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Biomass gasification for energy generation: parametric investigation on continuous updraft Gasifier

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Abstract Biomass has gained inevitable importance as a distributed source of energy after coal, oil and natural gas. The gasification is one of the cleaner technology to convert biomass into environmental friendly gaseous fuel. An updraft gasifier was designed and experiments were carried out using mustard seed(s) as feed. It was observed that the temperature distribution improved using circulation. The temperature achieved lied in the range of 600^{o}C-800^{o}C with and without circulation. Increasing the temperature from 400^{o}C- 800^{o}C and equivalence ratio (ER) from 0.15-0.3, increases the amount of H_2/CO from 0.29-2.67; whereas in the case of circulation it decreases from 0.65-0.41. The CO_2 produced is 70% with circulation and 50% without circulation. Increasing temperature reduces the fluctuating amount of NO_x from 1976 ppm to573 ppm under normal conditions. While SO_2 is 229 ppm without circulation and is almost zero for circulation. At the optimum ER value of 0.23, maximum value of lower heating value (LHV) and higher heating value (HHV) without circulation were observed to be 7743 Btu/lb and 8995 Btu/lb respectively while 3801 Btu/lb and 4397 Btu/lb with circulation.

Keywords: Biomass, Gasification, Temperature, Gas Composition

1. Introduction

There has been a surge of interest in renewable sources of energy because of the diminishing reserves of fossil fuels over time and also because of the environmental damages attached to it i.e. global warming and the greenhouse effect. Biomass is a resource containing the same kind of structure as fossil fuels and is environmentally friendly. Consensus has been developed in the recent Paris Climate Summit to ensure the reduction in greenhouse emissions [1]. Pakistan is a country which produces an abundant amount of biomass annually which has been neglected in the past for energy production. Owing to increase in the gap between supply and demand in energy section, there is a strict need to focus on sources which could fulfil the energy needs and yet be environmentally friendly. Biomass as a renewable source of energy, has significant environmental benefits, which include low emissions of carbon dioxide and other harmful substances [2].

Several attempts have been made for the production of energy using biomass via gasification. Biomass gasification has been proved to be a clean and efficient way of producing hydrogen. It is a well-known technology which can be classified based on gasifying agents i.e. air, steam, oxygen enriched air, oxygen and so on. [3]. Different biomass gasification reactor types have been developed and classified into three categories: fixed bed [4], fluidized bed [5] and moveable bed [6]. Different gasifiers have been used by many researchers in gasification using biomass as a raw material [7]. Zainal et al. [8] studied the gasification process using a downdraft fixed bed gasifier. They investigated the effect of air/fuel ratio on gas composition, calorific value and production rate. Rao et al. [9] studied the mass and energy balances in an updraft fixed bed gasifier. Mendis et al. [10] calculated the operational difficulties of the gasifiers and provided field monitoring results including gasifier performance characteristics during biomass gasification. Kureka et al. [11] have developed an updraft fixed bed gasifier for gasification of peat and biomass. Some researchers [12, 13] studied the detailed mass and energy balance studies of a downdraft gasifier, which is useful in designing more energy efficient gasification systems by reducing the inefficiencies in the existing systems. Wang et al. [14] performed experiments on two stage gasification at pilot scale and concluded that oxygen had higher impact on the composition of H_2 and CO. Further they established that the efficiency of carbon can reach 80% and syngas pertaining 70% of H_2+CO. H_2/CO resulting 1 is only possible if 99.5% of oxygen is provided.

Wang et al. [15] investigated the effect of air distribution of an agriculture updraft gasifier. They noticed the higher temperature of about 950^{o}C-1100^{o}C. They also determined that the composition of gases i.e. CO, H_2 and CH_4 increases along the height while CO_2 shows the peak value at the top of gasifier. Fernando et al. [16] developed a CFD model for an updraft gasifier and used that model to find out the optimum amount of air flow required for maximum production of CO. They discovered that the 7m^3/hr of air flow maximizes the production amount of CO which they found to be 6.4m^3 for a batch of 28kg Gliricidia.

Kihedu et al. [17] performed experimentation on auto-thermal updraft gasifier incorporating air and steam mixture and discovered that carbon conversion increased to about 91.5% which they observed to be 84.3% in case of air gasification.

Gunarathne et al. [18] found out the gasification characteristics of pre- treated biomass with steam explosion in an updraft gasifier and established that pretreated pallets gave high amount of CO while untreated pallets gave high amount of H_2. LHV was found to be high i.e. 7.3MJ/Nm^3 and 10.6MJ/NM^3 for air and steam gasification while tar content was found more in the pretreated biomass they found because of the presence of more phenolic compounds. On the other hand, Couto et al. [19] studied the influence of biomass gasification processes on the final composition of gas. The study showed that there are some discrepancies in the values given by various authors which highlighted the strong dependence of the syngas final composition from biomass conditions, type of gasifier, pressure and temperature of the process. They presented that in order to make precise studies on the use of syngas it will be necessary to consider that its composition will be rather constant.

