



Experimental studies on gasification of corn cobs in a fixed bed system

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ABSTRACT

A closed top, 6 kW_e, fixed, perforated bed, downdraft reactor had been designed, fabricated and was used to experiment the gasification of corn cob under forced air circulation mode. Producer gas composition, HHV of producer gas, specific gas generation, cold gas efficiency had been investigated by varying the equivalence ratio from 0.1 – 0.45. Studies revealed that corn cob could be gasified successfully. An equivalence ratio of 0.3 was observed to be optimal for it yielded maximum cold gas efficiency (62.83%), highest HHV of producer gas (4.58 MJm⁻³) associated with an optimal specific gas generation rate (2.12 m³ of gas/kg of corn cob). The CO₂/CO of the producer gas at an ER of 0.3 was observed to be 0.907 and is the lowest among all ERs. Tar and particulates content has been experimentally determined as 0.81 gm⁻³ and 0.355 gm⁻³ respectively. Fuel bridging was inferred to be minimal as O₂ content in the producer gas was zilch. Hence corn cob has been identified as a viable alternate fuel for gasification that could be used for decentralized power generation.

Keywords: Biomass, Gasification, Corn Cobs, Tar, Particulate matter, CO₂/CO

INTRODUCTION

It is projected that the global energy demand would be about 37% higher in 2035 than that was in 2015 with India and China accounting for almost 50% of the growth. Also the global per capita energy utilization is predicted to increase by 12% with total carbon emissions to increase by 25% [1]. Dependency on fossil fuels leads to severe environmental issues such as global warming, acid rain, emission of pollutants etc., [2]. Hence renewable energy resources such as biomass, wind, solar and geothermal attract great attention since they are clean and environmentally benign. It is estimated that among non-fossil fuels, usage of energy from renewables (including biofuels) is likely to grow from 3% to 8% in 2035 [1].

Of late attention is focused on biomass as an energy resource - as compared to other renewable sources - for energy generation, as it is evenly scattered over earth's surface unlike fossil fuels and emits abysmally lower greenhouse gases. Plantation of biomass crops for energy harvesting helps to mitigate climate change; reduces acid rain; abates soil erosion and water contamination; curtails pressure on landfills and also enhances wildlife habitation. Energy is sourced from biomass by adopting any of the 3 mechanisms namely Thermo chemical (Combustion, Gasification, Pyrolysis and Carbonization), Biochemical (Biomethanation, Fermentation, Composting etc.) and Physiochemical (Briquetting, Pelletisation etc.). Among these technologies gasification holds abundant promise for its limited space requirement, fuel flexibility, better energy recovery [3] and modularity.

At present India produces 915.67 million tons of biomass every year agro, forest and wasteland residues [4]. Installed capacity of grid interactive renewable power in India reached 31,692 MW out of which biomass power accounts for 4014 MW [5]. Considering the abundant cum distributed availability and merits of biomass utilization for power generation, it is significant to have focused attention on exploring additional biomass resources.

Corn, known as maize is one of the most emerging crops having wider adaptability under varied climatic conditions. In India corn is the 3rd most important food crop after wheat and rice. Estimated production of corn in India is 23.5 million tons in the year 2015 and is ranked as 8th based on its production [6]. Presently corn cobs generated during processing of maize is being dumped as a waste. This paper investigates the possibility of gasification of corn cob in a biomass reactor for to explore its potential as an alternate source of energy.

EXPERIMENTAL SECTION

Corn Cob – Physiochemical Characterization

Corn is used for various purposes such as animal fodder and food grain (sweet corn, baby corn, green cobs and popcorn). Indians widely consume corn flour for cooking. Corn is also being used as a basic raw material for many industrial products like oil [7], starch [8], alcoholic beverages [9], fiber [10], pharmaceutical, food sweeteners, food cereals, cosmetic, film, gum, textile, package and paper industries [11]. In the process of extraction of corn kernels residues such as cobs, leaves and stalks are obtained. Generally a corn crop upon processing yields 13% of its weight as kernels (useful product), 15% as cobs, 22% as leaves and remaining 50% as stalks [12, 13, 14]. Corn leaves and stalks are basically generated at field while cobs are generated at the processing units. Corn cobs, the hard cylindrical core bearing kernels comprises 3 layers namely pith, woody ring and chaff, as depicted in figure 1.

Efficient deployment of biomass necessitates proximate analysis, ultimate analysis and determination of HHV so as to establish the quality and quantitative energy content of these fuels [15]. Corn cob characteristics were determined using a proximate analyzer (muffle furnace + micro weigh balance with other supporting auxiliaries) and Ultimate analyzer. Moisture content (adopting ASTM E 871 – 82), volatile matter (adopting ASTM E 872 – 82) and ash content (adopting ASTM D 1102 – 84) were determined. Fixed carbon was assumed to be the rest. Calorific Value of the fuel was estimated using bomb Calorimeter (standardized using benzoic acid). Physical and chemical characteristics of corn cob – as obtained in these analyses - are presented in the tables 1, 2 & 3.

