gasifier, while those that are too small may not burn completely. The ash content of the feedstock should also be minimized to prevent slagging and fouling of the gasifier. The proper preparation of biomass/SDMSW pallets is a critical step in achieving high-quality producer gas. By controlling factors such as moisture content, size and shape

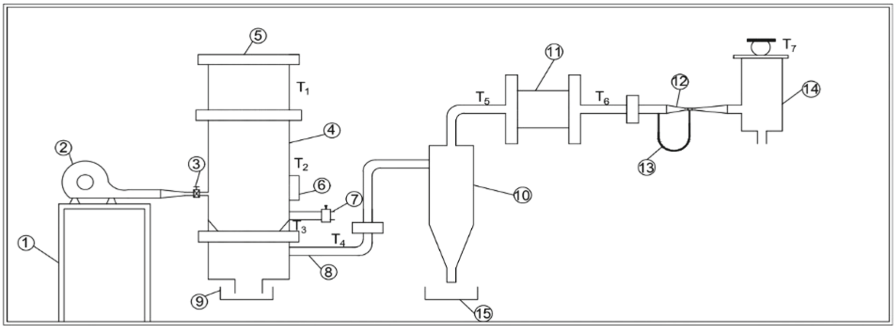

Fig. 2. The schematic layout of the experimental setup with cyclone separator

Fig. 3. Combination of SDMSW and wood

of the pellets, and ash content, the gasification process can be optimized to produce the maximum amount of high-quality gas. Therefore, it is important to pay close attention to the preparation of the feedstock to ensure the success of the gasification process.

2.2 Characterization of Biomass/SDMSW Pallets

To assess the suitability of the biomass/SDMSW pallets for generating high-quality producer gas, their composition was analysed. Samples were taken from the prepared pallets, and to ensure precision, three trials were conducted. The ultimate analysis was used to determine the composition of the samples, and the mean outcomes are displayed in Table 1. The proximate analysis was used to determine the quantity of byproducts that cannot be burned, with the findings presented in Table 2. The calorific values of the pallets were then calculated using a calorimeter, and the outcomes are recorded in Table 3.

Table 1. 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

Table 2. 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 3. 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

2.3 Design and Fabrication of Multi-Fuel Downdraft Gasifier

A schematic layout of a multi-fuel processing downdraft gasifier was illustrated in Fig. 2, designed to handle a processing rate of 30 kg/hour of both biomass and SDMSW [14]. Table 4 outlines the specifications of the modified gasifier.

The following factors should be taken into consideration when designing a gasifier.

2.3.1 Characteristics of the Feedstock

The design of a gasifier is significantly influenced by the fuel's characteristics, including energy content, moisture content, size and shape of feedstock, ash content, density, and others. For instance, downdraft gasifiers are appropriate for moisture content of up to 20% [11], and higher energy content and fuel density require a smaller reactor size. Throated gasifiers may experience bridging issues when the feedstock size is large, such as briquettes, and pellets are usually suggested for such gasifiers. Conversely, throatless gasifiers can handle a variety of feedstocks with different shapes and sizes.

2.3.2 Equivalence Ratio (ER)

The equivalence ratio refers to the ratio of actual air quantity to the stoichiometric air quantity, determining whether the process undergoes pyrolysis, gasification, or combustion. Moreover, it impacts the syngas composition, with higher values leading to lower H_2 and CO concentrations and higher tar production [11]. ER generally falls within the 0.2–0.4 range for most fuels.

2.3.3 Operating Temperature

Efficiency rises with temperature, but so do energy losses. Therefore, effective insulation of the reactor chamber is necessary to minimize these losses.

2.3.4 Residence Time

The gasification process is affected by residence time, which is the time spent by the fuel in the gasifier. Longer residence times tend to decrease the formation of tar compounds while increasing carbon conversion efficiency and gas yield.

2.3.5 Type of Reactor

The selection of the gasification reactor depends on the application, such as process heat or power generation. Crossdraft and updraft gasifiers are suitable for longer operating times and have a better response to fluctuating loads compared to downdraft gasifiers [14].

2.3.6 Superficial Velocity

The superficial velocity is the ratio of the syngas production rate to the cross-sectional area of the gasifier. It impacts gas production, energy content, power output, and tar production rates. The feedstock packing factor affects the superficial velocity and creates airflow resistance. A slow pyrolysis process occurs at low superficial velocity, resulting in high yields of char and unburned tars [14].

2.3.7 The Cross-Sectional Area of the Reactor

The size of the gasifier's cross-sectional area is determined by the rate of fuel consumption and the specific gasification rate. As the fuel consumption rate (FCR) increases, the area of the reactor and grate also increases, while the area decreases as the specific gasification rate (SGR) increases.