Toshiaki et al. [20] studied the gasification of an aquatic biomass with He/CO_2/O_2, the effects of the concentration of CO_2 and O_2 in the gasifying agent and the feeding rate on the gasification behaviour using downdraft fixed bed gasifier at 900^{o}C. Using CO_2/O_2 as the gasifying agent led to an increase in the conversion to gas and to syngas content because the gasification of char with CO_2 and decomposition of tarry compounds were promoted.

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Kuo et al. [21] studied the gasification performances of three biomass materials, including raw bamboo, torrefied bamboo at 250°C and torrefied bamboo at 300°C in a downdraft fixed bed gasifier through thermodynamic analysis. The cold gas efficiency and carbon conversion were adopted as the indicators to examine the gasification performances.

Arnavat et al. [22] developed a simple but rigorous tri-generation plant model for designing, optimizing and simulating small-medium scale plants including realistic biomass gasification model. They demonstrated that the presented model is a useful tool for assessing the performance of tri-generation plants using several types of biomass and enables meaningful comparisons to be made between configurations for real applications. However, there is still needed to study the effects of different parameters on gasification process in an updraft gasifier.

Therefore, a continuous updraft gasifier has been designed and the experimental runs are done. This study focuses on the operational parameters: specifically, temperature, equivalence ratio and its effects on other variables i.e. gas composition, H_2/CO ratio and temperature profile with time.

2. Materials and Methods

Figure 1 shows the process description and parameters involved in the experimental process. The experiments have been made in the bench scale facility. It is new, and has been 100%custom made. This installation is based on an updraft gasifier with a biomass throughput of ½ kg/hr. The material of construction is stainless steel with gasification part meter 4.026 in. and gas phase diameter 6.065in. The height of the gasifier is 1.72ft. It is a low value, but higher superficial gas velocities of oxygen might not be fed to the gasifier because of its small height. The gasification agent is oxygen, but steam or air can also be used.

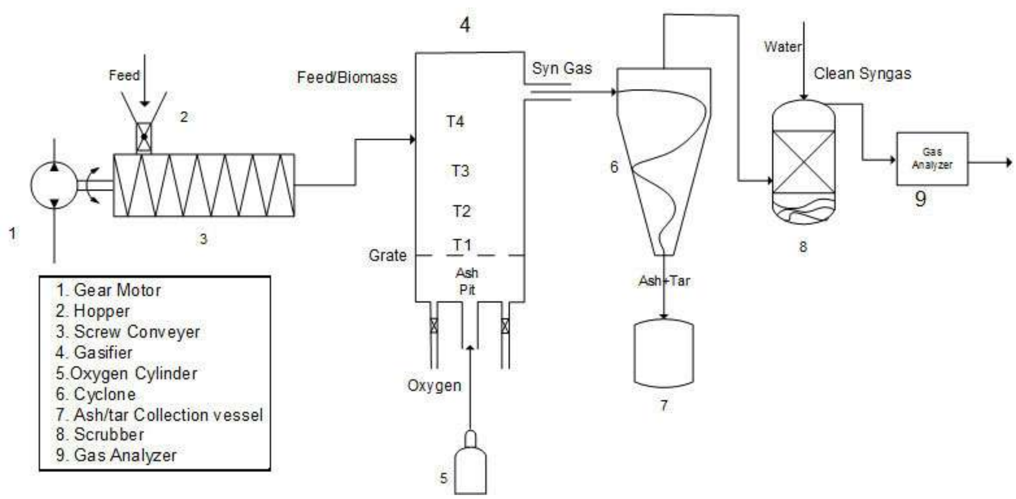

Figure 1 Flow diagram for Gasification Process

The biomass feed is entered from a cuboid shaped hopper where it falls down gravimetrically to the screw conveyor. In between a valve is used to control the amount of biomass entering. After passing thorough the valve, the feed enters into the screw conveyor which is controlled by a motor's on off mechanism to control the flow rate of feeding biomass. The screw conveyor conveys the feed to the reactor consisting of 5 zones named drying, pyrolysis, reduction, oxidation and ash collection zone. After the reactions have occurred produced ash is collected in ash collection zone at the bottom of the gasifier. Produced gas is sent to the cyclone for the removal of impurities and then to the scrubber for further purity. Finally, it is sent to the gas analyzer for the amount of gases produced and sent for collection/usage.