It was inferred from literatures that physical and chemical characteristics of biomass used in gasification shall conform to certain minimum criteria. Moisture and ash content should not be greater than 30% and 5% respectively [16]. HHV and bulk density of fuel shall be greater than 10 MJ/kg and 200 kg/m³ respectively [17]. Angle of repose for the biomass feed should be lesser than the angle of throat for its easiness to flow in throat zone [18]. Since corn cob satisfies all the above criteria, it can be used as a feedstock for the gasification.

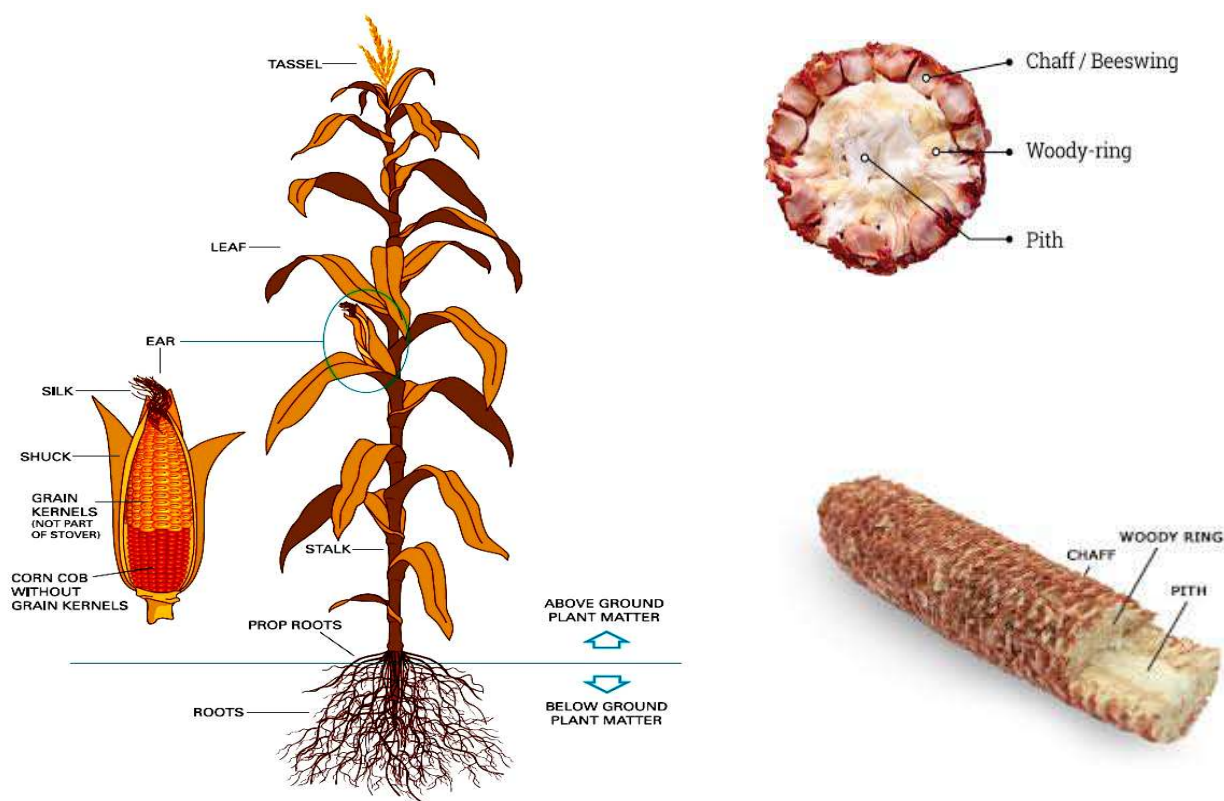


Figure 1 Parts of corn cob

Table 1 Proximate analysis (As received basis)

% Weight	Corn Cob
Moisture	14.7
Volatile Matter	66.3
Ash	2.4
Fixed Carbon	16.6

Table 2 Ultimate analysis

%Weight	Corn Cob
Carbon	44.7
Hydrogen	6.3
Oxygen	45.2
Nitrogen	1.2
Sulphur	0.09

Table 3 Other properties

Properties	Corn Cob
Calorific Value (MJ/kg)	15.45
Bulk density (kg/m ³)	203
Angle of repose (Degree)	31

Literature analysis further revealed experimental investigation of various fuels like sugar cane leaves, bagasse, bajra stalks and sweet sorghum stalks [19], beachwood, nutshells, olive husks and grape residues [20], Furniture wood and wood chips [21], hazelnut shells [22], rubber wood chips [23], saw dust [24], Refuse Derived Fuel (RDF) pellets [25], Cashew nut shell char [26], olive residues [27], sesame wood waste [28], maritime pine woodchips [29], olive pomace [30], empty palm fruit bunches (EFB) [31], olive kernel [32] babul wood, groundnut shell briquettes, groundnut shell, mixture of babul wood & groundnut shell and cashew nut shell [33] for gasification. Hence it is evident that no major research work was carried out on gasification of corn cobs.