2.3.8 Height of Reactor

The reactor height influences the gas production capacity and operation time, as well as the resistance to airflow. The combustion zone moves at a speed of 1 to 2 cm/min, and as the reactor column height increases, a stronger draught system is required [14].

2.3.9 Height of Fuel Bed

The bed height is equal to the reactor height and increasing it leads to higher airflow resistance. A thicker bed decreases the bed's downward movement, resulting in increased residence time, decreased tar formation, and increased gas yield.

2.3.10 Air-Flow Requirement

The airflow in a gasifier is influenced by the type of draught system employed. With a natural draught system, the airflow is governed by the superficial air velocity and the porosity factor of the bed.

2.3.11 Grate Area

The grate area is typically equal to the cross-sectional area of the reactor, and the specific gasification rate is determined by the grate area.

2.3.12 Specific Gasification Rate (SGR)

Downdraft gasifier design is based on a specific gasification rate or hearth load (Bh), the amount of producer gas per unit cross-sectional area of the throat, normally expressed as $Nm^3/h\ cm^2$. Bh max value in the gasifier is 0.9 for continuous operation, with a minimum range of 0.3–0.35 [14, 15].

The relationship obtained from the definition of the hearth load (Bh) is [14]:

$$Bh = \frac{Vg}{A_t} \text{Nm}^3/\text{hm}^2 \tag{1}$$

where, Vg is the volume of the producer gas (m^3), and A_t is the cross-sectional area of the throat (m^2)

An equation can be used to determine the diameter of the gasifier (D), with FCR representing the fuel consumption rate, kg/hr [19]:

$$D = \left(\frac{1.27 \times FCR}{SGR}\right)^{0.5} \text{m} \tag{2}$$

The volume of the gasifier can be determined by an equation:

$$V = A_g \times V_g \text{m}^3 \tag{3}$$

An equation can be used to determine the height of the gasifier (H):

$$H = \frac{SGR.t}{\rho_f} \text{m}^3 \tag{4}$$

Here, SGR is the specific gasification rate (kg/h m^2), t is the batch operation time (h), and ρf is the density of feedstock, kg/m^3.

To meet the air requirement, two nozzles or tuyers were utilized, and the diameter of each tuyer (d) was determined using the formula [15]:

$$d = \left(\frac{1.27 \times AFR}{v \times Z}\right)^{0.5} \text{m} \tag{5}$$

where AFR is the air-fuel ratio, v is the velocity of air inlet in the tuyer (m/s), and Z is the number of tuyer.

The gasifier was fabricated and assembled as per layout by developing 2-D and 3-D drawings as shown in Fig. 4.

Table 4. Design specifications of the gasifier

Parameter	**Dimension**
Length (L)	2.478 m
Thickness of gasifier (t)	0.003 m
Shell external dia (D_o)	0.274 m
Shell internal dia (D_i)	0.268 m
Volume of gassifier (v)	0.139 m^3
diameter of tuyer (d)	0.0127 m
No. of tuyers (Z)	2

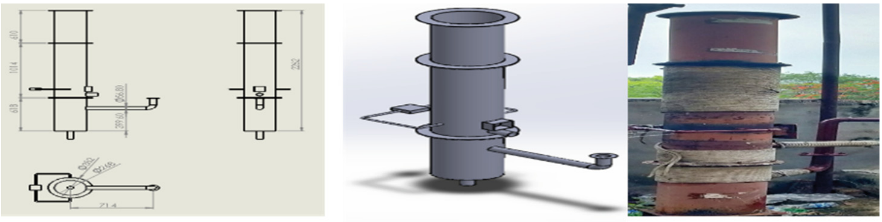

Fig. 4. Development of downdraft gasifier from 2-D and 3-D drawing

2.4 Design Considerations of the Cyclone Separator

A conventional cyclone separator is designed, fabricated, and installed in the gasifier setup to clean the particulate matter and tar present in the producer gas for further applications. The following factors should be taken into consideration when designing a clone separator.

