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Comparative studies on gasification of corn cob, *Casuarina* wood and coconut shell in a fixed bed gasifier

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ABSTRACT

A 6 kW_e, fixed bed, downdraft gasifier was used to compare its performance on 3 fuels: corn cob (CC), casuarina wood (CW) and coconut shell (CS). Air was administered above the throat through 4 equally spaced conduits in forced circulation mode. Gas composition, HHV of gas, specific gas generation (SGG) and cold gas efficiency was compared for the fuels by varying Equivalence Ratio (ER). Studies revealed that all fuels were gasified successfully. CO_2/CO of gas was observed as least at an ER of 0.3 for CC & CW while for CS it was at 0.35. Maximum HHV of gas from CC gasification (4.58 MJm^{-3}) is lesser compared with CW (4.81 MJm^{-3}), higher when compared with CS (4.23 MJm^{-3}). SGG associated with least CO_2/CO was observed as 2.12 m^3kg^{-1}, 2.39 $m^3 kg^{-1}$ and 3.05 m^3kg^{-1} for CC, CW and CS respectively. Optimal cold gas efficiency for CC gasification is 62.83%, whereas it is 70.18% and 72.74% for CW and CS gasification respectively. Tar content was least for CS gas and particulates content was maximum for CC gas.

Keywords: Gasification, corn cob, casuarina wood, coconut shell, CO_2/CO, HHV, SGG, Tar

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INTRODUCTION

As per data compiled in 2015 by RE Division, Ministry of Power, Government of India 5,77,758 villages are electrified leaving 19,706 villages are still to be electrified [1]. India's energy generation will grow by 117% in 2035, while consumption rises by 128% with 115% increase in CO_2 emissions [2]. Despite annual increase of global energy consumption by 1.5% in recent years, carbon emissions associated with energy consumption remained stable in 2014 [3]. Increased renewable energy consumption and energy efficient operations of utilities favor the carbon stabilization, address climate change. Serious impact on the environment such as global warming [4] necessitates the utilization of renewable energy resources for power generation. Among the renewable energy resources, biomass can contribute significantly to reduction of CO_2 emissions. Biomass & associated power potential in India is 915.67 million tons & 33291.4 MW respectively [5]. Installed grid interactive biomass power in India was 4,831.33 MW in March 2016 [6].

Casuarina: Kingdom – Plantae, Subkingdom – Tracheobionta, Superdivision – Spermatophyta, Division – Magnoliophyta, Class – Magnoliopsida, Subclass –Hamamelididae, Order – Casuarinales, Family – *Casuarinaceae*, Genus – *Casuarina Rumph*. ex L, Species – *Casuarina equisetifolia* L [7] is commonly grown in tropical and subtropical areas and makes excellent firewood. Coconut: Kingdom – Plantae, Subkingdom – Tracheobionta, Superdivision –Spermatophyta, Division – Magnoliophyta, Class – Liliopsida, Subclass – *Arecidae*, Order – Arecales, Family – *Arecaceae*, Genus – Cocos L, Species – *Cocos nucifera* L, [8], grows on sandy, saline soils and prefers areas with abundant sunlight and regular rainfall. Currently India produces 11.93 million tons of coconut (3rd largest producer). The husk and shells of coconut can be used as fuel and are a source of charcoal [9]. Corn: Kingdom – Plantae, Subkingdom – Tracheobionta, Superdivision –Spermatophyta, Division – Magnoliophyta, Class – Liliopsida, Subclass – Commelinidae, Order – Cyperales, Family – *Poaceae*, Genus – Zea L, Species – *Zea mays* L, [10], generally known as maize, is one of the most versatile crops having wider adaptability under varied climatic conditions. Estimated corn production in India is 23.5 million tons in 2015 and is ranked as 8^{th} based on its production [11]. Generally a corn crop upon processing yields 13% of its weight as kernels (useful product), 15% as cobs, 22% as leaves and the remaining 50% as stalks [12, 13, 14]. Presently corn cobs generated during processing of maize is being dumped as a waste.