Experimental & Instrumentation set up

Lack of research / literature on corncob gasification had prompted us to design a gasifier using a proven and a widely adopted fuel viz., causerina wood and to use the same gasifier with suitable modifications for gasifying corncobs. It was planned to adopt a fixed bed (so as to accommodate bulky and denser fuels), forced draught (to avoid coating of tar in downstream equipment like blowers), dry bottom (to resist water induced corrosion and to eliminate accumulation of carcinogens) and down draught (to minimize tar as throat section induces thermal cracking of tar) gasifier for the experimental analysis. Figure 2 details the procedure adopted for designing the gasifier. Mild steel sheets were used for fabricating the designed setup for its lower cost and better machinability characteristics. The dimensions of the designed and fabricated gasifier are depicted in figure 3.

The overall experimental setup comprises a 6 kW_e downdraft gasifier, centrifugal blower, regulated air supply system, cyclone separator, dust filter, producer gas piping system and a flare pipe. Geometry of the reactor was made to be a cylindrical shell lined inside with medium density castable refractory to withstand high temperature. Reactor consists of upper and bottom reactor portions, rolled to the designed dimensions using rolling machine and was welded together. Biomass was fed through a hopper provided at the top of reactor. Provisions were made to close and open the hopper for fuel charging. Air supply was administered in the reaction zone (just above the throat) through 4 equally spaced conduits. Butterfly valve was placed in the air inlet line for regulating the air flow. Sight glasses were provided at 45° angle to the reactor axis to view the interior of the reactor and to observe the reaction front. The gasifier throat was fabricated using mild steel, lined inside with medium density castable refractory possessing a throat angle of 45° to aid gravity assisted smooth flow of biomass and to facilitate tar cracking. A perforated steel grate was provided below the throat portion of reactor which served as a fixed bed and also ash separator. The residual char and ash falling from the grate were collected in a closed ash chamber positioned below the perforated stainless steel grate. The region surrounding the air entry just above the throat functions as a combustion zone while the region between throat and grate functions as a reduction zone. The region above the combustion zone functions as pyrolysis zone and drying zone respectively.