2.4.1 The Number of Effective Turns (N_e)

The effective number of turns in a cyclone refers to the number of rotations the gas undergoes as it passes through the outer vortex of the cyclone.

$$N_e = \frac{1}{H}\left(L_b + \frac{L_c}{2}\right) \tag{6}$$

where

N = number of turns inside the device (no units)
H = height of inlet duct, m
L_b = length of cyclone body, m
L_c = length (vertical) of cyclone cone, m

2.4.2 Cut Point Diameter (d_{pc})

Cut point diameter refers to the particle size at which the separation efficiency of a particle separator, such as a cyclone, is 50%. Particles with a size smaller than the cut point diameter will be collected less efficiently, while particles with a larger size will be collected more efficiently by the separator.

$$d_{pc} = \left(\frac{9\mu W}{2\pi N_e V_i\left(\rho_p - \rho_g\right)}\right)^{0.5} \tag{7}$$

where

d_{pc} = diameter of the smallest particle that will be collected by the cyclone
μ = gas viscosity, kg/m. s
W = width of the inlet duct, m
N_e = number of turns

Table 5. Design specifications of the cyclone separator [24]

Parameters	**Notation**	**Proportions**	**Dimension (m)**
Diameter of cyclone Body (Barrel)	D	D	0.1524
Length of the body	L_b	2D	0.3048
Length of the cone	L_c	2D	0.3048
Height of the Inlet	H	0.5D	0.0762
Width of the Inlet	W	0.25D	0.0381
Length of vertex finder	S	0.625D	0.0952
Diameter of the gas exit	D_e	0.5D	0.0762
Diameter of dust outlet	D_d	0.25D	0.0381
Total Length of cyclone	$L_b + L_c$	4D	0.6096

V_i = inlet gas velocity, m/s
ρ_p = particle density, kg/m^3
p_g = Density of gas, kg/m^3

The efficiency of the cyclone is the primary concern in gas cleaning. The mass balance of solid particles in the cyclone can be analyzed by considering the mass flow rate of the feed (M_f), the mass flow rate of particles collected (M_c), and the mass flow rate of escaped particles (M_e).

$$M_f = M_C + M_e \tag{8}$$

The separation efficiency can be calculated as the ratio of mass flow rate of particles collected to the mass flow rate of particles fed into the cyclone.

$$\eta_c = \frac{M_c}{M_f} = \frac{M_c}{M_c + M_e} = 1 - \frac{M_c}{M_e} \tag{9}$$

2D2D cyclone separator [14] is designed, fabricated, and employed in a downdraft gasifier for effective dust and tar cleaning from the producer gas as shown in Fig. 5. Also, a wet scrubber is fitted after the cyclone separator to remove tar presented in the producer gas [11] (Table 5).

2.5 Performance of the Gasifier

The flow rate of the producer gas is calculated from the flow rate Eq. (10).

$$\text{Gas flow rate, } Q_g = A_g V_g \quad m^3/s \tag{10}$$

The Efficiency of the gasifier can be calculated from Eq. (11).

$$\eta = (m_g \times CV_g)/(m_p \times CV_p) \tag{11}$$

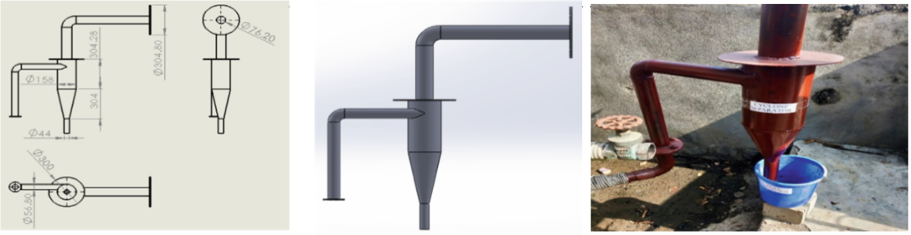

Fig. 5. Development of cyclone separator from 2-D and 3-D drawing

Fig. 6. 3-D model and gasification unit

The multi-purpose gasifier unit is established for co-gasification SDMSW and biomass feedstocks with integrated cleaning system to obtain tar free syngas for effective utilisation of heat and power application as shown in Fig. 6.

3 Experimentation

The experimental setup, as depicted in Fig. 6, underwent the gasification process with the feeding of individually composed pallets into the gasifier. After completion of the gasification process, the producer gas is gathered at the third stage and undergoes cooling and cleaning. The amount of producer gas produced for each sample composition is determined by utilizing a venturi meter, and the speed of the producer gas is measured with the help of an anemometer. The effectiveness of the gasifier is calculated using Eq. (11) and the results are recorded in Table 6.

4 Results and Discussion

Table 6 shows the results of an experiment where the performance of a producer gas cleaning system for a downdraft gasifier processing segregated dry municipal solid waste (SDMSW) and biomass blends were evaluated. The experiment involved varying the blending ratio of biomass and SDMSW from 100% biomass to 100% SDMSW, with 10% increments. The variables measured include the calorific value of pellets, velocity, flow rate, time, the volume of gas, mass of gas, calorific value of producer gas, and efficiency. The velocity and flow rate of gas increase as the proportion of SDMSW in the blend increases. The results show that the calorific value of the pellets decreases as the proportion of SDMSW in the blend increases (Figs. 7 and 8).