2.1 Gasifier Design

Figure 1 (unit 4) shows the continuous type, fixed bed updraft gasifier operated on counter current profile. Fixed bed gasifier, is a vertical cylindrical reactor, which consists of the following sections: gas phase part, bed part, feedstock section/gasification part, grate, ash collection part and gas outlet. The feed coming from the feeding system falls into the gasifier. After the reaction, the gas formed goes into the top part i.e. gas phase part and is collected from the top. The char bed is formed because of pyrolysis which is the main step in the gasification process. In the end ash formed passing through the grate finally goes into the ash collecting zone where it is collected. The dome shaped upper part of the gasifier is called gas phase part which is 6.625-inch external diameter and 6.065-inch internal diameter where all the gases accumulate and are collected from the top with the extension of 1 inch stainless steel pipe. The mid part of the gasifier is the main part of the gasifier where all the reactions occurs also called bed part. The main reaction of gasification like oxidation, reduction and pyrolysis takes place in this zone. It is the shape of vertical from top to bottom direction. A pipe of stainless steel schedule 40 with 4.026-inch internal diameter and 4.500-inch external diameter is used for the reaction vessel. The grate was made of 10mm thick mild steel. The figure 1 unit 4 shows the selected grate. A highly perforated grate solution with 5mm hole size diameter is developed. The fourth part of the gasifier is ash collection unit which is also specially designed for this experiment. Two handle valves are attached to the ash collection unit. One for the ash collection and second for the air entrance if needed in future whilst we are focusing on oxygen as a gasifying agent in this work. The tee is attached at the gas outlet where 2-inch pipe is attached for gas collection and then another 1 inch pipe is attached with that 2-inch pipe giving it to the generator. Other two ½ inch handle valves are attached at the lid of the gasifier for the extra gas collection points if needed for other purposes. Thermocouples are used for temperature profile measurement. Temperatures were measured via thermocouples- Type K thermocouples were placed at several points in the gasifier shown in figure 1(unit 4) which indicates the vertical profile of the gasifier with respect to temperature. The assumption was made that the temperature gradient remains constant horizontally providing constant profile along the cross section.

2.2 Gasification Methodology

The gasification of the biomass has been done at around 750-850^oC to get the optimum result. The process was done with and without circulation of gases. The experimental protocol involves three stages:

1. Reaching up to 500^oC using oxygen/fuel in the torch.
2. Biomass is introduced inside the gasifier. The feeding rate of the biomass is predetermined.
3. Feeding system is controlled electronically using on and off mechanism.

The feeding rate is controlled by the motor speed i.e. the feeding rate is 1/2kg/hr. Furthermore, in order to calculate the % syngas, measurements are done by E-Instruments E8500 gas analyzer. As the temperature is very high so safety precaution must be taken in consideration among the people participating in the process.

2.3 Feeder Calibration

It is imperative to calibrate the devices before the start of experiment because it can affect the results. The initial feeding rate was kept to be ½ kg/hr with the purpose of calibration number of trials were conducted. The feeding rate was controlled by pulsing the motor using on and off mechanism in accordance with the required feeding rate.

Table 1 Calibration of Feeder

Feed	Mustard Seed (Brassica Juncea)
Particle Size	1.23mm
No. of revolutions per minute	8
Feed per revolution	43g
Feed per minute	345g

2.4 Proximate Analysis

The approach and methods used to determine individual properties are described in the following sections.

2.4.1 Moisture Content

The moisture content in the sample was determined according to BS EN 1477-3:2009 standard [23]. Three ceramic dishes with lids were pre-conditioned to remove moisture by heating at 105°C for 2 hours in a drying oven and then cooled to room temperature in a desiccator. After cooling, the dishes and their lids were weighed. After weighing the dishes, a minimum fuel sample of 1g weighed was spread evenly over the respective dishes and heated in the drying oven at 105°C for 2 hours. Before removing the samples from the drying oven, the lids were replaced and the assemblies transferred to the desiccators for cooling to room temperature. The moisture content (MC) expressed in percentage was calculated according to equation 2.1

$$MC(\%) = \left(\frac{M2-M3}{M2-M1}\right)*100 \qquad (2.1)$$

where, M_1 is the mass of the empty crucible and lid
M_2 is the mass of crucible and lid and sample before heating
M_3 is the mass of the crucible, lid and residue after heating

2.4.2 Ash Content

Ash content is the measure of mass of the inorganic matter left water ignition of a fuel under standardized conditions [24]. Prior to combustion of the fuel samples, three empty ceramic dishes were preconditioned in the muffle furnace to remove volatile matter by heating to 550°C for 2 hours. After conditioning, the dishes were cooled to room temperature in a desiccator and weighed. Approximately 1g of dried sample was spread over each dish and then heated in the furnace for 550°C for 2 hours to ensure complete combustion. The dishes with residues were then transferred to the desiccators, cooled to room temperature and weighed. The ash content on dry basis was calculated using equation 2.2.

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$$AC(\%) = (\frac{M2-M3}{M2-M1})*100*(\frac{100}{100-Mad}) \qquad (2.2)$$

where, M_1 is the mass of the empty crucible and lid
M_2 is the mass of the crucible, lid and sawdust before heating
M_3 is the mass of the crucible, lid and residue after heating
M_{ad} is the mass fraction of moisture of the general analysis sample on wet basis, as percent

2.4.3 Volatile Matter Content

Volatile matter expresses the mass of the material loss, deducting that due to moisture, when a test sample is subjected to heat in the absence of air under specific conditions. Volatile matter normally consists of various hydrocarbons which affect burning characteristics of the solid carbonaceous fuel such as biomass. In this study the volatile matter was determined according to CEN/TS 15148:2009 [25] standard procedure. Three fused silica crucibles with lids were preconditioned to remove volatiles by heating at 900°C for 7 min. After this time, the crucibles with residues were cooled in the desiccators to room temperature and weighed. The net weight loss of the material was determined was determined by subtracting the loss due to moisture content. The volatile matter (VM) content on dry basis was calculated using equation 2.3.

$$VM(\%) = (\frac{M2-M3}{M2-M1})*(100-M_w)*\frac{100}{100-Mad} \qquad (2.3)$$

where, M_1 is the mass of the empty crucible and lid
M_2 is the mass of the crucible, lid and sawdust before heating, in grams
M_3 is the mass of the crucible, lid and residue after heating
M_w is the mass fraction of moisture in the sawdust as a percentage
M_{ad} is the mass fraction of moisture of the general analysis sample on wet basis as a percentage.