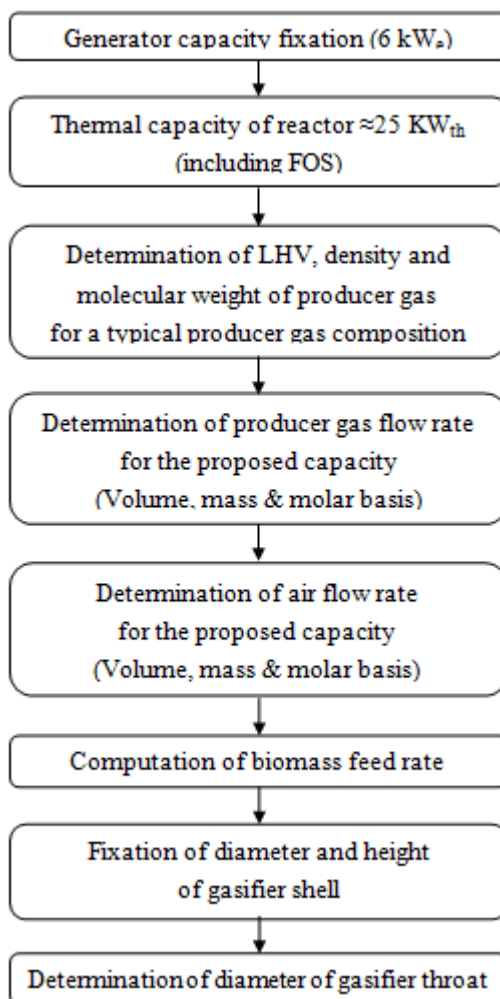


Figure 2 Gasifier design procedure

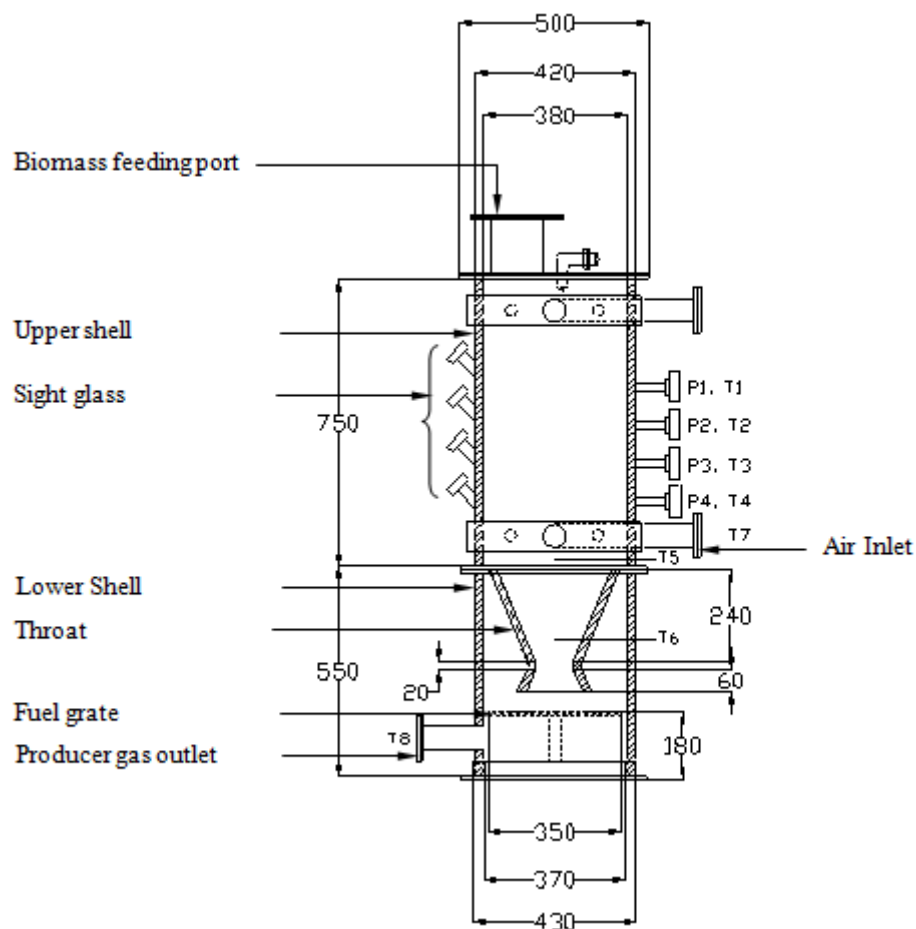


Figure 3 Gasifier dimensions

The entire reactor assembly was supported on a mild steel stand. The producer gas emanating from the reactor was passed through a cyclone separator for removing the suspended particulates and was burned through the flare pipe. Figure 4 & 5 depicts the schematic and the photographic view of experimental setup.