Considering significant available potential of CC, CW & CS, it is decided to explore the resources for energy recovery by adopting gasification technology (owing to its flexibility in utilizing various biomass & better energy conversion [15]). This paper investigates and compares the gasification of CC, CW, & CS as a feedstock in a downdraft gasifier.

EXPERIMENTAL SECTION

Fuel Characterization – A Comparison

Biomass – being used as a fuel/feedstock for gasification requires physical (bulk density, angle of repose) and chemical (proximate analysis, ultimate analysis & determination of HHV) characterization so as to ascertain its quality & quantitative energy content [16]. Physical & chemical characteristics of CC, CW and CS, influencing biomass gasification– as obtained from the analysis - are presented in the tables 1, 2 & 3.

Table 1 Proximate analysis (As received basis)

% Weight	Corn Cob	Casuarina Wood	Coconut Shell
Moisture	14.7	12.5	10.8
Volatile Matter	66.3	67.5	64.2
Ash	2.4	2	1.8
Fixed Carbon	16.6	18	23.2

Table 2 Ultimate analysis

% Weight	Corn Cob	Casuarina Wood	Coconut Shell
Carbon	44.7	47.5	51.4
Hydrogen	6.3	5.9	5.6
Oxygen	45.2	42.5	40.2
Nitrogen	1.2	2.1	1.7
Sulphur	0.09	0.05	0.03

Table 3 Other properties

Properties	Corn Cob	Casuarina Wood	Coconut Shell
Calorific Value (MJ/kg)	15.45	16.39	17.73
Bulk density (kg/m^3)	203	430	324
Angle of repose (Degree)	31	41	36

Based on literature study, biomass used as feedstock in gasification shall satisfy certain minimum criteria. Moisture content & ash content shall be lesser than 30% & 5% respectively [17]. HHV & bulk density of fuel shall not be lesser than 10 MJ/kg & 200 kg/m^3 respectively [18]. Angle of repose for biomass to be used as a feedstock shall not be greater than the angle of throat for its easiness to flow in throat zone [19]. As CC, CW and CS confirms all the above criteria, these fuels can be deployed as a feedstock for gasification.

Experimental & Instrumentation Set Up

The experimental setup comprises a 6 kW_e downdraft gasifier, centrifugal blower, air supply system, cyclone separator, producer gas piping system & flare pipe. Reactor consists of upper and bottom reactor portions made to be a cylindrical shell lined inside with castable refractory to withstand high temperature. Biomass was fed through a hopper provided at the top of reactor. Air supply was administered above the throat through 4 equally spaced conduits & was regulated using butterfly valve. The gasifier throat of was fabricated using mild steel, lined inside with castable refractory possessing a throat angle of 45^0 to aid smooth flow of biomass & to facilitate tar cracking. A perforated steel grate was provided below the throat portion to serve as a fixed bed & ash separator. The residual char & ash falling from the grate were collected in a closed ash chamber positioned below. The region surrounding the air entry just above the throat functions as combustion zone while the region between throat & grate functions as reduction zone. The region above combustion zone functions as pyrolysis zone & drying zone respectively. The entire reactor assembly was supported on a mild steel stand. The producer gas emanating from the reactor was passed through cyclone separator for removing the suspended particulates & was burned through the flare pipe. Figure 1 & 2 depicts the schematic and the photographic view of experimental setup.

