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Research Note

Biomass Characterization and Gasifier Design for Agricultural Residues

K. M. Akkoli*, S. A. Goudadi, M. M. Shivashimpi, S. N. Topannavar

Hirasugar Institute of Technlogy, Nidasoshi, India

P A P E R I N F O

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A B S T R A C T

An analysis of the experimental characterization of the three agricultural residues redgram stalk, soyabean stalk, and chilli stalk (biomass) was carried out and the higher heating values (HHV) were determined using the available correlations from the literature. The selected agricultural residues proximate analysis results show moisture about 4.2 to 7.4%, the volatile matter about 79.3 to 85.8%, fixed carbon about 4 to 8.94%, and ash about 2.5 to 5.5%. The ultimate analysis results present elemental compositions such as carbon about 46 to 49%, hydrogen about 5%, oxygen about 30%, and the nitrogen about 3.1 to 3.7% with very low sulfur content. The HHV of agricultural residues varies from 14MJ kg^{-1} to 19MJ kg^{-1}. The design of the downdraft gasifier to accommodate agricultural residues was carried out taking into account the characteristics of the agricultural residues and the specifications of the internal combustion (IC) engine. The characteristics of the agricultural residues depict that the three agricultural residues are suitable for gasification and can be used in a single gasifier.

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INTRODUCTION

Energy is the most crucial need for the development of rural and industrial life in India. The government strives to continuously supply network power to rural areas, but still not possible due to low load factors, long distribution lines with low load densities and the associated high transmission and distribution losses [1]. In this context, the best way to meet the rural electricity needs is decentralized electricity production [2]. Decentralized electricity production is not expected to cause any environmental pollution and should use locally available resources. Renewable energy sources meet these requirements and provide the required power. The most important and practical sources of renewable energy are biomass, solar and wind [3]. Biomass is a potential carbon-neutral domestic fuel, as a result, there is growing interest in these alternative and renewable energy sources and their raw materials [4], as greenhouse emissions will double over the next 50 years [5]. Biomass provides 12% of total energy in the world and India; it is estimated to be around 32% of total energy consumption [6]. This energy can be used for both domestic and agricultural applications. Biomass can come in different forms: municipal solid waste, forest residues, energy plants and agricultural residues [7]. The potential for producing electricity from biomass in India is estimated at around 20 GW [8, 9]. Agricultural residues have a major contribution in biomass, the Indian Ministry of New and Renewable Energy (MNRE 2009) estimated that approximately 500-550MT of agricultural crop residues are generated each year in India [10]. Conventional methods of using agricultural residues for energy have very low efficiency. Thus, it is necessary to develop an appropriate and reliable energy conversion method to have better conversion efficiency. Different conversion technologies are already practiced and used internationally but for agricultural residues, the system must be designed and optimized for the region. The different energy conversion technologies are physical, thermochemical and biochemical. The thermochemical conversion includes direct combustion, pyrolysis, and gasification [11]. Gasification is the most attractive energy conversion technology in the Indian scenario, as its output gas can be used for both thermal and engine applications [12]. Gasification is the process of partial combustion of biomass under the controlled supply of air or oxygen, the gas produced is called gasifier or if it is cleaned for use in the internal combustion engine called synthesis gas. The gas is rich in H_2 and CO components, the potential for further energy [13]. Gasifiers are generally classified into two types fixed bed and fluidized

*Corresponding Author E-mail: km_akkoli@yahoo.co.in (K. M. Akkoli)