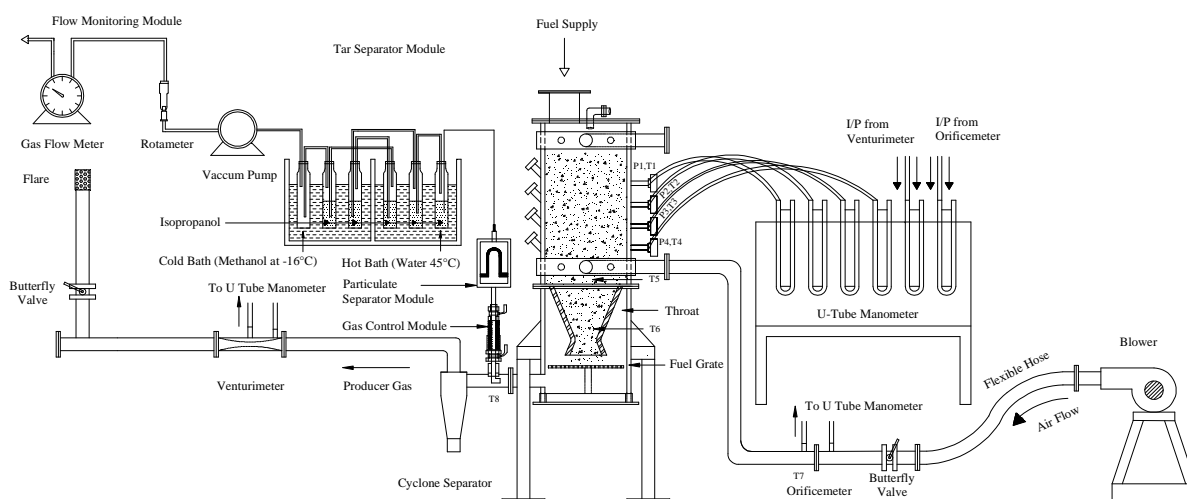


Figure 4 Schematic diagram of experimental setup



Figure 5 Photographic view of experimental setup

A Siemens make online gas analyzer (Oxymat 61 estimating O_2 using paramagnetic principle, Calomat 6 estimating CO , CO_2 & CH_4 using Non Dispersive Infrared Multilayer technology and Ultramat 23 estimating H_2 using thermal conductivity principle) were used to establish producer gas composition. An orifice meter coupled with water filled "U" tube manometer was connected after the butterfly valve in the air inlet line for measuring the air flow rate. Producer gas flow rate was measured by using venturi meter made up of mild steel with water filled "U" tube manometer, placed in the producer gas line. Venturi was chosen for measurement of producer gas flow while orifice for air flow monitoring for to avoid the possibility of erroneous reading due to deposition of tar in orifice meter since the cross section of orifice is smaller than the throat of venturi. K type (Chromel-Alumel) thermocouples (T1 to T8) were used to monitor air inlet temperature, temperature distribution inside the reactor and producer gas exit temperature at regular intervals. Temperature at various positions was logged using Agilent make (34907A) data acquisition system. Reactor surface temperature was measured with a Kane make Infrared Thermometer (UEI-INF 200). The pressure buildup across the reactor at different positions (P1 to P4) was measured using water filled "U" tube manometer. A slip stream of producer gas was sampled for quantifying the tar and particulate matter at the exit of the gasifier but prior to cyclone separator. The sampling set up was fabricated as per international guidelines [34]. Equipment like Soxhlet extractor, rotary vacuum flash evaporator, calibrated analytical balance (1 mg accuracy), quartz thimble filter, muffle furnace, desiccator, volumetric flask and funnel were used for quantification of tar.

EXPERIMENTAL SECTION

Pre weighed sacks comprising corn cobs, each weighing 5 kg, were prepared and placed near the reactor for continuous operation. To initiate the gasification process, a known quantity of charcoal was ignited and fed to the gasifier through the hopper. A metered quantity of air was admitted to the gasifier using a blower and butterfly valve arrangement to ensure sustenance of red hot charcoal bed above the grate, followed which corn cobs were fed. Flue gas was observed at the flare pipe within 5 minutes. A flammable gas was obtained at the flare pipe after 25 minutes of starting. Experimental studies were initiated after the gasifier attained steady state which was ensured by observation of constant temperature both in reduction zone and producer gas. Fuel feeding rate was noted by charging the gasifier with fuel - on an hourly basis - to a predetermined level.

Equivalence Ratio, bed temperature, volatile matter, moisture content and gasifying medium are the 5 main parameters that influence gasification [26]. As the designed reactor is of auto-thermal type, the bed temperature of the gasifier cannot be changed. Volatile matter and moisture content of the sourced corn cobs are invariably constant. Atmospheric air was used as the gasifying medium. Hence it is inferred that the only influential parameter that could be varied is the equivalence ratio. Thus it was decided to establish the gasifier performance for different equivalence ratios towards identifying the operating condition that yielded maximum efficiency.

RESULTS AND DISCUSSION

Influence of equivalence ratio on producer gas composition

Equivalence ratio (ER) - defined as the ratio of actual air supplied to that of the stoichiometric air requirement for a given quantum of fuel - does have a significant role on the composition of producer gas. Butterfly type valve was used to control the quantity of air flow and hence the ER.

Figure 6 depicts the variation of producer gas composition for different ER. There is subtle rise in H_2 initially with increase in ER and at higher ER it follows a decreasing pattern which concur the observations of Lv et al. [35]. This trend in molar concentration of H_2 may be attributed to increase in availability of O_2 at higher equivalence ratios, thereby aiding formation of H_2O . Molar concentration of CO increases up to 0.3 ER and then decreases. CO_2 concentration follows a reverse trend as that of CO owing to the possibility of reverse Boudouard reaction. CO is observed to be maximum (15.43%) at 0.3 ER where CO_2 reaches minimum (14%). The trend observed for CO and CO_2 content are analogous to the experimental inferences cited by Zainal et al. [21] and Venkat et al. [26].

Concentration of CH_4 is found to be in receding trend with increase in ER. An increase in ER results in increased reaction temperature and hence CH_4 formed at lower ERs undergo endothermic reaction with water vapour and are transformed to CO, CO_2 and H_2 . CH_4 content from the experimentation of corn cob is found to be hovering around 0.87% - 2.4% which is in line with the findings of Bacaicoa et al. [36]. In an ideal gasification system, the molar concentration of O_2 in the producer gas should be zero. However during experimentation, presence of traces of O_2 was noticed at lower ER, which might probably be due to bridging and channeling of fuels at lower fuel consumption rates. Table 4 presents the composition of producer gas observed by various researchers on different fuels with that of corn cob.

