



An Investigation on The Parametric Study of Co-gasification in Allothermal Circulating Fluidized Bed Gasifier.

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Abstract

Co-gasification of coal and bagasse in circulating fluidized bed gasifier (CFBG) is an emerging technique. The objectives of the current study are to investigate the influence of different parameters (temperature, ER values and feed composition) on the yield of producer gas in temperature range of 750 °C to 950 °C under reducing atmosphere. The study revealed that higher ER values (0.24 to 0.38) not only effected the composition of the producer gas but also has strong influence on the temperature profile in the riser section of the gasifier. In the temperature range of 792 °C-882 °C, the molar ratio of H₂/CO was decreased from 0.71 to 0.66, but with further increase in temperature (888 to 931 °C) the molar ratio increased from 0.72 to 0.81. However, the molar ratio of CO/CO₂ decreased from 0.85 to 0.74 (for shift of temperature from 792 to 882 °C) and then decreased from 0.74 to 0.60 for the temperature range of 882 to 931 °C. The increase of bagasse fraction in low-grade coal leads to the decrease in the concentration of CO, H₂ and CH₄, however, an increase in the CO₂ concentration was observed due to increased fraction of oxidants in the feedstock.

Keywords: Co-gasification, Fluidized bed, synthesis gas, Bagasse

1. Introduction:

Pakistan is a coal-rich country, with vast unexplored resources of low rank coal ranging from sub-bituminous to lignite, spread all over the country. According to approximate estimates, the total coal resources of Pakistan are more than 185 billion tons [1]. In Pakistan, sugar industry is the 2nd largest agricultural based industry after textile. Bagasse is the residue from the crushing of sugarcane [2]. Bagasse is 34 % of the cane crushed with average moisture contents of 50% [3], so total available bagasse from 78 sugar mills is estimated

more than 19.72 million tonnes. Sugarcane bagasse is primarily burnt inefficiently in boilers to meet the heating requirements for the sugar industry. The surplus bagasse is about 10% of the total produced in sugar mills. Currently, 90% of available bagasse is used for direct combustion in bricks cooking and balance is being used in paper board, etc [4]. Both biomass and coal are carbonaceous materials, originating from plants and have the same basic elemental constituents [5].

Gasification is an efficient, economic and sustainable thermo-chemical conversion method

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used for the conversion of solid fuels into gaseous fuels, which not only can be used for direct combustion but also as feedstock for the synthesis of various value-added chemicals. Gasification route generates lower levels of effluence than direct combustion [6]. The co-gasification of coal and renewable carbon-based seems to be attractive technology to produce liquid fuels from synthesis gas [7]. The co-gasification process not only reduces carbon footprint on the environment, but also improves syn-gas (H_2/CO) ratio in the produced gas [8]. Moreover, higher hydrogen contents in biomass, makes it suitable choice as a blend to compensate the often-low hydrogen (H) content of coal. The disadvantages of biomass as gasification feedstock are the low energy density, higher moisture and oxygen contents, although producing a high hydrogen yield. These deficiencies of biomass is compensated by blending it with a higher energy content coal [7].

Recently, significant research work in co-gasification of various coals and biomass mixtures [9] can be seen such as: Japanese coal and cedar wood [8], coal and sawdust [10], soft and hardwood chips with coal [11], coal and silver birch wood [12], rice husk and coal [13], olive pomace, coal and pet coke [14], coal, pine and polyethylene [15]. About 70-85% of the carbon in the feedstock is converted into the producer gas and the ratio of H_2/CO produced depends on the hydrogen and carbon content of the feedstock and the type of gasifier used. The producer gas from co-gasification of biomass and coal differs from natural gas in terms of heating value, composition, and flammability characteristics [3].