2.4.4 Fixed Carbon Content

The solid residue left after the determination of volatile matter of the wood powder is known as fixed carbon. This type of carbon is linked to the carbon related reactions during gasification process. Increased fixed carbon content in the feedstock can reduce the rate of the fuel conversion in the gasifier reactor where combustion mechanism such as fragmentation and attrition are limited. In this study, fixed carbon was calculated by difference using equation 2.4.

$$FC(\%) = MC (\%) – AC (\%) – Volatiles (\%) \qquad (2.4)$$

3. Results and Discussions

Proximate and Ultimate analysis was done for the Mustard seed and it was found that results were in comparison with the analysis for olive residues by Ollero et al. [29]. Finally, the results were obtained considering the parametric investigation on biomass gasification specifically temperature. All the results were taken at ER 0.23.

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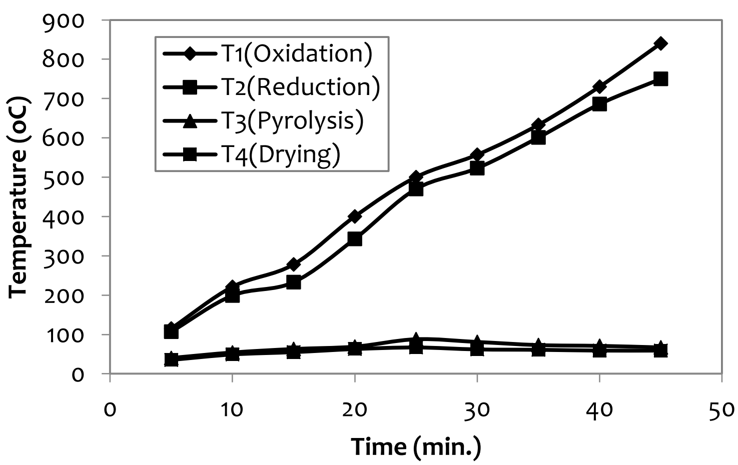
Table 2 Proximate and Ultimate Analysis of Mustard Seed (Brassica Juncea)

Proximate Analysis		Ultimate Analysis	
Moisture Content(%)	7.60	Carbon(%)	41.82
Volatile Matter(%)	62.76	Hydrogen(%)	8.35
Ash Content(%)	3.68	Nitrogen(%)	0.36
Fixed Carbon(%)	25.58	Oxygen(%)	40.55
		Sulphur(%)	0.18

3.1 Temperature Profile of Bed

Figure 2 show the temperature profile of bed as a function of time. T1 and T2 are the temperatures of the oxidation and reduction which increased uniformly with and without circulation. It is found that temperature reduced quickly above the reduction zone (T3 & T4) i.e. 750^{o}C to 60^{o}C as shown in Figure 2 in the absence of circulating conditions which is due to biomass build-up due to continuous feeding from the top. Marcelo et al. [26] studied the same properties using biomass such as bagasse, rice husk, saw dust and elephant grass and achieved about 750^{o}C, while in this study more than 800^{o}C temperature is achieved.



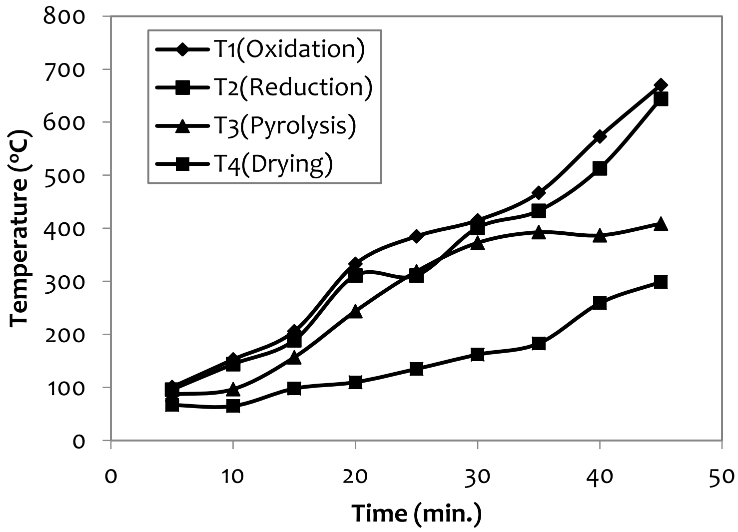
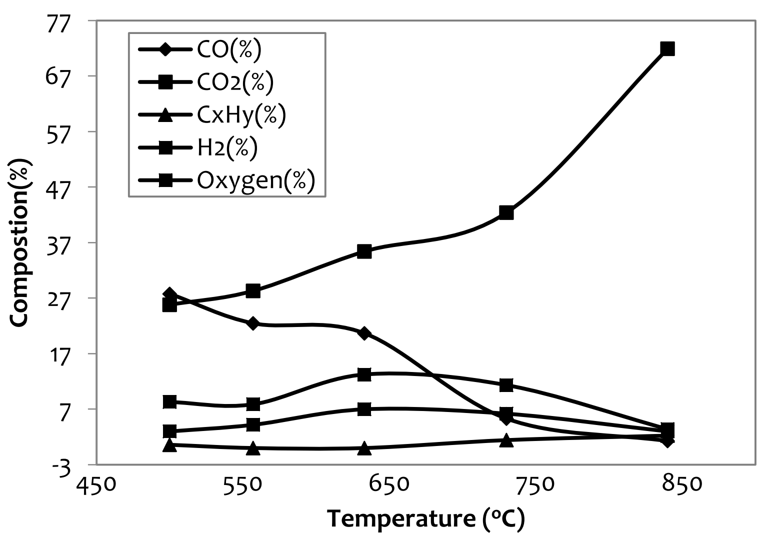