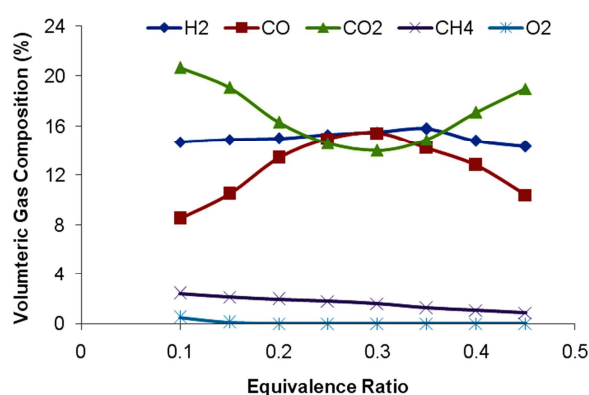
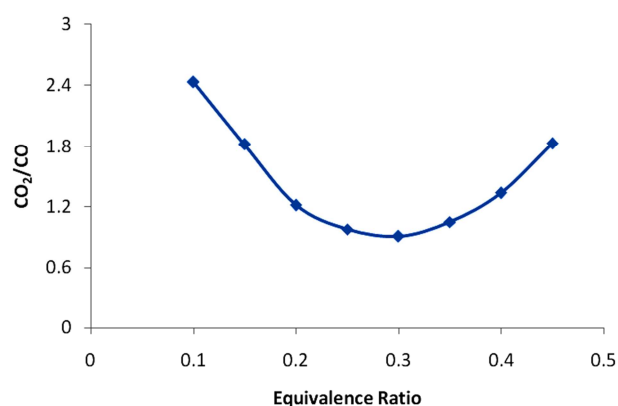


Figure 6 Influence of ER on gas composition

Figure 7 Variation of CO_2/CO

Variation of CO_2/CO Vs Equivalence Ratio

Variation in the ratio of CO_2 to CO for different ER is shown in figure 7. A least ratio of CO_2 to CO indicates better gasification of the fuel. Analysis performed on the results reported by researchers (Dogru et al. [22], Jayah et al. [23], Paulo et al. [24], Rao et al. [25] and Venkat et al. [26]) reveal that the ratio of CO_2 to CO ratio should be less than 1 for better gasification efficiency. During corncob gasification, the ratio attains value lesser than 1 between an ER of 0.25 to 0.3 and hence the optimum ER has been identified to lie within this range.

Variation of combustibles and inerts Vs Equivalence Ratio

The HHV of the producer gas is influenced by presence of combustibles. Since air gasification is adopted, the volumetric composition of inert constituents (N_2 and CO_2) outnumbers the volumetric composition of combustible constituents (CO, H_2 and CH_4). The range of combustible products with respect to varying ER was estimated to be between 25% - 33% of producer gas generated. Maximum % of combustible (32.53%) and minimum % of inert (67.47%) was observed at an ER of 0.3. Figure 8 illustrates the variation of % combustibles and % inerts, with respect to different ER.

Table 4 Composition of producer gas from various fuels

Fuel	Volumetric composition of producer gas (%)							Researcher
	H_2	CO	CO_2	CH_4	C_2H_6	N_2	O_2	
Furniture wood	14.05	24.04	14.66	2.02	0.01	43.62	1.69	[21]
Hazelnut shells	11.1 -14.7	8.56 -20.66	9.52 -10.33	1.4 -2.36	Traces	NA	NA	[22]
Rubber wood	12.5 -18.3	18.4 -22.1	8.5 -11.4	1.1 -1.4	NA	NA	NA	[23]
Sawdust	10.2 -18.9	15.7 -22.7	9.73 -14.57	1.08 -3.65	NA	NA	NA	[24]
Casuarina Wood	14.4	16.3	11.0	2.0	NA	56.3	NA	[26]
Cashew nut shell char	11.1	21.6	2.9	0.4	NA	64.0	NA	
Olive kernels	7.78	4.81	19.47	2.99	Traces	NA	NA	[27]
Corn cobs	15.5	15.43	14	1.6	-	53.47	0	(ER=0.3)

The range of combustibles and inert yielded from gasification of corn cobs are comparable to that of gasification of other bio fuels like hazelnut shells [22], rubber wood [23], sawdust [24], RDF pellets [25], casuarina wood & cashew nut shell char [26], olive kernel [27], and empty palm fruit bunches [31].