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bed. Fixed bed gasifiers are further classified as downdraft, updraft, and cross draft [14]. The 75% of gasifiers currently using are downdraft [15]. The important criteria for selecting the gasifier for biomass energy are the availability, type, size, and characteristics of biomass. Proximate and ultimate analyses are used to characterize the biomass. The moisture content and other characteristics of individual agricultural residues greatly influence the energy content [16]. Thermogravimetric analysis (TGA) is the rapid and appropriate method for the characterization of biomass [17]. Agricultural residues are suitable for gasification because the gas produced can be used for agricultural and domestic applications [18]. For the medium-sized woody agricultural residues, the downdraft gasifier is suitable and used when the required power is less than 1 MW. Also, the output gas produced had to be relatively clean for use in the internal combustion engines. The downdraft gasifier with air as a gasification agent can be used up to 1.5MW electricity generation [19]. The downdraft gasifier is preferred over all other types of gasifiers because it has the best performance in terms of gas composition (CO, CH_4, and H_2) and quality (lower tar and dust). The agricultural residues are available abundantly in agriculture-based country India and they are suitable for gasification. The suitable gasifier is to be designed for agricultural residues and used for domestic and agricultural applications in the rural areas [20, 21].

MATERIALS AND METHOD

The agricultural residues from redgram stalk, chilli stalk and soyabean stalk from Kharif season were collected from fields in the Belgaum region of Karnataka state. These residues were sun-dried, ground into a powder and sieved to the size of 850µm to have required homogeneity for characterization. The sieved powder is stored in airtight bags for future use. The proximate analysis using the PerkinElmer thermogravimetric analyzer gives the moisture (M), volatile matter (VM), ash (A) and by difference fixed carbon (C) according to ASTM (American Society for Testing Materials) standards. The ultimate analysis using the Thermo Finnigan CHN element analyzer gives the chemical compositions in terms of carbon, hydrogen, nitrogen, sulfur, and oxygen (CHNSO) of agricultural residues. The proximate and ultimate analysis of the prepared agricultural residues was carried out at Sophisticated Analytical Instrument Facility (SAIF), Indian Institute of Technology, Bombay. The HHV of agricultural residues was determined using the correlations from the literature and the values were compared for different correlations of proximate and ultimate analysis.

The downdraft gasifier is suitable for large woody biomass containing highly volatile materials. The downdraft or cocurrent gasifier in which the fuel and gasification agent (air or oxygen) both move in the downward direction in the gasifier. This design produces very low tar and high temperature (400^0C) producer gas. The tar is much less 10-100ppm as compared to other designs. The downdraft gasifier is a proven design for some biomass for small-scale electricity production. The downdraft gasifier can be an Imbert or stratified downdraft gasifier. The Imbert gasifier is closed top, throat gasifier and the air are supplied by the nozzles located in the oxidation zone, at the level of the throat. The stratified gasifier is a throat less open top gasifier in which air is supplied from the top along with fuel and sometimes secondary air is supplied to the oxidation zone. The design of the gasifier suitable for agricultural residues is carried out. The design of the gasifier was carried out using design procedure from the literature, for the application of the engine taking into account the type of raw material available, the properties and the output gas requirement. Later the gasifier can be used for the different applications, but the application of the engine is considered as the basis of the design.

RESULTS AND DISCUSSION

Proximate and ultimate analysis

In the proximate analysis, the samples were analyzed with an air atmosphere. The linear heating ramp for the analysis was of 20^0C min^{-1} to the maximum temperature of 940^0C. The first step in weight loss is from 30^0C to 200^0C temperature where the moisture from the biomass is released. The second step is from 200^0C to about 400^0C to release volatile matter; major weight loss takes place at this point. In the third stage, ash and fixed carbon measured by the difference method. The ultimate analysis was used to determine the percentage mass of carbon, hydrogen, nitrogen, and oxygen. The results of the analysis of agricultural residues are presented in Table 1 and also plotted in Figure 1 (proximate analysis and ultimate analysis).

The proximate analysis shows that volatile matter 79.3% to 85.8%, moisture 4.2 to 7.4% which is within the range required for gasification which is 30% and for the ambient gasifier less than 20% otherwise which will reduce the efficiency of the gasifier and calorific value. The very low ash content 2.5 to 5.5% will reduce clogging and bridging. The fixed carbon content 4 to 8.94% is moderate for gasification. The ultimate analysis gives a detailed chemical composition, carbon 46.9 to 49.2%, hydrogen 5.1 to 5.9%, oxygen around 30% and nitrogen 3.1 to 3.7% with very low sulfur content. The lower nitrogen and sulfur present in agricultural residues are implying a lower level of pollution. Figure 1 shows the different properties of three agricultural residues which are closer values for all residues and implies that three agricultural residues can be used in a single gasifier. The HHV was determined using the different correlations for the proximate and ultimate analysis results from the literature given in Table 2.