Figure 2 Temperature Profile of bed with time for (a) without circulation (b) with circulation

3.2 Temperature Effect on Gas Composition

Figure 3 shows the effect of temperature on gas composition with and without circulation of gases. The decreasing trend in the amount of CO (27%-3%) is noticed without circulation while increasing trend (9%-15%) is observed with circulation. High temperature moves the trend towards more CO_2 production which is not recommended. The amount of H_2 was noticed to be increasing without circulation up to 14% while the increase is little in case of circulation with the increasing temperature i.e. 6%. The amount of CO_2 is considerably reduced i.e. 72%-50% in case of circulation hence increasing CO content. Ningbo et al. [27] study is in agreement with the present study where low temperatures' effects are comparable without circulation.



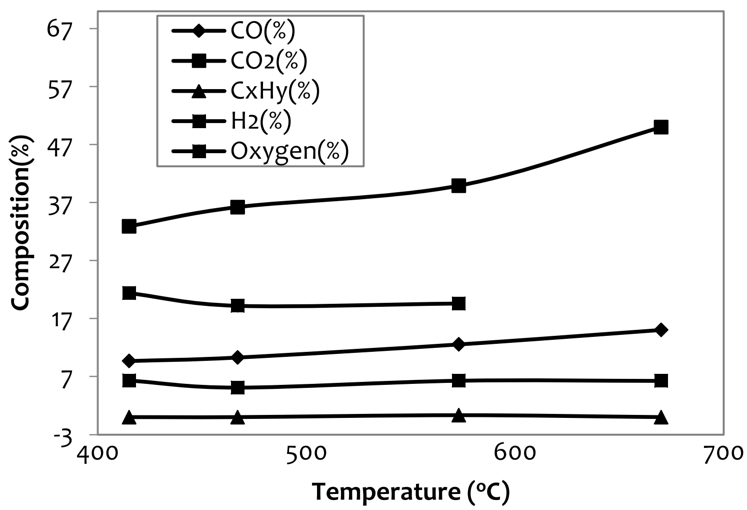
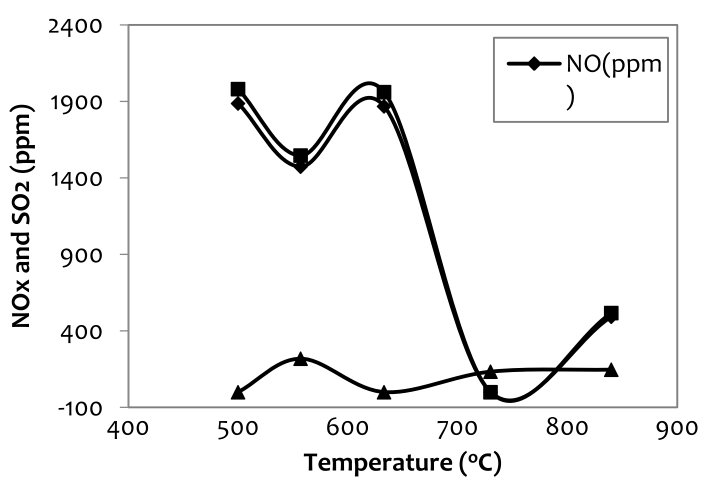


Figure 3 Temperature Effect on Gas Composition for (a) without circulation (b) with circulation

3.3 Temperature Effect on NOx and Sox

The effect of temperature on NO_x and SO_2 with and without circulation is shown in figure 4. NO_x shows the fluctuating trend with the sudden drop after 600 ^oC, which drop from 1960 ppm to 515 ppm. Whereas zero amount of SO_2 is noticed at 670 ^oC. For circulation NO_x shows a little increase till temperature of 590 up to 860ppm whereas SO_2 is almost zero throughout. So, circulation helps removing SO_2 due to the absorption. The biomass used in this study releases very less amount of SO_2 which shows positive trend. Zakir et al. [28] studied the effect of temperature on NO_x and SO_x and found the reducing trend less than 100ppm above 670^oC. In this study, negligible amount of SO_2 is observed.