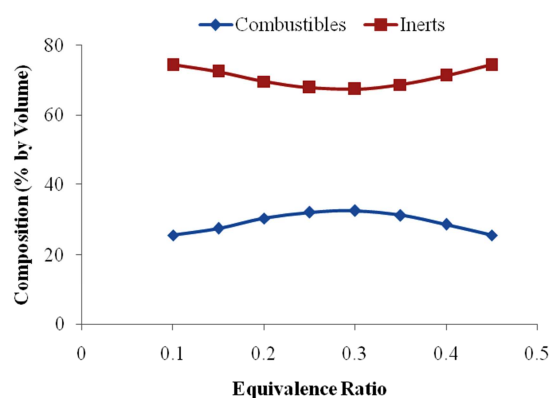


Figure 8 Variation of combustibles & Inerts

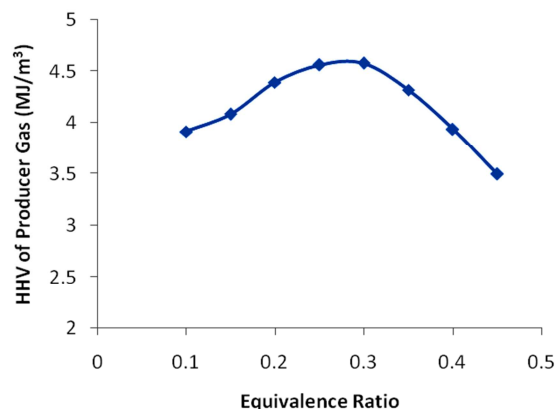


Figure 9 Variation of HHV of gas

HHV of producer gas Vs Equivalence Ratio

The HHV of the producer gas increases with equivalence ratio initially, attains a peak at the best operating point and then decreases with the increase in equivalence ratio. Figure 9 depicts the variation of HHV of producer gas with different ER. The decrease in HHV is due to the decrease in CO & H₂ content in the producer gas generated. HHV of producer gas from corn cob attained a maximum value of 4.58 MJm⁻³ at an ER of 0.3. The presence of combustibles is found to be maximum at this ER. Rajeev et al. [19] reported HHV in the range of 3.56 – 4.82 MJm⁻³ while gasifying fuels like sugarcane leaves, bagasse, bajra stalks and sweet sorghum stalks while Bhoi et al. [33] experienced HHV of 4.37 MJm⁻³ – 4.79 MJm⁻³ from gasifying various biomass feeds.

Specific gas generation Vs Equivalence Ratio

Specific gas generation (SGG) is the volume of producer gas generated per kg of fuel. Figure 10 depicts the variation of specific gas generation with respect to increase in ER. The SGG is found to be increasing from 1.58 m³kg⁻¹ to 2.4 m³kg⁻¹ with increase in ER from 0.1 to 0.45. SGG at ER = 0.3 is found to be 2.12 m³kg⁻¹. Comparison on the SGG using different fuels - as reported by other researchers - with that of corn cobs is presented in table 5. SGG reported from various researchers vary from 1.62 m³kg⁻¹ – 4.18 m³kg⁻¹ (Dogru et al. [22], Rao et al. [25], Venkat et al. [26], Sheth et al. [28], Bhoi et al. [33]).

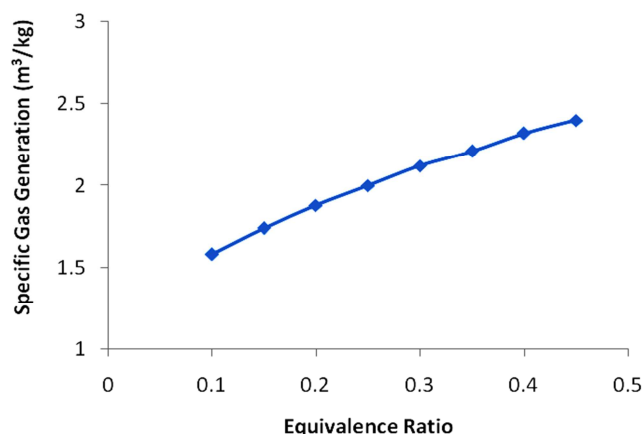


Figure 10 Variation of SGG

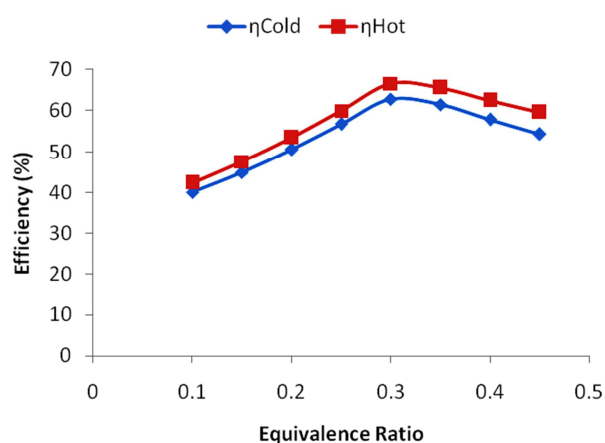


Figure 11 Variation of cold & hot gas Efficiency

Efficiency Vs Equivalence Ratio

Cold gas efficiency is a measure of the effectiveness with which a gasifier is able to convert a solid fuel into a burnable gas. Hot gas efficiency includes the sensible heat energy available in the producer gas. The cold gas efficiency is influenced by SGG and HHV of producer gas. Hence for better conversion efficiency the gasifier is to be operated in the range where SGG is optimum with maximum HHV of producer gas. Figure 11 depicts the variation of cold gas and hot gas efficiency with respect to different ER. Both the efficiencies adopt increasing trend

up to an ER of 0.3 and decline thereafter. This trend may be due to fact that combustibles in producer gas increases till ER of 0.3 and thereafter decreases.