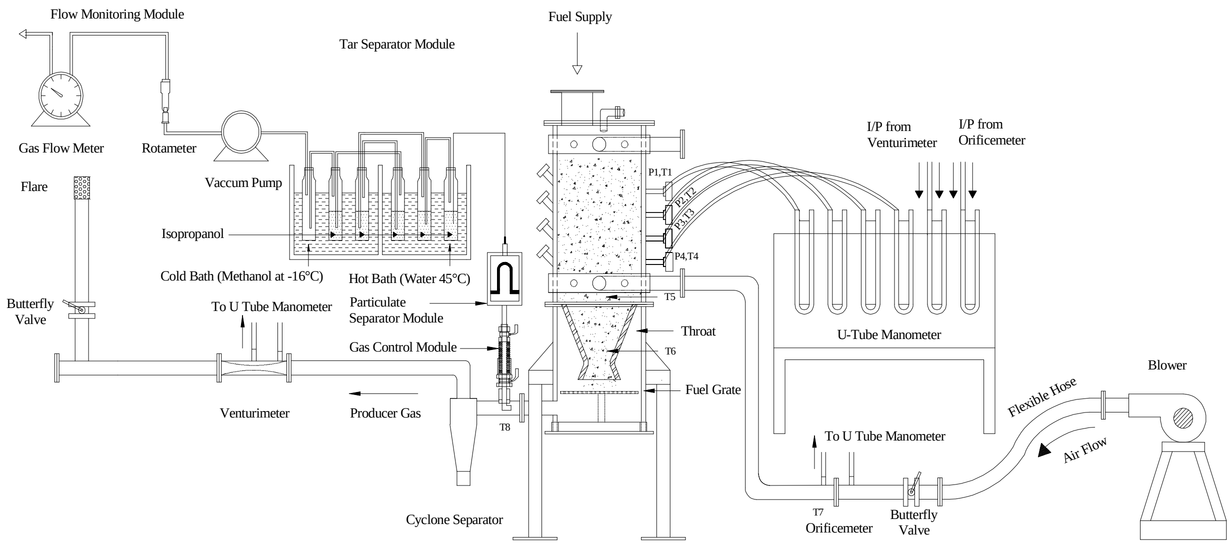

Figure 1 Schematic diagram of experimental setup

Figure 2 Photographic view of experimental setup

A Siemens make online gas analyzer (Oxymat 61 estimating O_2, Calomat 6 estimating CO, CO_2 & CH_4 and Ultramat 23 estimating H_2) were used to establish gas composition. Orifice meter & venturi meter coupled with water filled "U" tube manometer were used to measure air flow rate and producer gas flow rate respectively. K type (Chromel-Alumel) thermocouples were used to monitor air inlet temperature, temperature distribution inside the reactor & producer gas exit temperature. Temperatures were 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 was measured using water filled "U" tube manometer. Producer gas was sampled for quantifying tar & particulates at exit of gasifier but prior to cyclone separator. Sampling & analysis set up was fabricated as per international guidelines [20].

Experimental Process

Pre-weighed batches of CC (5kg), CW (15 kg) & CS (10 kg) were placed nearer to gasifier for continuous operation during its gasification. To initiate the gasification process, a known quantity of charcoal was ignited & fed to the gasifier through hopper. A metered quantity of air was admitted to the gasifier using a blower & butterfly valve to ensure sustenance of red hot charcoal bed above the grate, followed which CC were fed. Flue gas was observed at the flare pipe within 5 minutes. A flammable gas was obtained at the flare pipe after 20 – 30 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 & producer gas. Fuel feeding rate was noted by charging the gasifier with fuel - on an hourly basis - to a predetermined level. Since air was used as the gasifying medium, volatile matter & moisture content of the respective biomass feedstock are constant & bed temperature of the gasifier can not be altered, it is decided to operate the gasifier by varying the equivalence ratio (among the 5 major influencing parameters for gasification). The experiments were repeated for CW & CS as feedstocks. The performance of the gasifier for CC, CW & CS as feedstocks was compared by varying the equivalence ratio and the optimum operating condition that yielded maximum efficiency was determined.

RESULTS AND DISCUSSION

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

Influence of ER on H_2

Figure 3 depicts that H_2 is uniformly increasing at lower ER & decreases later. Increase in gasification temperature due to increase in ER is the reason for observed increasing trend of H_2 at lower range of gasification. Whereas, at higher ER of gasification range, owing to the prevailing excess oxygen, oxidation reaction dominates and H_2 to H_2O conversion takes place leading to drop in H_2. Maximum yield of H_2 is found to be 15.5%, 14.55% & 12.5% for CC (at an ER = 0.3), CW (at an ER = 0.3) & CS (at an ER = 0.35) respectively. Lower hydrogen & moisture in CS compared to CC & CW results in lower % of H_2 in the gas.