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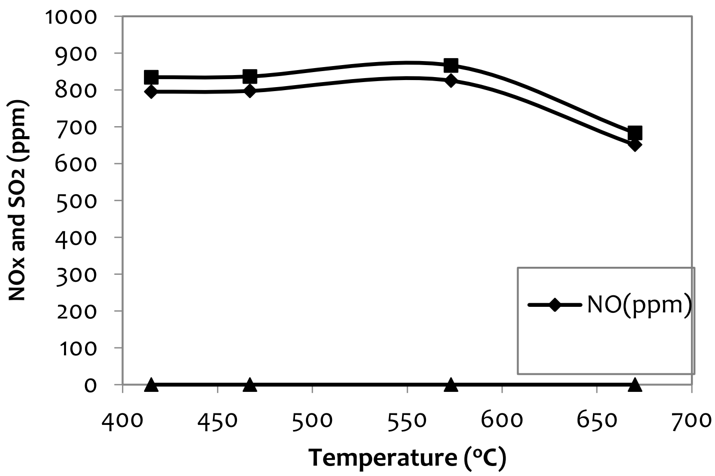

Figure 4 Temperature Effect on NO_x and SO_x for (a) without circulation (b) with circulation

3.4 Temperature Effect on H_2/CO ratio

Temperature has major effects on gasification products. Figure 5 shows the temperature effect on H_2/CO ratio. Ratio increases from 0.3 to 2.6 with the increase of temperature up to 840^{o}C which shows increase in the heating value. While H_2/CO ratio decreases from 0.65 to 0.4 with circulation over the temperature up to 670^{o}C. This indicates that circulation does not favour H_2 production at high temperature while the process without circulation favours H_2 production. Ningbo et al. [27] studied the effect of temperature on H_2/CO ratio and found the maximum value of 2.8 near 950^{o}C without circulation. In this study, same value have been observed around 840^{o}C.

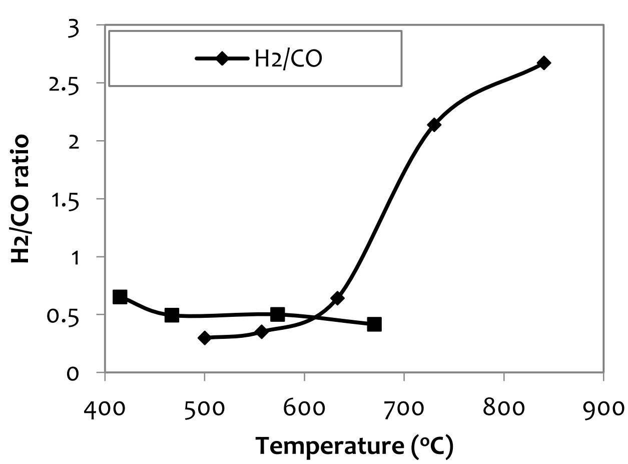

Figure 5 Temperature effect on H_2/CO ratio

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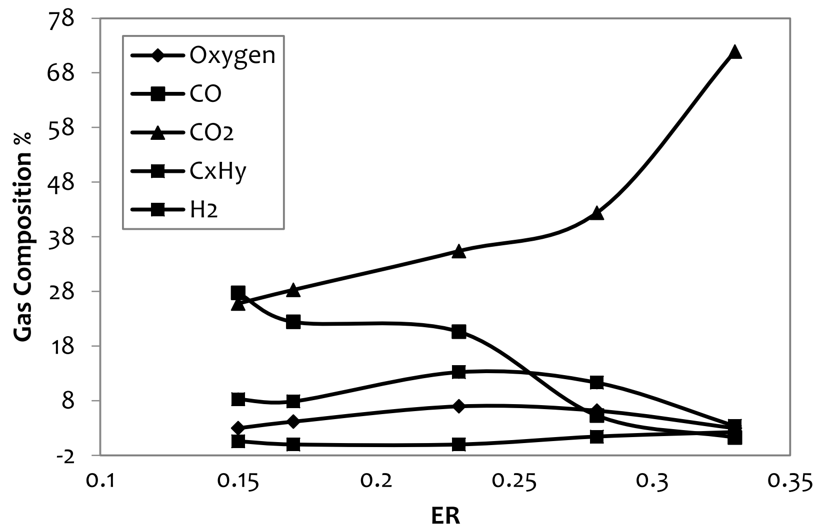
3.5 ER Effect on Gas Composition

The experimentation involving ER parametric study is set in the range between 0.15 to 0.33. Figure 6 shows the effect of ER on gas composition. Maximum amount of CO i.e. 26% is obtained at the ER 0.15 whereas the maximum amount of H_2 i.e. 13% is obtained at 0.23. The amount of CO_2 increases up to 72% with the increase of ER which is due to the presence of high amount entrapped O_2 in the biomass which does participate in the reaction along with the supplied oxygen. Circulation gives more uniformity in trends. It shows the uniform increase in the amount of CO (9%-15%) and H_2 up to 6.3% with increasing ER whereas the maximum amount of CO is noticed at 0.33 and H_2 at 0.23. The amount of CO_2 increased up to 50% uniformly with the increase of ER but it is considerably less than the amount noticed without circulation (70%-50%).