Most of the previous co-gasification studies have focused on the process parametric studies conducted in various gasifiers [16, 17], while little attention was focused on the mechanism of co-gasification using blends of low-grade coal and biomass in CFBG. Co-gasification processes require novel custom fitted technology and optimized operating parameters for the coal and region-specific sugar cane residues. Fluidized bed gasification (FBG) is a promising thermal conversion technology for variety of fuels (solids and

liquids) [18]. Specially, it is well-suited for low-grade fuels and waste materials [19]. Furthermore, utilization of flue gases from the external pre-heater (EPH), not only provide the necessary heat for endothermic reactions of heterogeneous and homogeneous phases of gasification process but also CO_2 along with moisture content of the flue gases were used as gasifying agent which resulted in the increase of H_2 and CO concentrations in the producer gas.

2. Materials and Methods

The blends of bagasse and low-grade high volatile coal are used as fuel feed stock for gasification. The received coal (varying size range 75 to 10 mm) from Chamalang mine (CH_{SB}) was crushed and sieved into an average size of 710 μm . Whereas, bagasse collected from local sugar mill was dried in open atmosphere and its average particle size was 490 μm . A CFBG rig made of SS-316 (schedule 80) was fabricated and operated. The riser section; assembled in two equal sections and flanged together having inner diameter of 80 mm and height 3900 mm. Six thermocouples of S-type were installed along the riser height for temperature measurement as shown in Figure 1. The additional heat for gasification process, a natural gas fired furnace, cylindrical in shape with the following dimensions ($L = 915$ mm and $I.D = 130$ mm), lined with fire bricks and glass wool was installed in series. It was installed horizontally to the plenum section of the riser assembly. The sand bed of height 170 mm (1.5 kg of sand with density 2400 kg/m^3) was maintained in the riser. It took about two hours to attain the ignition temperature ($500^\circ C - 600^\circ C$) of coal.

3. Results and Discussion

3.1. Factors influencing Co-gasification in CFBG

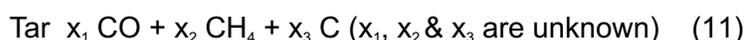
The temperature, ER values and feed composition are the parameters investigated for their influence on producer gas composition in this study. Coal gasification involves the series of oxidation reactions (partial or complete) that primarily

depends on the temperature and ER values [20, 21]. Low temperature favours the combustion reaction (CO_2 formation), while high temperature favours the partial oxidation reactions (CO formation). Other reactions occurring during the process are

water gas (WG), Boudouard and Methanation[22]. Furthermore, simplified series of gasification reactions are presented by equation 1-10 [23-25] as given in Table 1.

Table 1: Series of gasification reaction

Heterogeneous Reaction			Heterogeneous Reaction		
Reaction	Type	Eq. No	Reaction	Type	Eq. No
$2\text{C} + \text{O}_2 \rightarrow 2\text{CO}$ or $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$	POR Combustion(1)	(1)	$\text{CO} + 0.5 \text{O}_2 \rightarrow \text{CO}_2$	OVP	(6)
		(2)	$\text{H}_2 + 0.5 \text{O}_2 \rightarrow \text{H}_2\text{O}$ $\text{CH}_4 + 0.5 \text{O}_2 \rightarrow \text{CO} + \text{H}_2$		(7)
$\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2$	WG	(3)	$\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$		WGS
$\text{C} + \text{CO}_2 \rightarrow 2\text{CO}$	BR	(4)	$\text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2$	DMR	(10)
$\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4$	Methanation	(5)			



Biomass fuels are complex in nature and exhibit more de-volatilization tendency due to its high percentage of volatile components (70-86% on a dry basis) compared to coal (30%). Therefore, pyrolysis plays a larger role in biomass gasification than in coal gasification [5]. Biomass normally produce small amount of char and major fraction of gaseous products, tar and condensable volatile matters (upon pyrolysis). Recently, researchers exhibited the fact that biomass char followed the series of reaction (equation 1 to 5), whereas all the volatiles and tar are thermally cracked into gaseous products during the reactions from equation 6-11, respectively [26]. Tar formed in the above reaction is cracked into CO and CH_4 , where CH_4 further reacts with already present CO_2 (equation 10) and releases H_2 by the cracking of methane as exhibited in equation 11[27].

