Proceedings of the World Congress on Engineering 2014 Vol II,
WCE 2014, July 2 - 4, 2014, London, U.K.

Experimental Studies on Thermal Behavior of Downdraft Gasifier

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Abstract—The present work is an attempt to study the thermal behaviour of an existing $5\,kW_e$ downdraft biomass gasifier (DBG) unit with different equivalence ratios (ER) . Karanj wood was used to generate the producer gas from the gasifier unit. ERs of 0 .19, 0.21, 0.29 and 0.32 were used for the present investigation. Studies were conducted to see the thermal performance of digester by measuring the temperature in various zones of DBG. Volume flow rate of producer gas and tar content were measured for all aforementioned ERs. It was observed that gasification process was best with ER 0.32 in terms of highest yield of gas and lowest tar content. This study will lead to improve the design of existing gasification process.

Keywords:* *Biomass, Downdraft gasifier, Equivalence ratio, Tar, Producer gas

I. INTRODUCTION

The world is presently facing with the twin crises of fossil fuel depletion and environmental degradation. Random extraction and abundant consumption of fossil fuel is resulting in depletion of underground reserve of carbon resources. According to an estimate, the petroleum reserve will last for 218 years for coal, 41 years for oil, and 63 years for natural gas, under a business-as-usual scenario [1]. Moreover, the price of crude oil is monotonically increasing for last few decades. The adverse affect of use of fossil fuel is the liberation of billion tons of carbon dioxide rendering increase in pollution and stimulating the green house effect. Thus there is a need for alternative source of energy to meet the sustainable power generation along with reduction of green house gas emission. Use of biomass is a promising fuel to meet such demands. The biomass gasification is a promising energy-efficient technology that can contribute significantly to renewable energy generation.

Biomass undergoes thermo-chemical conversion to generate product gas. The conversion takes place at the gasifier. Complete combustion of biomass produces water vapor, carbon dioxide and surplus of oxygen. Thermo-chemical conversion of biomass with sub-stoichiometric air generates carbon monoxide, hydrogen and traces of methane and non-useful products like tar and dust [2].

Manuscript received March 15, 2014; revised March 31, 2014.

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The main purpose of biomass gasification is the production of low- or medium heating value gas which can be used as fuel gas in an internal combustion engine for power production [3]. A large amount of surplus crop residue is either burnt due to unavailability of space or remains underutilized due to various reasons. This crop residue can be utilized for power generation through gasification at a higher efficiency [4]. The negative price of waste materials provides the financial incentive for biomass gasification [5]. The conversion of biomass through thermo chemical conversion path helps to protect environment and ecology as well [6, 9]. Gasification is still in a stage of variation and there has been no dominant design yet. In most markets it is unable to compete with other technologies. [7].

In the present study, gasification experiments are carried out with karanj wood as a biomass material in the down draft biomass gasifier (DBG). The purpose of the study is to evaluate the performance of the gasifier for the various equivalence ratios (ER). This study gives a thorough analysis of thermal behavior of various zones along the DBG. Present study will be helpful in designing and improving DBG.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. Experimental Setup

The downdraft gasifier used for present experiment is shown in Fig 1. The gasifier is coupled to an electric generator with a generating capacity of $5\,kW_e$ (electric power). It consists of four parts: (1) inverted cone frustum shape hopper, (2) cylindrical shape reaction chamber, (3) conical shape ash chamber and (4) gas cleaning system.

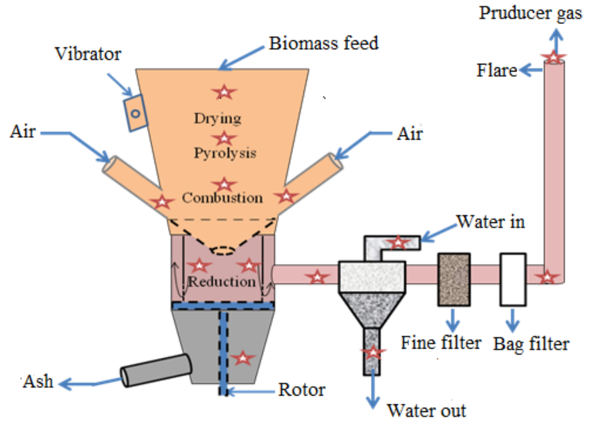

Fig. 1 Downdraft biomass Gasifier

The gasifier is divided into six zones starting from the top as (a) drying zone-I, (b) drying zone-II, (c) pre-pyrolysis zone (d) pyrolysis zone, (e) combustion zone and the reaction chamber considered as sixth zone (f) reduction zone.