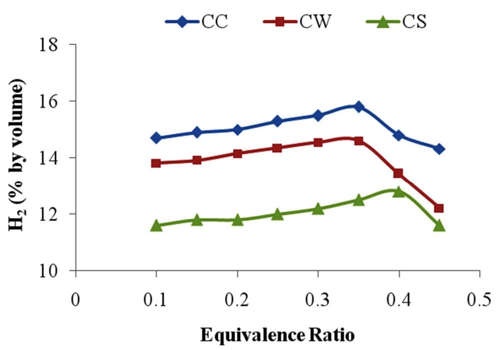

Figure 3 Influence of ER on H_2

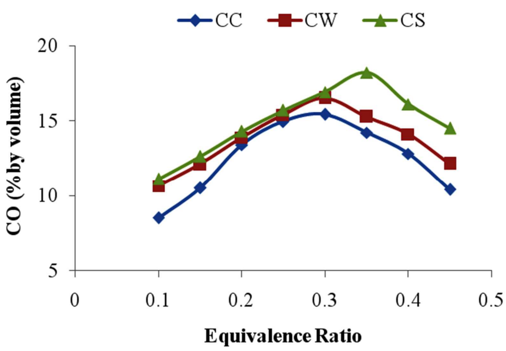

Figure 4 Influence of ER on CO

Influence of ER on CO

Figure 4 illustrates that % CO is increasing till an ER of 0.3 for CC & CW and 0.35 for CS, after which % CO decreases with increase in ER. Maximum CO is observed as 15.43%, 16.51% & 18.2% for CC, CW & CS, while converting into a burnable gas in a reactor. Increase in CO for CW & CS compared to CC might be due to its higher carbon content.

Influence of ER on CO_2

The trend of CO_2 opposite to CO is observed from figure 5. CO_2 decreases initially with ER and reverses its trend at higher ER. The decrease and increase in CO_2 might be due to the occurrence of reverse boudouard reaction at lower ER and the oxygenated reactions at the higher ER of the gasification range respectively. The lowest % composition of CO_2 is found to be 14%, 10.81% and 4.1% for CC (at an ER = 0.3), CW (at an ER = 0.3) and CS (at an ER = 0.35) respectively. Higher carbon content and reaction temperature might be the reason for the lowest % composition of CO_2 produced using CS as a feedstock in the gasifier compared to CC and CW. % yield of CO_2 for all the feedstock is observed to be the least corresponding to ER where maximum % yield of CO is observed.