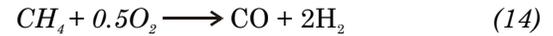
Gasification temperatures must reach at least 800°C . The higher temperature not only improve the conversion of coal-biomass blend but also assisted in the reduction of tar and other higher hydrocarbon (benzene and naphthalene etc.) content in the producer gas [28]. The temperature in the gasifier varied with the amount of oxidant or feed (coal-

bagasse blend) charged to the gasifier. Accordingly, in all thermal conversion processes the reaction temperature served a very important parameter as it affects the reaction rate, composition and the amount of producer gas [22]. The high temperature in the riser favors the endothermic reactions (equation. 3, 4, 10 and 11), which in turn influences the composition of the producer gas, due to the change in chemistry of the reactions. The reactions presented in equation 1, 2 and 5-9 have been reported as exothermic [29, 30]. Figure 2 presents the temperature distribution behavior along the riser height of CFBG. The temperatures within the dense bed zone (T2, T3 and T4) were uniform compared to the upper section of the riser (T5 and T6). Therefore, an intimate mixing of solid and gas took place all along the height of the fluidized bed. The position of the fluidized bed and temperature zone may vary due to the change in feed and stoichiometric air. The temperature along the riser height decreased gradually towards the gasifier outlet, as most of the homogeneous reactions including tar cracking took place in this zone (T5).

Whereas, Figure 4 depicted the temperature profile along the riser height due to variation in ER value.

Increase in ER value (0.24 to 0.38) not only caused the increase in temperature in the riser section of CFB but also enhanced the velocity of fluidized particles from 5.5 to 8.6 m/s (see Figure 5). Increase in ER value also change the position of fluidized bed as shown in Figure 6. The change in ER value leads to the corresponding change in temperature from 790°C to 942°C (see Figure 4). Hence, control of reaction temperature by regulating ER values along the riser height suggested that ER could be considered as one of the advantageous parameters of CFBG. Another work also reported similar trend regarding the temperature change with increasing ER values and change in bed position [21]. Figure 8 presents the experimental results of varying feed composition of two coal-biomass blends 91/9 and 94/6 (by weight) and subsequently their effects on the composition of producer gas at different temperatures. The increase of bagasse content in coal increased the availability of excess oxidant as shown in Table 1, which in turn increased the partial combustion reactions of hetero and homo

phases (partial oxidation of volatile products) through the series of gasification reactions;



Hence, increased fraction of bagasse in blend, leads to the rapid rise in temperature for coal-biomass blend 91/9. This suggests that the increased fraction of bagasse in blend has the synergistic affects between the coal (coke) and biomass during this conversion process. Moreover, increased temperature provides the necessary energy for endothermic reactions (pyrolysis) of gasification process, which are dominant at initial stage. However, as the time elapsed, there was high rise in temperature for coal-bagasse blend 94/6, due to the presence of higher fractions of carbon contents in coal.