Cold gas efficiency as reported by other researchers are : 50% to 60% for an ER range of 0.2 to 0.35 (Sheth et al. [28]), 38% to 62% while varying air-fuel ratio from 0.8 m³/kg to 1.78 m³/kg (Catharina Erlich et al. [31]), 64% to 72% (Bhoi et al. [33]), 42% to 82% by varying the ER from 0.15 to 0.4 (Bacaicoa et al. [36]), maximum of 70% (Singh et al. [37]) and 43.3% to 63.6% (Kuhe et al. [38]).

Tar and Particulates Vs Equivalence Ratio

Quantification of tar and particulate matter is a laborious process requiring a considerable amount of time. Hence, it was decided to ascertain the tar and particulate matter at the best gasification condition i.e., at an ER of 0.3 for the feedstock. Producer gas sampling for the estimation of tar and particulate matter is performed at the exit of the reactor but prior to the cyclone separator. The tar and particulate matter sampling system – devised adopting international norms - consists of 4 modules viz. gas preconditioning, particle filter, tar collection and volume metering. The sample gas after preconditioning was admitted in to a quartz thimble filter for estimation of particulate matter. Difference in weight of the thimble filter was used for determination of particulate matter. Clogged tar in the thimble filter was duly accounted using a separate procedure involving soxhlet extractor and rotary vacuum flash evaporator.

Tar collection module comprises 6 nos. of impinger bottles housed equally in hot bath and cold bath maintained between -15°C to -20°C and +35°C to +40°C respectively. The tar collected in the impinger bottles was quantified using rotary vacuum flash evaporator. Figure 12 depicts the tar and particulates content in a producer gas generated which had been experimentally estimated as 0.81 g/m³ and 0.355 g/m³ respectively.

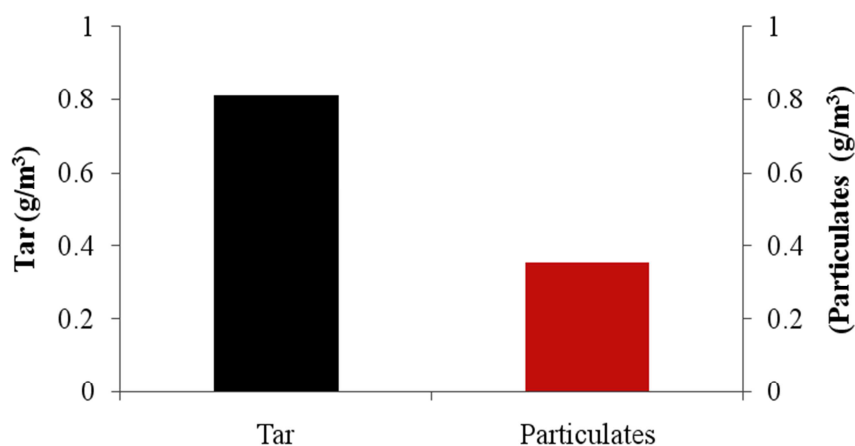


Figure 12 Tar and Particulates in the producer gas

Presence of tar content in producer - as reported by researchers – ranges from 0.12 g/m³ (Adegoroye et al. [39]) to 7 gm⁻³ (Narvaez et al. [40]). The range of tar generation seems to be wide as it is influenced by a variety of site specific local conditions such as volatile matter, lignin content, moisture content, porosity and density of feedstock, ER, gasification temperature etc.,

CONCLUSION

An attempt had been made towards utilizing corn cobs - an agricultural waste by product – for gasification. A 6 kW_e, closed top, fixed bed, downdraft reactor was designed and fabricated to study the reactor performance on fuelling with corn cob. From the experimental outcome, it is observed that corn cob can be gasified without any major hassles. Composition of producer gas, cumulative composition of combustibles & inerts, HHV of producer gas, specific gas generation, cold gas efficiency and hot gas efficiency have been determined at various equivalence ratios of 0.1 to 0.45. Experimental results divulge that an ER of 0.3 is ideal for gasification of corn cob. Cold gas efficiency and HHV of producer gas were observed to attain a pinnacle of 62.83% and 4.58 MJm⁻³ at this ER. The tar and particulates are measured as 0.81 gm⁻³ and 0.355 gm⁻³ respectively. Hence it is construed that corn cobs could be gasified at ease and can definitely be looked as an additional alternate source of energy for rural un-electrified habitations where cultivation of corn cob is abundant.

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