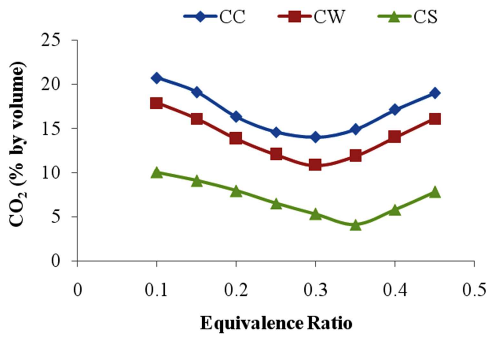

Figure 5 Influence of ER on CO_2

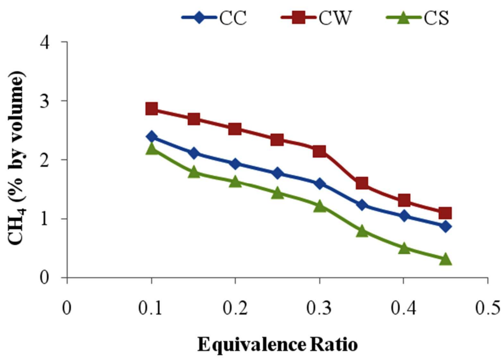

Figure 6 Influence of ER on CH_4

Influence of ER on CH_4

Figure 6 depicts variation of CH_4 content with respect to ER. CH_4 is found to be receding with increase in ER as it leads to increase in gasification temperature. At elevated temperatures, CH_4 produced in the gasifier, undergo endothermic reactions with water vapour and is converted to CO, CO_2 & H_2. Hence yield of CH_4 decreases at higher ER. CH_4 formed upon gasification of CC (1.6%) is found to be almost 0.75 times and twice as that of obtained from CW (2.15%) and CS (0.8%) gasification respectively.

Gas compositions obtained in the present study are in close agreement with the results reported by researchers (Krushna Patil et al. [21], Chawdhury and Mahkamov [22], Panwar et al. [23], Jaojaruek et al. [24], Chao Gai et al. [25], Sang Jun Yoon et al. [26] & Venkat et al. [27].

Effect of ER on CO_2/CO

CO_2/CO is the indicator of gas quality & the efficiency in the gasification process. The minimum value of CO_2/CO leads to the better conversion of biomass feedstock into producer gas. Variation in the CO_2/CO for different ER is shown in figure 7. For CC & CW, CO_2/CO attains values less than unity from 0.25 to 0.3 ER & from 0.2 to 0.4 ER respectively. Whereas for CS, CO_2/CO lies below unity from 0.1 to 0.45 ER. For all the biomass feedstock, the least value of CO_2/CO coincides with the best operating point (ER of 0.30 for CC & CW and ER of 0.35 for CS) for attaining higher HHV of producer gas and the highest efficiency. From the studies performed by researchers (Venkat et al. [27], Dogru et al. [28], Jayah et al. [29], Paulo et al. [30] and Rao et al. [31], it is inferred that the ratio of CO_2/CO should be less than 1 for better gasification efficiency.

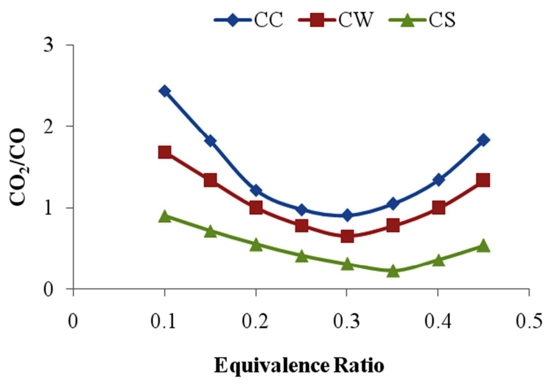

Figure 7 Effect of ER on CO_2/CO

Variation of % Combustibles & Inerts Vs ER

% combustibles plays a pilot role on the HHV of producer gas and hence the efficiency. Figure 8 illustrates that the % combustibles increase up to the best operating point and recedes thereafter with increase in ER. % combustibles of CC are found to be in between the CW and CS. % combustibles for CC, CW and CS tend to coincide at the later stage of gasification range after its best operating point. The composition of combustibles obtained upon gasification of CW appears to be higher since it has higher CO & CH_4 content compared to CC and increased H_2 & CH_4 content compared to CS. % composition of combustibles generated while using CC, CW and CS as biomass feeds in the downdraft reactor, at the best operating point is 32.53%, 33.21% & 31.5% respectively.