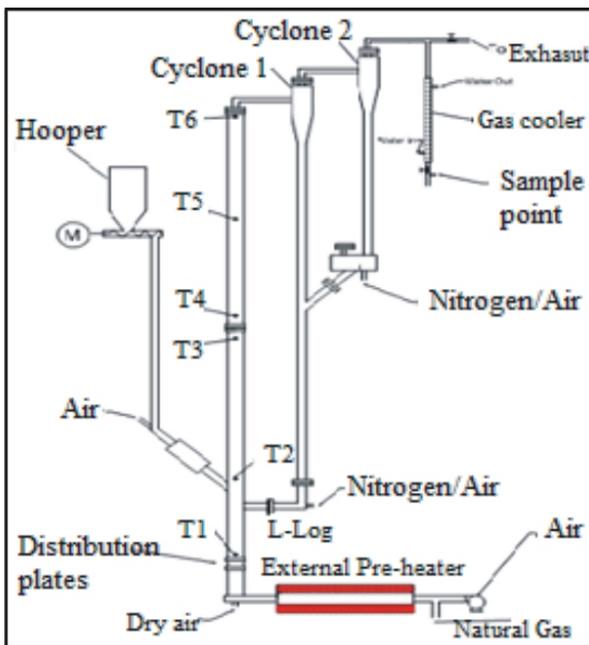
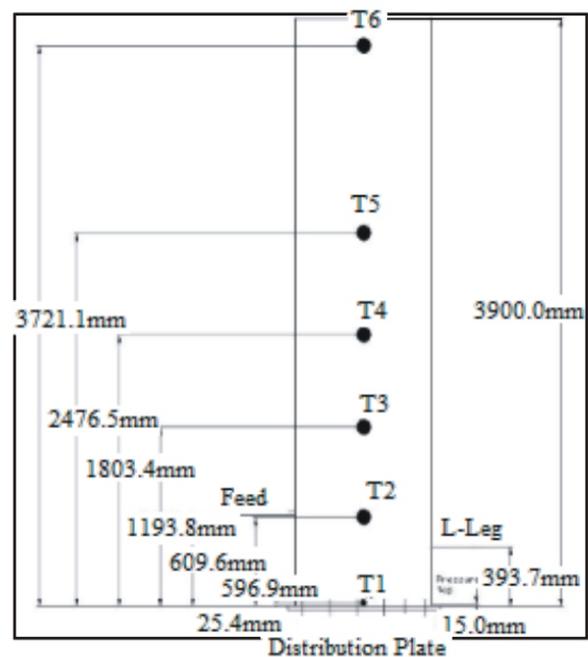