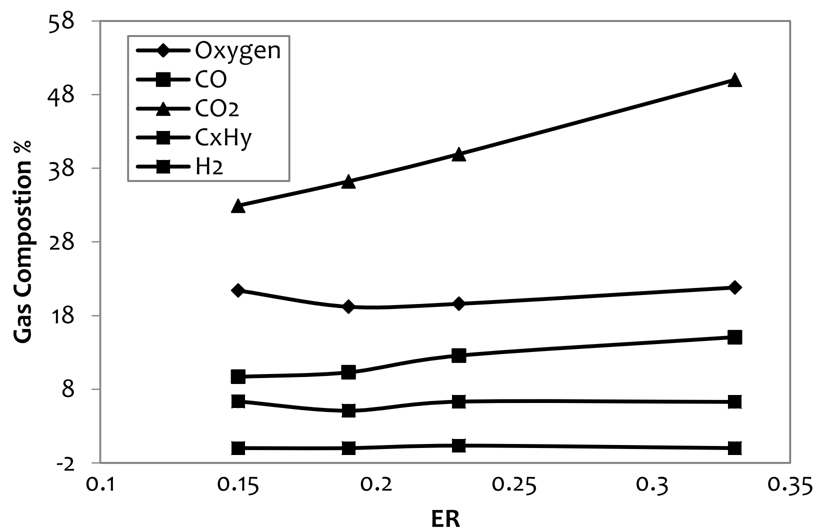


Figure 6. ER Effect on Gas Composition (%) for (a) without circulation (b) with circulation

Ningbo et al. [27] studied the effect of ER on gas composition presenting the maximum about of CO i.e 25 whereas in this study maximum amount of CO is observed to be 25.8 at ER 0.15 which continue to decrease with the increase/decrease of ER.

3.6 Effect of ER on NO_x and SO_2 formation

Effect of ER on NO_x and SO_2 with and without circulation is shown in figure 7. NO_x shows the fluctuating trend with the sudden drop (1960ppm to 517ppm) after ER of 0.23 whereas SO_2 is considerably less zero is noticed at 0.23 without circulation. For circulation, the trend different. NO_x shows a little increase up to 866ppm till ER of 0.26 whereas SO_2 is almost zero throughout. So, circulation helps removing SO_2 due to the absorption.

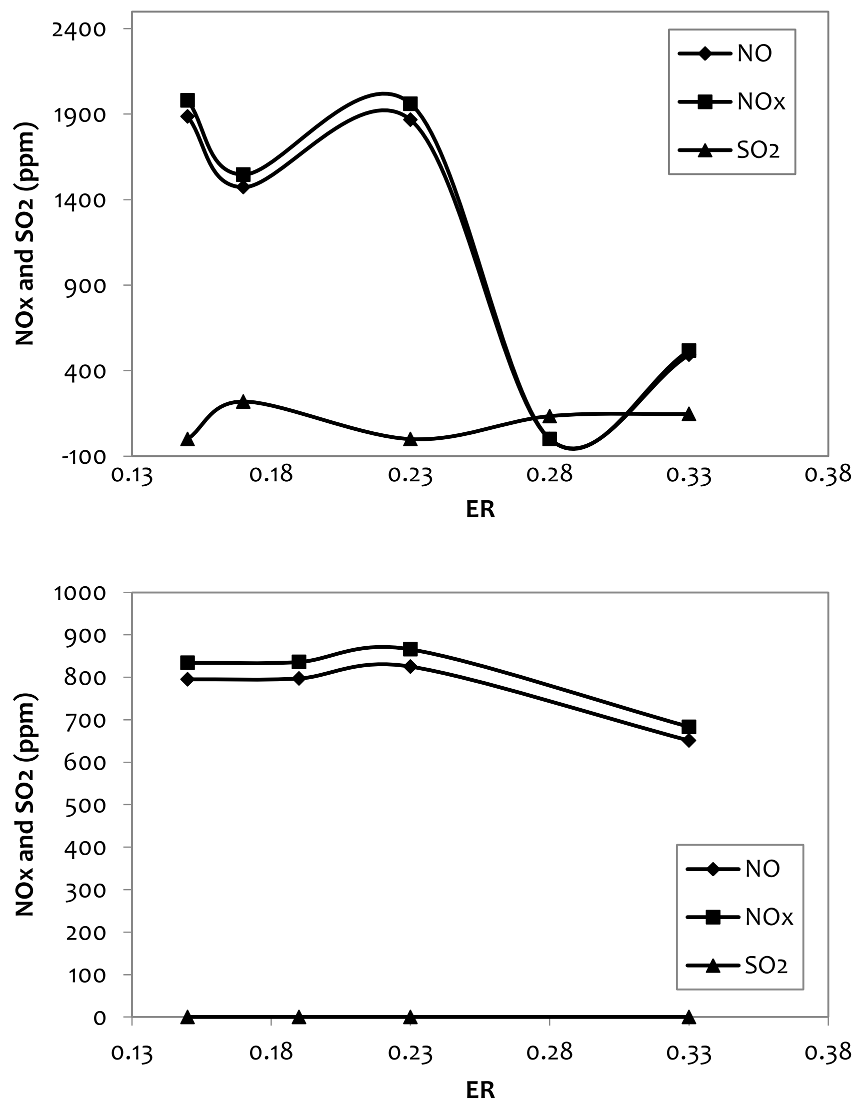


Figure 7 ER Effect on NO_x and SO_2 formation for (a) without circulation (b) with circulation