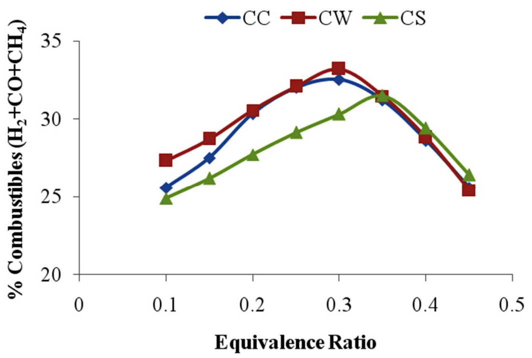

Figure 8 Variation of % combustibles Vs ER

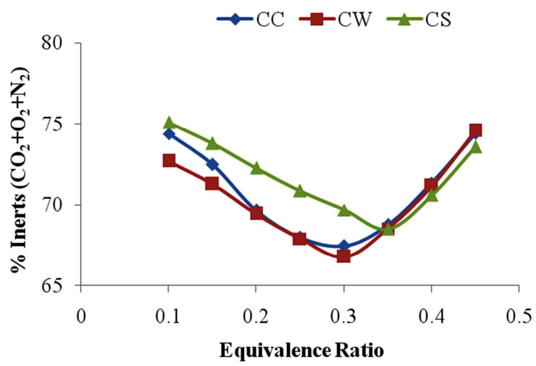

Figure 9 Variation of % inerts Vs ER

Figure 9 depicts that the trend of % inerts is opposite to that of % combustibles. % composition of inerts decreases with increase in ER up to the best operating point and increases thereafter. % N_2 composition in the inerts, for all the biomass feedstock is more than 50%, increases with increase in ER and varies from 53.2 – 55.41%, 54.22 – 58.53% and 63.9 – 65.78% for CC, CW and CS gasification respectively.

The range of combustibles and inerts observed from other researchers Krushna Patil et al. [21], Chawdhury and Mahkamov [22], Panwar et al. [23], Chao Gai et al. [25], Sang Jun Yoon et al. [26], Venkat et al. [27] and Dogru et al. [28] are in close agreement with the findings from CC, CW and CS gasification.

HHV of Producer Gas Vs ER

Figure 10 depicts the effect of ER on HHV of gas generated in the gasification. HHV of gas obtained from CC, CW & CS gasification increases up to best operating point and recedes thereafter, owing to increase in combustibles up to best operating point with increase in ER. HHV of gas obtained for CC, CW & CS gasification at its best operating point is 4.58 MJm^{-3}, 4.81 MJm^{-3} & 4.23 MJm^{-3} respectively. The lower value of HHV of gas generated upon the gasification of CS compared to CC & CW is due to the lower % of H_2 & CH_4 in spite of higher % of CO. Albeit energy content of H_2 & CO is almost equal, CH_4 contributes almost thrice that of CO. Lower presence of CH_4 in CS gasification, in comparison with CC & CW, leads to the lower HHV of gas.

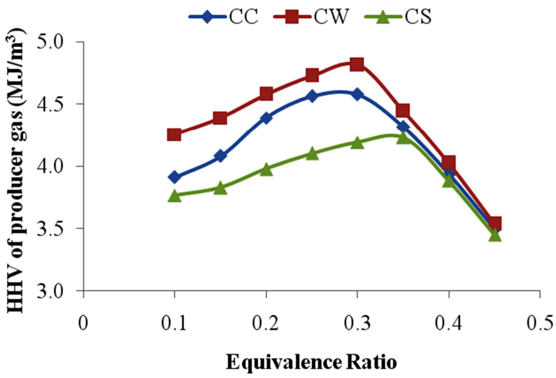

Figure 10 HHV of producer gas Vs ER

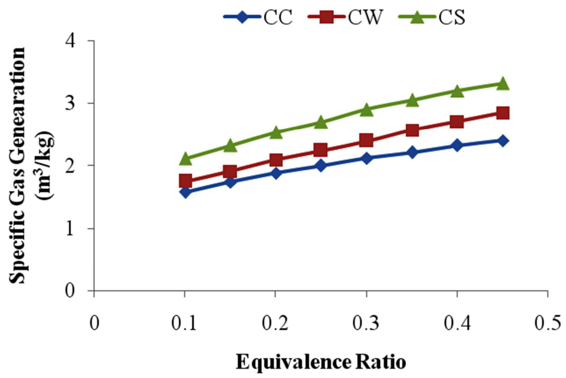

Figure 11 Specific Gas Generation Vs ER

Panwar et al. [23] reported that the of HHV of producer gas obtained during the gasification of babul wood ranges between 4.27 MJm^{-3} and 5.07 MJm^{-3}. Sang Jun Yoon et al. [26] estimated the HHV of producer gas as 4.54 MJm^{-3} and 5.5 MJm^{-3} for gasification of rice husk and rice husk pellets respectively.