Figure 1.(a) Schematic diagram of CFBG



(b) Position of thermocouples along the riser height

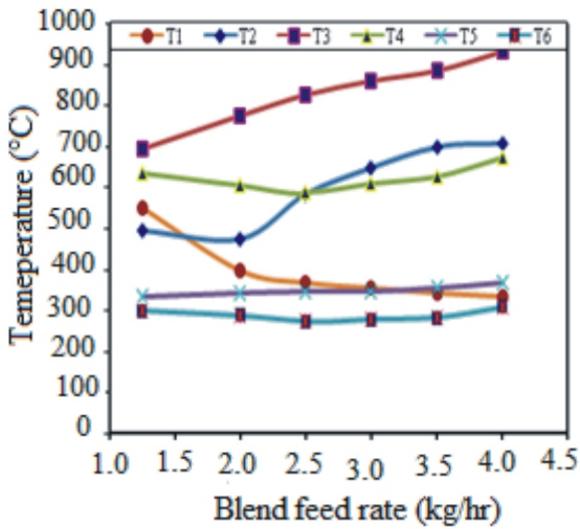


Figure 2: Temperature profile along the riser height

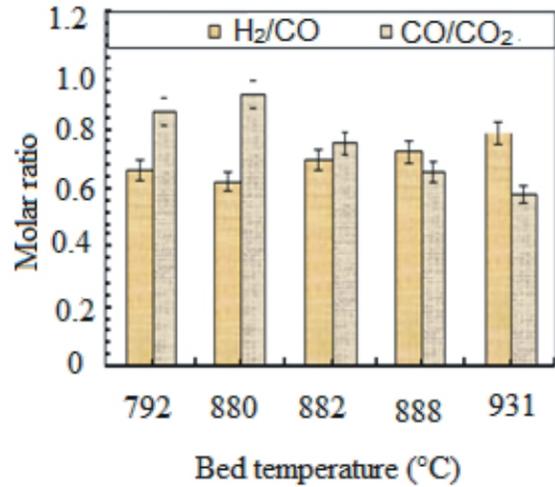


Figure 3: Effect of temperature on the composition of producer gas at fixed ER

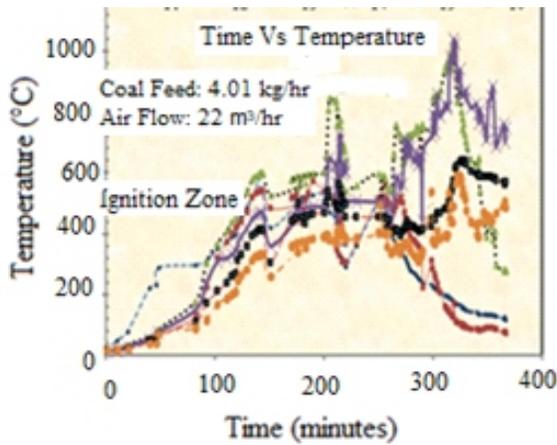


Figure 4: The temperature profile of the gasifier with change in ER

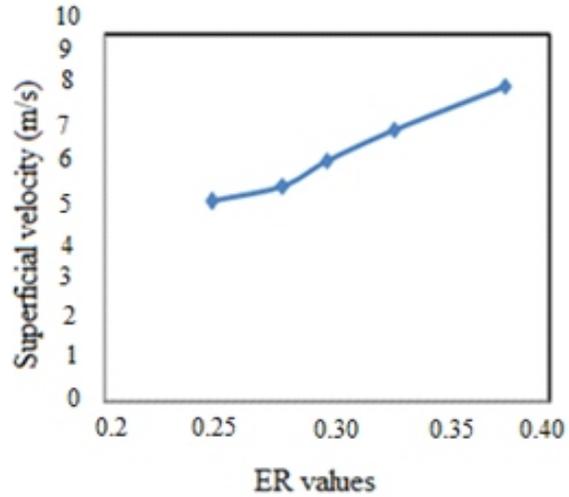


Figure 5: Impact of increasing ER value on the fluidization velocity of bed material

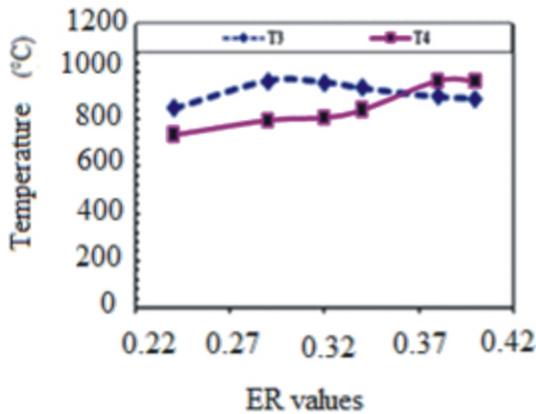


Figure 6: Impact of increasing ER Values on the position of fluidized bed.