ISBN: 978-988-19253-5-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

The gas outlet at bottom (from the reduction zone) is connected with the various downstream systems e.g. venturi scrubber, cyclone separator, coarse filter, fine filter and a flare with valve. Gas produced in the reaction chamber is scrubbed and cooled in scrubber. The water is recirculated from water tank to the scrubber with the help of scrubber pump. Gas is separated from water in a cyclone separator connected to the scrubber and same goes to the filtration units (coarse and fine filters connected in series). Cool and clean producer gas is then available at the flare for utilization.

The height of the gasifier is 1860 mm. The diameter at the pyrolysis zone is 440 mm and the diameter at the reduction zone is 346 mm. The height of the reduction zone is 330 mm and that of oxidation zone is approximately 256 mm. The ash produced during gasification is removed by rotating the rotor inside the reaction chamber. The arrangement is provided to unclog the biomass.

To know the thermal behavior of the gasifier, 17 thermocouples are placed inside the gasifier at various locations along the radial as well as vertical directions. The K type thermocouples (Chromel –Alumel) are used to observe the thermal behaviour of gasification. Table I shows the location of the thermocouple at various positions, its distance from the top of the hopper and diameter of locating zone.

TABLE I.
THERMOCOUPLE AT VARIOUS LOCATIONS

Location	Number of thermocouples	Distance from top of the hopper (mm)	Diameter of the zone (mm)
Drying zone-I	4	309	656
Drying zone-II	4	547	536
Pre-pyrolysis zone	3	679	440
Pyrolysis zone	2	804	392
Combustion zone	2	894	300
Reduction zone	2	1219	346

B. Experimental Procedure

The gasifier was instrumented with the thermocouples, airflow meter and manometers. Manometer and airflow readings were taken by manual measurements while temperature records were collected through a data acquisition system (Agilent make) connected to a computer and thermocouples.

Before starting the experiments, the reaction chamber was filled with 5kg of charcoal. Subsequently the hopper was mounted over the reaction chamber. The hopper was fed with 85 kg of biomass through the feed door at the top. The feed door was closed after loading the solid biomass. Saw dust was added to the fine filter container after several rounds of manual stirring. The main MCB (Isolator) Switch as well as control panel were switched on. Simultaneously, the pump switch was turned on from the control panel and the flare valve was slightly opened. Controlled amount of air was allowed to enter into the reaction chamber through air nozzles. The biomass in the gasifier was ignited by bringing diesel/oil dipped lighted torch onto the two air nozzles one after another, so that flame is sucked into the combustion chamber. Gas production was detected at the flare by burning with a kindler. It was observed that medium heating value gas was generated within 5 minutes from the start of the gasification process.

Heat generated in the combustion chamber propagates to the pyrolysis and drying zone and biomass starts releasing volatiles and convert to char which drops down to the reduction chamber. Special ash handling mechanism was provided at the bottom of the reduction zone so that no clinkers can form.

III. RESULTS AND DISCUSSION

A. Characterization of Biomass

In the present study wood from Karanj tree sized with an electric cutter were used to generate producer gas. The wood pieces of 25 mm diameter and 20 mm length (approx) were used for the gasification. The ultimate analysis for the composition of carbon (C), hydrogen (H), nitrogen (N) and sulphur (S), was carried out using Euro EA Elemental Analyzer [ASTM standard D 5373-02 (2003) method] . The calorific value of wood was determined by using bomb calorimeter. Proximate analysis were also conducted as per ASTM standard D5373-02 (2003) to evaluate the percentages of volatile matter (VM) content, ash content, fixed carbon and moisture content [ASAES 269-4 (2003)] in wood samples. Table-II presents the ultimate and proximate analysis of the wood samples.