3.7 Effects of Equivalence ratio on H_2/CO ratio

Figure 8 shows the effect of ER on H_2/CO ratio. Ningbo et al. [27] studied the effect of ER on H_2/CO ratio. They observed the maximum value of 2.1 while in this study maximum value of 2.67 has been observed without circulation of gases while in case of circulation it is reduced considerably. Ratio increases with the increase of ER which shows that the heating value increases with the increase of ER while it decreases with circulation.

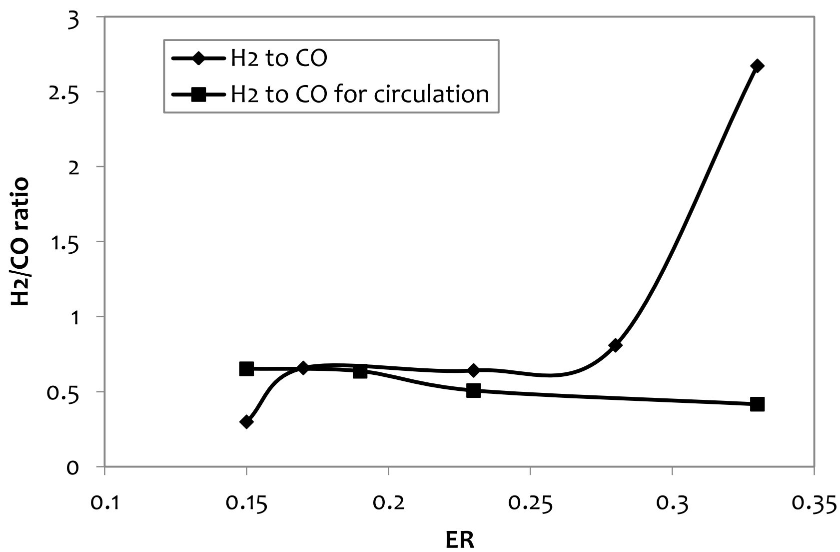


Figure 8 ER Effect on H_2/CO ratio

3.8 Calorific Value

The lower heating value (LHV) and higher heating value (HHV) without circulation are observed to be 7743 Btu/lb and 8995 Btu/lb while 3801 Btu/lb and 4397 Btu/lb with circulation. Both values were taken at the optimum ER i.e. 0.23. LV et al. [30] and Mansaray et al. [31] studied the heating values for different biomass material and comparable results have been found which indicates improved performance at optimum ER value.

Conclusion

A new updraft gasifier was designed and experiments were carried out for parametric investigation. Temperature profiling of bed, effect of temperature on NO_x and SO_2 formation, effect of temperature on gas composition, effect of equivalence ratio on gas composition, H_2/CO ratio and are studied for circulation of gases and without circulation. The following results were observed:

1. Better temperature profiling is achieved using circulation throughout the gasifier whereas temperature shows abrupt decrease above the reduction zone without circulation which is due to the biomass build-up in the gasifier.
2. CO shows the decreasing trend from 27% to 2% with increasing temperature whereas shows increasing trend from 7% to 11% with the start of circulation. Therefore, circulation gives the better reaction properties at high temperature.

3. Increasing temperature reduces the amount of NO_x and SO_2 but with the use of circulation uniformity in the decreasing trend is noticed whereas circulation considerably helps to remove SO_2.
4. With the increase of temperature increases H_2/CO ratio which is recorded between 0.2 to 2.6 without circulation but a decreasing trend is recorded with circulation so circulation does not favour the H_2 formation.
5. Increasing temperature showed the increasing trend of CO_2. Most of the O_2 is being converted to CO_2 at high temperature due to the presence of large amount of oxygen in the feed. Whereas circulation showed the uniform increasing trend in CO_2 but still less than the amount without circulation.
6. CO shows the decreasing trend with increasing ER whereas shows increasing trend with the start of circulation. So circulation gives the better reaction properties even at high ER.
7. Increasing ER increases H_2/CO ratio which is recorded between 0.2 to 2.6 without circulation but a decreasing trend is recorded with circulation so circulation does not favour the H_2 formation.
8. Increasing ER reduces the amount of NO_x and SO_2 but with the use of circulation uniformity in the decreasing trend is noticed whereas circulation considerably helps to remove SO_2.
9. Increasing ER showed the increasing trend of CO_2 to about 70%. Most of the O_2 converted to CO_2 at high ER due to the presence of large amount of oxygen in the feed whereas circulation showed uniform increasing trend of CO_2 to about 50% which is quite less than the amount without circulation.
10. The lower heating value(LHV) and higher heating value(HHV) without circulation were observed to be 7743 Btu/lb and 8995 Btu/lb while 3801 Btu/lb and 4397 Btu/lb with circulation. Both values were taken at the optimum ER i.e. 0.23.

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