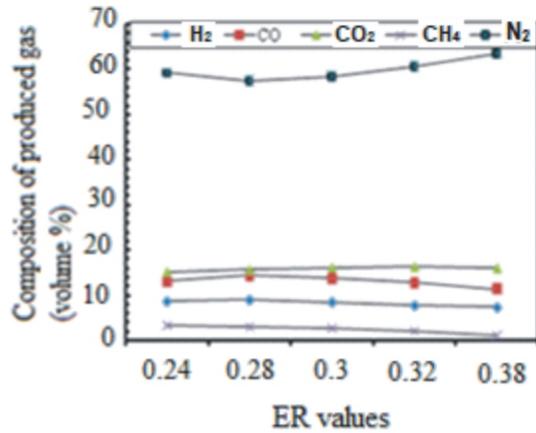


Figure 7: Effect of ER value on composition of producer gas

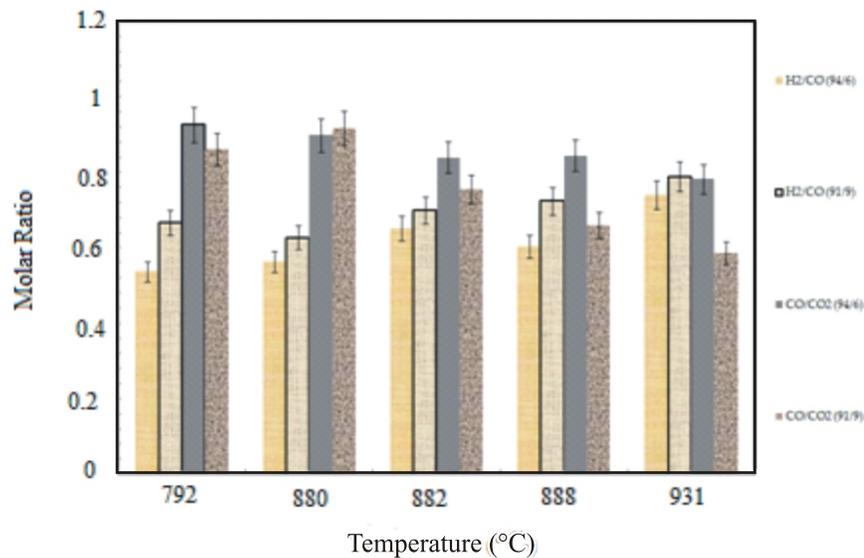


Figure 8: Effect of feed composition on the Producer gas for coal-bagasse blend 91/9 and 94/6.

Table 2: Proximate and Ultimate analysis of CH_{SB} and sugar-cane Bagasse

Proximate Analysis (%)			Ultimate analysis (%)		
Parameter	Bagasse	Coal	Element	Bagasse	Coal
Fixed carbon	12.28	51	Carbon	43.07	59.08
Volatile matter	81.33	39.8	Hydrogen	6.6	5.60
Moisture	1.03	0.9	Oxygen	43.41	22.82
Ash	5.35	8.3	Sulphur	0.16	2.79
HHV MJ/kg	17.88	22.20	Nitrogen	1.41	1.409

Table 3: Composition of the Producer gas for coal-bagasse blend (91/9) for temperature change

Case (91/9)	ER=0.30	1	2	3	4	5
Coal: Bagasse (91/9)	Kg/hr	3.64	3.64	3.64	3.64	3.64
Pressure	Atm	Sand bed height 170 mm				
Avg. Bed Temp T3 and T4	°C	792	880	882	888	931
Air	m ³ /hr	6				
Air flow in EPH	m ³ /hr	25	25	25	25	25
Natural gas flow	m ³ /hr	1.5				
Measured	Dry (vol.)	Gas composition molar fraction				
Temperature in °C		792	880	882	888	931
H ₂	%	7.7	7.9	8.1	8.4	8.63
CO	%	9.3	9.9	10.45	10.25	9.84
CO ₂	%	16.2	15.8	15.2	15.64	15.76
CH ₄	%	3.4	3.1	2.8	2.1	1.8
N ₂	%	63.4	63.3	63.45	63.61	63.97
H ₂ /CO	Ratio	0.71	0.62	0.66	0.72	0.81
CO/CO ₂	Ratio	0.85	0.92	0.74	0.65	0.60

3.2. Temperature effect

Figure 3 illustrates the composition of the producer gas at fixed ER value (0.30) and for temperature change from 792°C to 931°C. Between this temperature range, a series of heterogeneous and homogeneous reactions took place and the gas composition indicated that from 792°C to 882°C, H₂/CO molar ratio decreased from 0.71 to 0.66, but after this, H₂/CO ratio increased and gained the values of 0.72 and 0.81 for temperatures of 888°C and 931°C, respectively. Conversely, the molar ratio CO/CO₂ decreased from 0.85 to 0.74 with temperature variation from 792 °C to 882 °C, however, with further increase in temperature (from 882 °C to 931 °C), a decrease in the CO/CO₂ ratio was observed from 0.74 to 0.60, respectively. These trends may be explained as follow:

CO₂ formation or CO formation (equation 1) being exothermic reactions depicted a decreased in their CO/CO₂ ratios. Initially, the oxidation reactions of heterogeneous phase were dominant and resulted to the increase in CO concentration compared to H₂. Therefore, lower molar ratios of H₂/CO were due to higher CO concentration in producer gas.

Higher temperature (from 882°C to 931°C) increased the reactivity of endothermic reactions such as: Water gas, Boudouard and dry methane reforming, therefore, significant increase in H₂ concentrations was noticed compared CO, which resulted in increase of H₂/CO molar ratio. Moreover, thermal cracking of char, tar and other higher hydrocarbons were favoured at this temperature, which caused further increase in H₂ concentration in the producer gas.