Specific Gas Generation Vs ER

SGG (m^3 of gas/kg of fuel) is the key performance indicator for gasifier. Figure 11 reveals the effect of ER on SGG. SGG increases with increase in ER for all fuels. SGG for CC, CW & CS is in ascending trend at any ER. It might be due to its higher surface area, increase in reactivity due to increased carbon content and higher gasification temperature.

SGG estimated upon gasification of different fuels by other researchers ranges between 1.5 m^3/kg (Krushna Patil et al. [21]) & 4.18 m^3/kg (Venkat et al. [27]) and the SGG observed during the present research for all the feedstock is observed to be within the range reported.

Gasification Efficiency Vs Equivalence Ratio

Cold gas efficiency is the effectiveness with which gasifier is able to convert solid fuel into a burnable gas. Hot gas efficiency includes sensible heat available in producer gas. Cold gas efficiency is influenced by SGG & HHV of gas. Hence for better conversion efficiency gasifier is to be operated in the range where SGG is optimum with maximum HHV of gas.

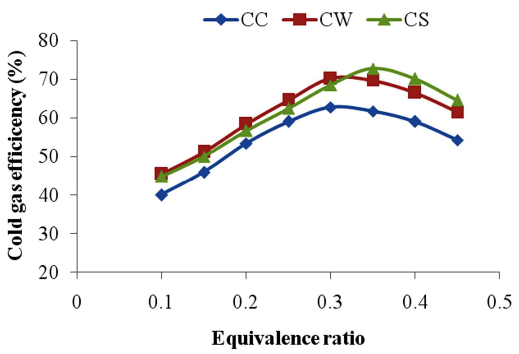

Figure 12 Variation of cold gas efficiency

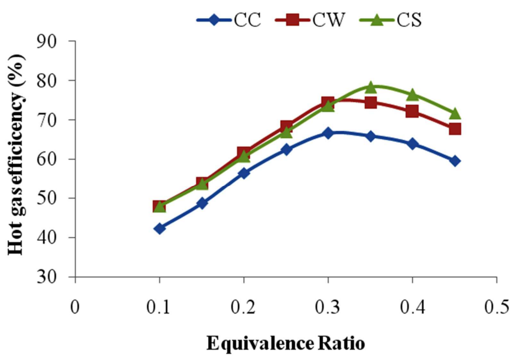

Figure 13 Variation of hot gas efficiency

Figure 12 & 13 depict variation of cold gas efficiency & hot gas efficiency with respect to ER for CC, CW and CS gasification. Both efficiencies increase up to the best operating point and recedes thereafter. The rise in % combustibles with increase in ER up to the best operating point results in increase in both efficiencies. Both efficiencies for CC, CW & CS gasification is in ascending trend at its best operating point, which might be due to the increase in SGG. Though the SGG is at higher side, the HHV of producer gas generated through CS gasification is lower than CW gasification. Hence, both efficiencies of CS gasification – coincide with CW at the ER 0.1 – 0.15 and 0.1 – 0.2 respectively – is lesser than CW at ER 0.2 – 0.35.

Chao Gai et al. [25] reported that gasification efficiency for non woody biomass (corn straw) varies from 21.17% to 73.61 %. Venkat et al. [27] reported cold gas efficiency of 72% for cashew nut shell char gasification. Carlos R Altafini et al. [32] reported cold gas efficiency of 62.86% for saw dust gasification.

Tar and Particulates Vs ER

Quantification of tar & particulate matter is a laborious process requiring a considerable amount of time. Hence, it was decided to ascertain the tar & particulate matter at the best gasification condition. i.e., at an ER of 0.3 for CC, CW and 0.35 for CS. Producer gas was sampled for quantifying tar & particulate matter at the exit of gasifier but prior to cyclone separator. The sampling & analysis set up was fabricated as per international guidelines [20].