TABLE II.
ULTIMATE AND PROXIMATE ANALYSIS OF KARANJ
(% BY WEIGHT DRY BASIS)

Ultimate analysis		Proximate analysis	
N (%)	4.462	Moisture (%)	13.40
C (%)	44.547	Volatile matter (%)	82.47
H (%)	8.872	Ash content (%)	1.26
S (%)	-----	Fixed carbon (%)	16.27
Ash (%)	1	Heating value (MJ/kg)	18.52
O (%)	41.119		

B. Thermal Behavior of The Downdraft Gasifier

In the present work the thermal behavior of the gasifier was studied with variation of equivalent ratio (ER). Equivalent ratio(ER) is defined as ratio of (actual air flow rate to biomass flow rate) to the (stoichiometric air flow rate to biomass flow rate) [8]

$$ER = \frac{A/F_{actual}}{A/F_{stoichiometric}} \qquad (1)$$

ER was varied in the range of 0.19-0.32 during the experiments. The thermal behavior of the gasifier was evaluated for the continuous operation of 8 hrs. Figures 2-5 present the same for the various ER. In all these figures the variation of temperature with operation time for different zones (Table-III) are presented. Transient behavior for all the zones was observed during the first 2 hours of operation. Similar behavior was observed for the pre-pyrolysis zone till 90^0C. The temperature in the combustion zone drastically increases from ambient temperature to 800^0C - 1000^0C for all the cases. Afterward it slightly decreases and then for some hours it remains stable. As the combustion is a spontaneous reaction, some fluctuations were observed during the combustion in all the cases. The pyrolysis zone behaves transiently from ambient temperature to 208^0C .