Most of the homogeneous reactions took place in the free board area (initiated at T4) to exit of the riser (T6). The high temperature in the fluidized bed (882°C-931°C) was also favourable for the occurrence of dry methane reforming reaction (endothermic) to shift the equilibrium from reactants to products, thus

producing more H₂ and in turn decreased CH₄ and CO₂ concentrations in the producer gas. Similar type of results was reported by previous study discussing the impact of temperature on H₂ yield in producer gas. While, the low temperature in the upper section of the rise, shifted the equilibrium of the water gas shift reaction (equation 9) from products to reactants by consuming CO₂ and H₂. So, it indicated that at high temperature DMR reaction was more important than the WGS reaction. It was found quite in fare agreement with the findings of investigators [31], who also reported similar findings for low rank coal and biomass co-gasification.

Decrease in CH₄ concentration was due to the oxidation of methane (equation 8) that was supported by low temperature zone. Similar findings were reported in the literature [32]. However, decreasing trend in molar ratio of CO/CO₂ was due the high concentration of CO₂ from flues gases of external pre-heater.

Hence, increase in the concentration of CO, H₂ and CO₂ with the decrease in CH₄ concentration in the producer gas was observed. However, the diluting effect of N₂ and CO₂ from flue gases of external-heater and N₂ from air, have decreased the volume fraction of CO, H₂ and CH₄ in the final producer gas.

3.3. Equivalence ratio Effect

Figure 7 exhibits the effect of equivalence ratio (ER), on the fractional components of producer gas (i.e. H₂, CO, CO₂ and CH₄) by holding all other conditions constant like feed rate and feed composition. The change in composition of the producer gas with ER values can be explained as below:

Producer gas composition seems to be affected by the two different factors associated with the change in ER values i.e., temperature and increased fraction of oxidant. Higher ER values implied more oxygen entering the gasifier for the oxidation reactions of heterogeneous (equation 1 & 2) and

homogeneous phases (equation 6, 7 & 8) which resulted in increase of CO₂ concentration than CO. Besides, all these reactions are exothermic in nature, hence, increased the bed temperature as shown in Figure 6. Similar trend in bed temperature increase from 948°C to 1026°C with the increasing in ER value (0.31-0.47) was also reported previously [33]. However, increase in ER dilutes the energy contents of the producer gas due to increased fraction of N₂ in the producer gas.

In this study, it was observed that ER values has also impact on the presence of CH₄ concentration in the producer gas. It is suggested that the decrease in CH₄ concentration with the increase in ER value was perhaps due to the partial combustion reactions (equation 8 and equation 10) of homogeneous phase, which led to the increase in the fraction of CO and H₂ in producer gas. Results of this study were also found quite in agreement with the similar work [22], who also reported a decrease in CH₄ molar concentration and higher hydrocarbons with the increase in ER value.

Between the ER values of 0.24-0.28, the average bed temperature changed from 792°C to 879°C, these conditions were favourable for the cracking of higher hydrocarbons, tar and endothermic reactions, such as water gas, Boudouard and Dry methane reforming (DMR) (equation 3, 4 & 10) respectively, which in turn enhanced the molar fraction of H₂ and CO in the producer gas, while decreasing CO₂.

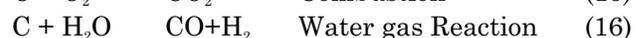
For ER > 0.30, the temperature increased with increasing ER values as shown in Figure 6. Moreover, the position of the fluidized bed also changed position T3 to T4 or T5, where most of the homogeneous reactions particularly partial oxidation of the volatile products and DMR reactions took place. The concentrations of H₂ and CO decreased due to consumption of H₂ and CO in oxidation of volatile products and resulted in the increase of CO₂

concentration. Perhaps partial oxidation reactions become more important than DMR (equation 10) and WGS (equation 9) reactions. Sudden changes (first increased then decreased) in CO content and increase in concentration of CO₂ with the increase in ER value and temperature indicated that both of the reactions i.e., Boudouard (equation 4) and WGS (equation 9) took place simultaneously in the process.