The correlations used above reveal that the ultimate analysis results are suitable for determining the HHV of biomass than the proximate analysis. Equations (1), and (2) for the proximate analysis results estimates inexact HHV. Equation (3) is the best correlation based on the proximate analysis. The Equations (4) to (6) give the HHV very close to each other with the results of the ultimate analysis illustrated in Figure 2.

This comparison also shows that the three components carbon, hydrogen and oxygen are important parameters in the correlations with obtaining less error in the estimation of HHV [22].

Design of downdraft gasifier

Consider a converted diesel engine that can run on 100% producer gas with the specifications given in Table 3. The IC engine to use producer gas requires a higher compression ratio of about 1:15 to 1:16 and spark ignition. The design of the downdraft gasifier to operate a 4 stroke, single-cylinder diesel engine with spark-ignition, operating on 100% producer gas is as follows. For designing a gasifier the first step is to find out the required gas supply rate.

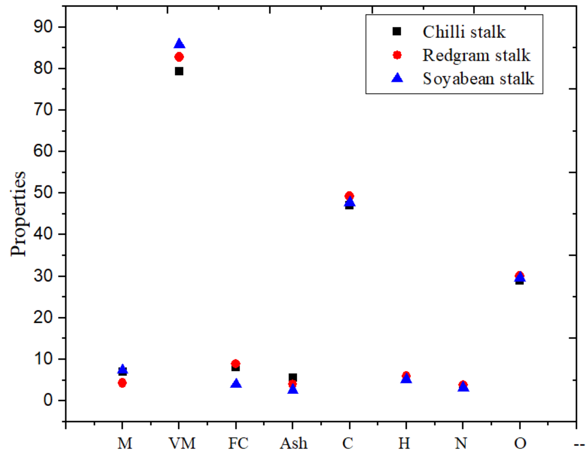

Figure 1. Proximate analysis and ultimate analysis

TABLE 1. Proximate and ultimate analysis [23]

Crop residue/ Properties	Redgram stalk	Soybean stalk	Chilli stalk
Proximate analysis (% w)			
Moisture	4.20	7.46	7.013
Volatile matter	82.8	85.83	79.37
Fixed carbon (by difference)	8.94	4.03	8.01
Ash	4.01	2.67	5.5
Ultimate analysis (% mass)			
C	49.23	47.83	46.97
H	5.949	5.12	5.58
N	3.789	3.13	3.2
O	30.03	29.63	28.93

