

Thermochemical Conversion of Coal and Coal-Biomass Blends in an Autothermal Moving Bed Gasifier: Experimental Investigation

Abhijit Bhagavatula*, Naresh Shah

Department of Chemical and Materials Engineering, University of Kentucky, Lexington, USA
Email: *abhijitbv@gmail.com

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Abstract

A unique laboratory scale auto-thermal moving bed gasifier was designed for studying the thermochemical conversion of coal-biomass blends. For this purpose, two coals (lignite and sub-bituminous), two biomass materials (corn stover and switchgrass), and their respective blends were used. Gasification characteristics of the fuels were evaluated with an emphasis on improving the producer gas composition. The efficiency and product gas compositions reveal that utilizing the inner stainless-steel tubing better promotes heat transfer upwards in the axial direction when compared to utilizing quartz insulation. The H_2/CO ratio at the same operating conditions is much higher due to the increase in bed temperature and heat transfer upwards in the axial direction. This improved the overall efficiency by at least 20%. Using pure oxygen and steam, efficiency greater than 50% was obtained for blends with corn stover at steam to oxygen ratio of 2:1. Also, using air as the gasifying agent greatly improved the H_2/CO ratios and overall efficiency in blends with corn stover. In contrast, blends with switchgrass were not very effective with respect to the overall gasification characteristics. Blending switchgrass with coal may not be viable option from the viewpoint of generating high quality producer gas for downstream operations.

Keywords

Coal, Biomass, Autothermal Moving Bed Gasifier, Gasification, Syngas

1. Introduction

Energy is the cornerstone to economic stability and development. For several years, fossil fuels have stimulated worldwide economic growth. Only recently have we realized that this accelerated economic growth has not occurred without

a penalty. Combustion of fossil fuels has driven the atmospheric concentration of carbon dioxide, the most significant greenhouse gas (GHG), and also emission of environmentally harmful compounds (sulfur, nitrogen (N) and heavy metals) to levels not seen for several decades [1] [2]. Coal-fired power plants are still the largest source of electricity generation in the United States (contributing to about 42% of net electricity generation) and will keep their lead until 2040 [3] [4]. It is expected to contribute significantly to the future energy needs in many nations [5] [6], especially in fast-developing countries such as China and India [5]. However, combustion of fossil fuels accounts for about 75% of total GHG emissions [7]-[12]; therefore, coal utilization deserves special attention given the likelihood of continued use for electricity generation and the potential for coal to partially replace petroleum for chemicals and transportation fuels. In short, fueled by the following factors, the past few years have seen an upsurge in interest in gasification of biomass [10]:

- 1) Reduction in greenhouse gas emissions caused due to the combustion of fossil fuels.
- 2) Need for energy independence emerging due to the depleting resources and fluctuating prices of oil and natural gas.
- 3) Developing interest in renewable and locally available energy resources.

If grown in a regenerative manner, biomass systems and respective biofuels as sub-systems can be considered to be renewable as their combustion does not produce any net CO₂ emissions (CO₂ neutral) [13] [14] [15]. One method of reducing CO₂ emissions from coal-fired power plants is to substitute part of the coal feed with a renewable fuel such as biomass or waste fuels. Hence many countries have initiated incentives in recent years to encourage the co-utilization of biomass for energy production [16] [17]. Biomass in general has a high content of hydrogen (H), making it suitable as a blend to compensate for the often-low H content of coal. Biomass as gasification feedstock, although giving a high hydrogen yield, has the disadvantage of low energy density because of its high oxygen and moisture content. This shortcoming is compensated for when blended with a higher energy content coal. Other challenges such as the seasonal limitation of biomass are somewhat mitigated through co-conversion with coal. The higher tar release (due to excessive volatile release and low gasification temperature from biomass gasification) is also reduced as blending with coal increases the temperature, enhancing tar cracking. Blending biomass and coal as feedstock can reduce the shortcomings of each fuel and boost the efficacy of the overall system [18] [19] [20] [21] [22]. The high tar content of product gases from biomass gasification is a major and widely recognized problem. These high tar contents arise mainly from the lower temperatures and shorter residence times in gasifiers constructed for biomass processing compared to those designed for coal gasification. Tar yields from lignocellulosic biomass materials tend to be considerably higher than tar yields from coals [23] [24].

The quest for substitutes to fossil fuels, the need to mitigate the negative environmental effects of fossil fuels utilization and the necessity to safely and eco-

onomically dispose wastes have encouraged the development of alternative sources of energy and promotion of low-quality fuels. Co-conversion of coal and biomass/wastes for energy purposes and chemicals are among these alternatives.

Gasification is the most crucial step and also the bottleneck during the thermochemical conversion of solid carbonaceous feed. Therefore, a thorough investigation of this process is necessary in order to produce valuable products using downstream processes like Fischer-Tropsch synthesis and water gas shift reaction. Coal gasification is an established technology that has been used over the years to convert coal partially or completely to syngas [11]. The oxidizing agent can be chosen as air, oxygen, steam, or a mixture of these. The resulting gas has a low calorific value (3.8 - 5.6 MJ/Nm³ versus 38 MJ/Nm³ of natural gas) when air is used. This can be increased (10 - 18 MJ/Nm³) by using oxygen or steam but in the latter case, sufficient heat should be provided because steam gasification is an endothermic process. In some cases, steam is added to air to increase the level of hydrogen in the syngas [23]. Oxygen, though primarily used for the process of combustion, is a popular gasifying agent. It may be supplied to a gasifier either in pure form or through air.