Moreover, lower composition of combustible gases in the producer gas was ascribed to the diluting effects of N₂ and CO₂ with the increase in ER value and as well as high temperatures. These results were found in agreement with the result published in previous studies [32, 34, 35].

3.4 Feed Composition Effect

Figure 8 illustrated that with the decrease of bagasse proportion in coal-bagasse blend (94/6 and 91/9), an increase in molar ratio of H₂/CO (0.53-0.74) and (0.66-0.78) was observed, respectively for temperature change 850°C to 964°C. It also reflected that the concentration of H₂ decreased with the decrease in proportion of biomass in feed stock. Although, the concentration of H₂ remained quite unpredictable in co-gasification, since many of the researchers have reported decrease in its concentration with increasing fraction of biomass [36]. Hence, these results are in fair agreement with others. Conversely, there was higher decrease in molar ratio of CO/CO₂ (0.92-0.78) for coal-biomass blend (94/6) compared to coal-biomass blend 91/9 (0.86-0.58). This huge decrease in the molar ratio of CO/CO₂ for coal-biomass blend 94/6 was ascribed to the higher percentage of carbon in feed stock (as given in Table1), which increased the molar fraction of CO₂ in the producer gas due to the following char reactions:



Moreover, higher temperature (850°C to 965°C) always favoured the cracking of higher

hydrocarbons, which contributed towards further increase in the concentration of CO_2 in the producer gas i.e., $\text{Tar } x_1 \text{CO} + x_2 \text{CH}_4 + x_3 \text{CO}_2$, where x_1 , x_2 & x_3 are unknown. The results obtained were fairly in agreement with previous studies [8, 20]. Coal-biomass blend 91/9 produced the higher concentration (3.4-1.2 vol %) of CH_4 than coal-biomass blend 94/6 (2.73-0.84 vol %) due to the increased fraction of volatile matters in feed stock.

4. Conclusions:

Apart from abatement of CO_2 emission, co-gasification of coal-bagasse blend is an efficient utilization of renewable energy resources. The investigation on operational parameters for gasification in CFBG showed that the composition of the producer gas was strongly influenced both by change in ER, feed composition and temperature profile of the gasifier.

Low temperature (792°C to 882°C) favoured the exothermic reaction and resulted in the increase in molar fractions of CO and CO_2 in the final product. While the high temperature (from 882°C and 931°C) increased the molar fractions of H_2 and CO in producer gas due to thermal cracking of tar and other hydrocarbon, moreover high temperature favoured the endothermic reaction of the process.

Increasing ER from 0.24 to 0.38, while keeping other conditions unchanged, the rise in corresponding temperature was observed from 790 °C to 940 °C. The increase in temperature provided the necessary energy for endothermic reactions of gasification process. Moreover, an increase in ER value resulted in the decrease of H_2/CO ratio and increase in CO/CO_2 ratio in the producer gas. Although, molar percentages of combustible elements (CO, H_2 and CH_4) in the producer gas was low due to the dilution effect of CO_2 and N_2 from the flue gases of allothermal process and gasifying agent. Increase in the proportion of coal in feed stock, increased the molar fraction of CO_2 , because of coal, containing higher percentage of carbon contents compared to bagasse. However, the concentration of CH_4 decreased due to the decreased

fraction of volatile matters in blended feedstock, as biomasses contain more volatiles compared to low rank coal.

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Abbreviations:

The following abbreviations are used in this manuscript:

POR: Partial oxidation reaction, OVP: Oxidation of volatile products, ER: Equivalence ratio, CFBG: Circulating fluidized bed gasifier. DMR: Dry methane reforming reaction, WGS: Water gas shift, WG: Water gas, BR: Boudouard reaction, GC: Gas Chromatography, EPH: External pre-heater, CH_{SB} : Chamalang Coal Sub-bituminous, HHV: Higher heating value.

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