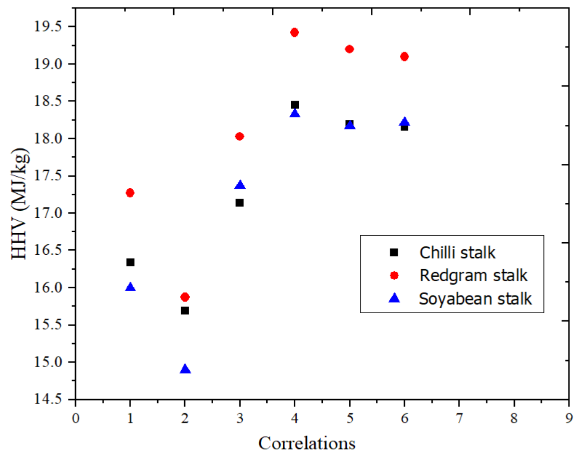

Figure 2. Variations of HHV for correlations

TABLE 2. HHV prediction using the correlations

Correlation	HHV (MJ kg^{-1})			Reference/Equation
	Redgram stalk	Soyabean stalk	Chilli stalk	
Based on proximate analysis HHV = 354.3FC + 170.08VM	17.27	16.00	16.34	[24] (1)
HHV = 0.196FC + 14.119	15.87	14.90	15.69	[25] (2)
HHV = 0.1905VM+ 0.2521FC	18.03	17.37	17.14	[26] (3)
Based on ultimate analysis HHV = 0.2949C+ 0.825H	19.42	18.33	18.45	[26] (4)
HHV = – 1.3675 + 0.3137C+ 0.7009H + 0.0318O	19.20	18.17	18.20	[27] (5)
HHV = – 0.763+ 0.301C+ 0.525H + 0.064O	19.10	18.22	18.16	[22] (6)

$$Vs = \frac{1}{2} RPM \times n \frac{\pi}{4} D^2 L \quad m^3h^{-1} \qquad (7)$$

$$Vg = \eta v \times \frac{Vs}{2.1} \quad m^3h^{-1} \qquad (8)$$

For maximum hearth load GH 0.9 m^3h^{-1}

$$At = \frac{Vg}{GH\ max}\ cm \qquad (9)$$

$$dt = \sqrt{\frac{4 \times At}{\pi}}\ cm \qquad (10)$$

Height h of the nozzle plane above the throat cross-section can be determined using.

$$\frac{h}{dt} = 1.2 \qquad (11)$$

The diameter of the firebox df and the diameter of the nozzle top ring dn can be determined using Figure 3 [28] by taking the ratio $\frac{df}{dt} = \mathbf{3.2}$ and $\frac{dn}{dt} = \mathbf{2.3}$, respectively. Assuming that 5 nozzles are used for supplying the required amount of air for gasification and noting the ratio of $\mathbf{100}\left(\frac{Am}{At}\right)$ as 6.3 for calculated throat diameter from Equation (12), the nozzle diameter will be calculated as follows.

TABLE 3. Engine specifications

Specification	Notation	Value
Bore	D	80 mm
Stroke	L	110 mm
No. of cylinders	n	1
Engine rpm	N	1500
Volumetric efficiency	Ŋv	80%

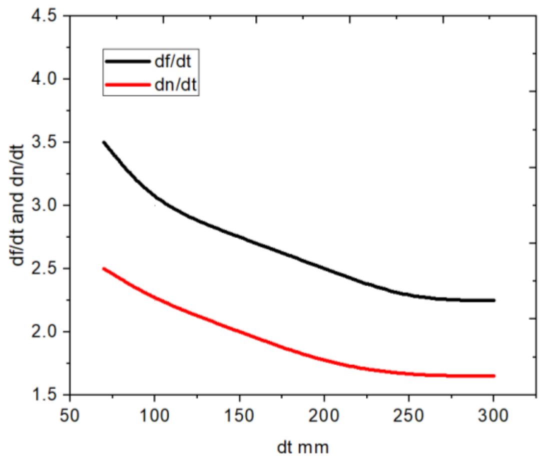

Figure 3. Nozzle ring diameter as a function of throat diameter [28]

$$100\left(\frac{Am}{At}\right) = 6.3, \frac{dm}{dt} = 0.25 \qquad (12)$$

The dimensions of the downdraft gasifier reactor area were obtained from the design procedure and are presented in Table 4.

According to the dimensions of the rector area obtained from the handbook of biomass downdraft gasifier engine systems [29] the sketch of the gasifier, the reactor area is shown in Figure 4. The other dimensions must be selected appropriately for the variable supply flow and output gas requirement of the gasifier.