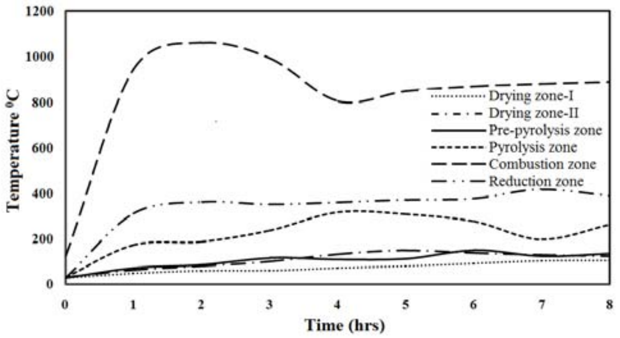

Fig 2. Thermal behaviour of gasifier along vertical axis for ER 0.19

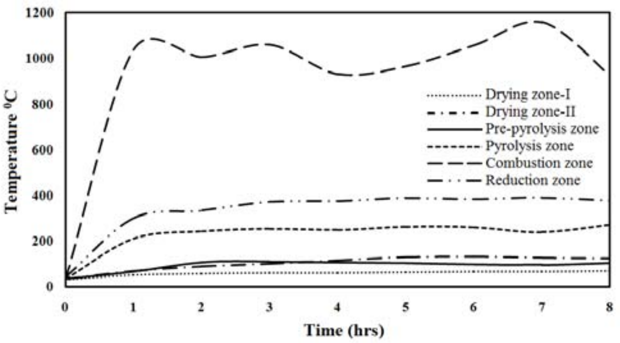

Fig 3. Thermal behaviour of gasifier along vertical axis for ER 0.21

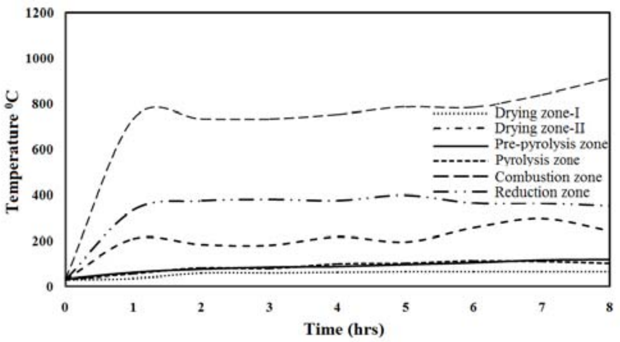

Fig 4. Thermal behaviour of gasifier along vertical axis for ER 0.29

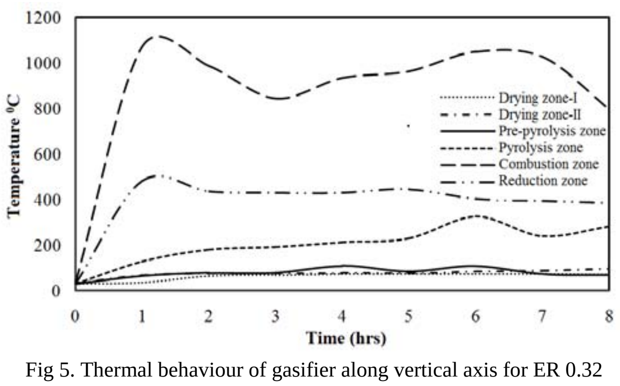

Fig 5. Thermal behaviour of gasifier along vertical axis for ER 0.32

The transient behavior of the reduction zone is observed from ambient temperature to 423 ^{0}C. Initially the temperature in the reduction zone increases rapidly during the first hour of operation and subsequently becomes stable.

The heat generated during the combustion dissipated to the pyrolysis and drying zone as well as towards the reaction zone. The pyrolysis of the biomass starts in pre-pyrolysis zone. Pyrolysis is the process of braking of the bonds in presence of the heat only. The VM, charcoal, producer gas and tar are liberated during the pyrolysis. As these matters passes from the combustion zone towards the reaction chamber, same will be influenced by the high heat release from the pyrolysis zone converting the tar into lower carbon. The heat release from pyrolysis zone reaches to the drying zone removing the moisture from the biomass. High heat content moisture may lead to water gas reaction in the reactor. If there is more moisture in the biomass then it results into the condensation of the tar. The tar is a higher hydrocarbon and sticky in nature which causes the problem in combustion in engine. In the reaction chamber the reduction reaction taking place. The reduction process is endothermic reaction. The product gas produced is then forwarded to the gas cleaning system.

Figures 2-5 represents the behavior of the gasifier at ER of 0.19, 0.21, 0.29 and 032, respectively. In Fig. 2, the temperature in drying zone-I is observed to be 70 ^{0}C while in drying zone-II, pre-pyrolysis zone, pyrolysis zone, combustion zone and reduction zone the same are observed to be 112 ^{0}C, 122 ^{0}C, 262 ^{0}C, 890^{0}C and 389^{0}C respectively. Similarly, temperatures as well as volume of gas production at different ER are given in Table –III.

TABLE III.
THERMAL BEHAVIOR OF GASIFIER AT VARIOUS ER FOR TEMPERATURE AND GAS FLOW RATE

ER	0.19	0.21	0.29	0.32
Producer gas flow rate (m^3/hr)	1.87	2.17	2.26	2.35
Location	(Temperature ^{0}C)			
Drying zone-I	70	62	72	63
Drying zone -II	112	128	117	94
Pre-pyrolysis zone	122	104	111	107
Pyrolysis zone	262	260	240	282
Combustion zone	890	923	913	800
Reduction Zone	389	378	364	385

From Table-III it is observed that gas production increases with increase in ER. Moreover, oxides of nitrogen production decrease with increase in ER.

C. Tar Content at Various Locations in Gasification Experiment

Formation of tar with producer gas was studied with different ER. Tar was collected from the various locations of the gasifier unit such as (1) end of cyclone separator (2) cooling water tank, (3) fine filter and (4) bag filters. Tar content at the identified locations in gasification unit with various ER is given in Table-IV. From this table it is observed that tar formation is lowest at ER=0.32. As ER decreases the same is observed to be increased.

TABLE IV.
TAR CONTENT AT DIFFERENT EQUIVALENT RATIO AT VARIOUS LOCATIONS OF GASIFIER UNIT

ER	0.19	0.21	0.29	0.32
Location	Tar Content (gm)			
Water container	83.49	68.76	53.13	46.24
Water Tank	170.40	154.89	131.37	126.88
Fine filter	64.83	57.14	47.29	32.57
Bag filter)	0.08	0.068	0.063	0.047
Total	318.79	280.85	231.86	205.73

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IV. CONCLUSION

In the present experiment thermal behaviour of the downdraft gasifier was studied for the various equivalence ratios, such as 0.19, 0.21, 0.29 and 0.32. Wood pieces of size 25 mm diameters and 20 mm length are used for the gasification. The yield of producer gas is observed to be increased with increase in equivalence ratio. Tar formation was also found to decrease with increase in equivalent ratio. Thus the optimum equivalence ratio obtained is 0.32. This study will help in improving the gasification process in down draft gasifier.

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