The calorific value of the producer gas decreases as the proportion of SDMSW in the blend increases as shown in Fig. 9. The efficiency of the gas cleaning system decreases as the proportion of SDMSW in the blend increases as shown in Fig. 10. According to the experimental data (Table 6), there is a relatively insignificant drop in gasification efficiency (around 5%) for blending ratios up to 60:40 (Biomass: SDMSW). However, there is a more significant drop in gasification efficiency (around 8%) for blending ratios of 50:50 (Biomass: SDMSW) and higher. Therefore, the optimal balance between maximum utilization of SDMSW and acceptable efficiency is achieved at a blending ratio of 60:40 (Biomass: Solid waste). The observations are in line with the studies conducted by Bhoi et al. (2018) and Cao, Fu, and Mofrad (2019), although the trends may vary based on the SDMSW quality and the calorific value of both biomass and SDMSW, leading to inconsistent results.

The volume and mass of gas decrease as the proportion of SDMSW in the blend increases, as shown in Figs. 7 and 8 respectively.

5 Conclusions

Based on the experimental results, the following conclusions can be drawn:

- The calorific value of the producer gas decreased with an increasing percentage of SDMSW in the feedstock blend, with the lowest value obtained for 100% SDMSW.
- The velocity and flow rate of the producer gas increased with an increasing percentage of SDMSW in the feedstock blend, indicating that higher proportions of SDMSW may lead to better gasification performance.
- The volume and mass of the producer gas decreased with an increasing percentage of SDMSW in the feedstock blend, with the lowest values obtained for 100% SDMSW.
- The efficiency of the gasification process decreased with an increasing percentage of SDMSW in the feedstock blend, with the lowest efficiency obtained for 100% SDMSW.
- The blending ratio of 60:40 (Biomass: SDMSW) showed the highest efficiency among the tested ratios, with a calorific value of producer gas of 3418.62 kcal/kg and an efficiency of 54.28%.

Table 6. 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	7.3	6.72	3478.68	67.18
3	80:20	3459.77	2.4	4.86	1400	6.81	6.26	3461.43	62.63
4	70:30	3439.83	2.57	5.22	1230	6.42	5.9	3442.16	59.04
5	60:40	3419.88	2.8	5.67	1040	5.9	5.43	3418.62	54.28
6	50:50	3399.93	3	6.08	860	5.23	4.81	3399.23	48.09
7	40:60	3379.99	3.1	6.28	720	4.52	4.16	3379.99	41.6
8	30:70	3360.04	3.3	6.69	640	4.28	3.94	3357.48	39.37
9	20:80	3340.09	3.4	6.89	530	3.65	3.36	3339.1	33.59
10	10:90	3320.15	3.5	7.09	445	3.16	2.9	3323.58	29.03
11	100% SDMSW	3300.2	3.7	7.5	360	2.7	2.48	3304.19	24.83

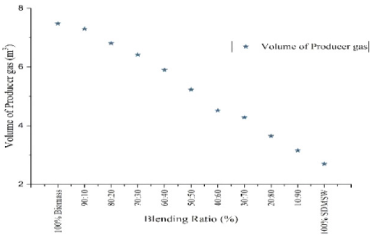

Fig. 7. Blending ratio vs volume of gas

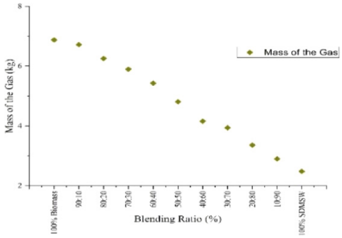

Fig. 8. Blending ratio vs Mass of gas

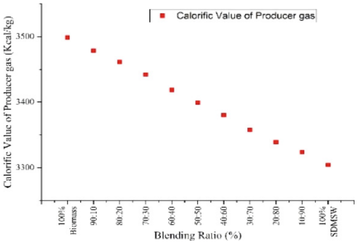

Fig. 9. Blending ratio vs CV of gas

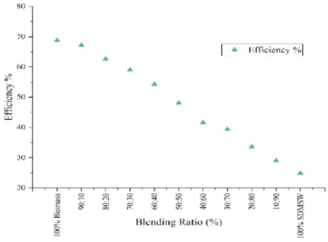

Fig. 10. Blending ratio vs efficiency

Acknowledgments. The support provided by MVSR Engineering College, Hyderabad, is greatly appreciated by the authors.

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