TABLE 4. Designed dimensions

Sl No.	Parameter	Value	Dimensions from data handbook [29]
1	Swept volume=Vs	29.76 m^3h^{-1}	-
2	Gas flow rate=Vg	11.34 m3h^{-1}	4-30 m^3h^{-1}
3	Throat c/s area=At	12.6 cm^2	28.27 cm^2
4	Throat diameter=dt	40 mm	60 mm
5	Height of nozzle above throat c/s =h	48 mm	80 mm
6	Diameter of firebox=df	128.2 mm	268 mm
7	Diameter of nozzle top ring =dn	92 mm	150 mm
8	Diameter of air nozzle=dm	2.52 mm	7.5 mm
9	Maximum biomass consumption	10	14 kgh^{-1}

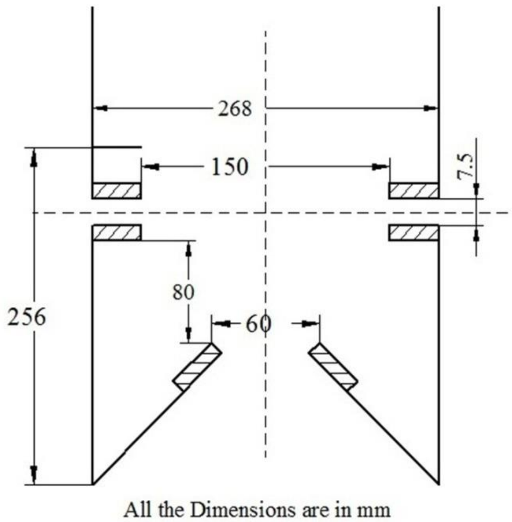

Figure 4. Reactor zone design sketch

CONCLUSIONS

The proximate analysis gives moisture 4.2 to 7.4%, volatile matter 79.3 to 85.8%, fixed carbon 4 to 8.94% and ash 2.5 to 5.5%. The ultimate analysis gives the carbon 46.9 to 49.2%, hydrogen about 5.1 to 5.9%, nitrogen 3.1 to 3.7% and oxygen nearly 30% with very low sulfur content. The HHV was determined for agricultural residues based on proximate analysis ranging from 14 to 18MJ kg^{-1} and based on an ultimate analysis ranging from 18 to 19MJ kg^{-1}. The correlations used are compared by the results obtained and an ultimate analysis correlation gives the least error in determining HHV of the biomass. The study shows that the three agricultural residues redgram stalk, soyabean stalk and chilli stalk have the appropriate compositions for gasification and can be used in a single gasifier. The gasifier is designed for the gas production rate from 4 to 30 m^3h^{-1} necessary for the operation of the internal combustion engine by consuming biomass of 14 kg h^{-1} maximum.

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Persian Abstract

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چکیده

تجزیه و تحلیل خصوصیات تجربی از سه باقیمانده کشاورزی ساقه قرمز، ساقه سویا، و ساقه چیلی (زیست توده) انجام شد و مقادیر حرارت بالا (HHV) با استفاده از همبستگی موجود در مقالات تعیین شد. باقیمانده‌های کشاورزی نتایج تجزیه و تحلیل تقریبی رطوبت حدود ۴/۲ تا ۷/۴ درصد، مواد فرار حدود ۷۹/۳ تا ۸۵/۸ درصد، کربن ثابت حدود ۴ تا ۸/۹۴ درصد، و خاکستر حدود ۲/۵ تا ۵/۵ درصد، را نشان می‌دهد. نتایج نهایی تجزیه و تحلیل ترکیبات اساسی مانند کربن حدود ۴۶ تا ۴۹ درصد، هیدروژن حدود ۵ درصد، اکسیژن حدود ۳۰ درصد و نیتروژن حدود ۳/۱ تا ۳/۷ درصد با محتوای گوگرد بسیار کم را نشان می‌دهد. HHV باقیمانده‌های کشاورزی از ۱۴ MJ kg^{-1} تا ۱۹ MJ kg^{-1} متفاوت است. طراحی سیستم گاز رسان پایین‌دستی برای جای دادن بقایای کشاورزی با در نظر گرفتن ویژگی‌های باقیمانده‌های کشاورزی و مشخصات موتور احتراق داخلی (IC) انجام شد. خصوصیات بقایای کشاورزی نشان می‌دهد که سه بقایای کشاورزی برای گازدهی مناسب هستند و می‌توانند در یک دستگاه بخور ساز استفاده شوند.