Figure 14 depicts comparison on tar & particulates in a producer gas generated during the gasification of CC, CW & CS. Tar of 0.81 gm^{-3}, 1.3 gm^{-3} & 0.62 gm^{-3} and particulates of 0.355 gm^{-3}, 0.158 gm^{-3} & 0.215 gm^{-3} are estimated for CC, CW & CS gasification respectively. Owing to lower volatile matter content & higher temperature at throat zone (due to higher carbon content) leading to effective tar cracking, tar content of producer gas from CS gasification is observed as 0.75 times of CC gas & half of CW gas. Particulate matter in producer gas from CC gasification is about 2.25 times higher than CW gas & 1.65 times higher than CS gas. This could probably be due to the lower bulk density & ease of crumbling characteristics of CC. Galindo et al. [33] reported 1.27 gm^{-3} tar & 0.217 gm^{-3} particulates for eucalyptus wood gasification. Tar for woodchips & pine pellets gasification were reported as 1.63 gm^{-3} & 0.85 gm^{-3} respectively [34].

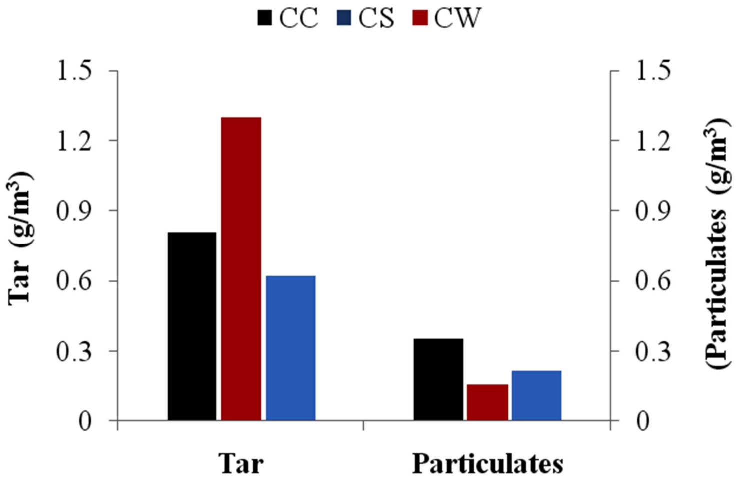

Figure 14 Tar and Particulates Vs ER

CONCLUSION

A 6 kW$_e$ downdraft gasifier had been used to study & compare the gasification of CC, CW and CS with air as gasifying medium. Gas composition, HHV of gas, SGG and gasifier efficiency were studied by varying ER from 0.1 to 0.45. From the studies, it is found that CO_2/CO ratio of the gas was least at ER = 0.3 for CC (0.907) & CW (0.655) and ER = 0.35 for CS (0.225). The lowest value of CO_2/CO coincides with the best operating point (ER of 0.30 for CC & CW and ER of 0.35 for CS) for attaining highest efficiency. The results of gasification at its best operating point for all the feedstocks are tabulated below.

Parameter	Corn Cob	Casuarina Wood	Coconut Shell
ER (Best Operating Point)	0.3	0.3	0.35
H_2 (% by volume)	15.5	14.55	12.5
CO (% by volume)	15.43	16.51	18.2
CO_2 (% by volume)	14	10.81	4.1
CH_4 (% by volume)	1.6	2.15	0.8
CO_2/CO	0.907	0.655	0.225
HHV (MJ/m^3)	4.58	4.81	4.23
SGG (m^{3}kg^{-1})	2.12	2.39	3.05
η_{Cold} (%)	62.83	70.18	72.74
η_{Hot} (%)	66.6	74.48	78.37
Tar (m^{3}kg^{-1})	0.81	1.3	0.62
Particulates (m^{3}kg^{-1})	0.355	0.158	0.215

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