In any gasifier, char gasification takes place following coal pyrolysis. The remaining carbonaceous solids from the pyrolysis reactions are further oxidized through heterogeneous reactions with carbon dioxide, carbon monoxide, steam, oxygen, and hydrogen. The major reactions that occur during the gasification process are described in Equations (1.1) through (1.7).

Reference [25] reported that biomass fuels with higher oxygen to carbon ratios have larger energy losses due to their high ratio of available chemical energy to heating value [25]. Highly oxygenated fuels are not ideal for gasifiers keeping in view the energy losses that can be incurred and hence, solid biomass can be more readily gasified if it is co-gasified with coal [16]. One of the major advantages of co-gasification is that it can utilize a much larger variety of available feedstock [26]. For the coal plants, partly gasifying biomass enables them to potentially obtain credits for the use of renewable fuel and also lower the economics since biomass is a low-cost feedstock. Also, co-conversion of coal-biomass blends is relatively cost-effective when compared to carbon capture and storage (CCS) which has a high energy penalty ranging between 15% and 40% and therefore, CCS would not be able to meet the emissions reduction targets suggested by International Panel on Climate Change (IPCC) [2] [27] [28]. However, several technical issues arise which need to be addressed to co-gasify coal and biomass [17]. Biomass has much lower bulk density, almost one-fifth that of coal; and higher moisture content than that of coal. Also, biomass has higher inherent oxygen content which, though increases the reactivity, also decreases the energy density [16] [29]. The heating values and particle densities of biomass are about half as much as that of coal. The overall energy density of biomass is about one-tenth that of coal. Therefore, a large volumetric flow of biomass is needed for mixing even a small percentage of biomass with coal for co-gasification. Due to these differences in the physical properties of the two fuels, delivery, sto-

rage and handling costs for biomass are much higher as compared with coal [16] [30]. The different compositions of coal and biomass also affect the thermodynamic efficiency of the co-gasification process. Biomass generally contains higher oxygen to carbon ratio which is useful for gasification as it increases the reactivity at lower temperatures and also lowers the amount of oxygen that is required to be added for the process [16] [25].

Although there is a large scientific knowledge base for separate gasification of coal and biomass, the application of co-gasification technologies is still a work in progress. It is important to develop a versatile technology that can benefit from different fuel compositions. Therefore, this research examined the co-gasification characteristics of different blends of coal and biomass in an auto-thermal moving bed reactor under varying reaction conditions.

	$C + O_2 \rightarrow CO_2$	$\Delta H = -394 \text{ kJ/mol}$	Equation (1.1)
Combustion	$C + 1/2 O_2 \rightarrow CO$	$\Delta H = -111 \text{ kJ/mol}$	Equation (1.2)
	$CO + 1/2 O_2 \rightarrow CO_2$	$\Delta H = -283 \text{ kJ/mol}$	Equation (1.3)
Boudouard Reaction	$C + CO_2 \leftrightarrow 2CO$	$\Delta H = +172 \text{ kJ/mol}$	Equation (1.4)
Vapo-Gasification	$C + H_2O \leftrightarrow CO + H_2$	$\Delta H = +131 \text{ kJ/mol}$	Equation (1.5)
Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	$\Delta H = -41 \text{ kJ/mol}$	Equation (1.6)
Methanation	$C + 2H_2 \leftrightarrow CH_4$	$\Delta H = -75 \text{ kJ/mol}$	Equation (1.7)

2. Materials

The US Department of Energy Coal Samples (DECS) used in this work were obtained from the Pennsylvania State University Coal Sample Database while the Center for Applied Energy Research at the University of Kentucky provided the biomass samples [19] [31]. For this work, biomass (CS and SG) was blended individually up to 30% by weight with two different ranks of coals, namely, DECS-38 sub-bituminous coal (SB) and DECS-25 lignite coal (LG). The samples were crushed and sieved to 150 μm before blending to limit the effects of intraparticle heat transfer. The coal-biomass blends were prepared in proper proportions and homogenized by constant stirring in the sample holders to ensure sufficient dispersion.

These coals were chosen based on economic considerations, their low sulfur content, and relatively high percentage of carbon present since the ultimate goal is to gasify these blends in a moving bed reactor for the production of syngas that can be used as feedstock for downstream processes such as Fischer-Tropsch Synthesis used for producing liquid fuels. Also, keeping in view of the overall gasification process, blends of higher percentages of biomass (in excess of 30% by weight) was not possible for the conditions at which the gasifier was operated since biomass is a low density, low heating value fuel and addition of more biomass would make the gasification process less efficient. Hence, a maximum of 30% by weight of biomass was chosen for this study. Proximate analysis of the feedstock samples was conducted according to ASTM standard D7582-12 using

a Netzsch Jupiter STA 449 Simultaneous Thermal Analyzer.

The percentages of C, H, and N in the feedstock samples were determined according to ASTM standard D5373-08 [32] using a LECO 628 Series Carbon/Hydrogen/Nitrogen Analyzer comprising of a dual-stage furnace operating at 1050°C while the percentage of sulfur in the sample was determined according to ASTM standard D4239-12 [33] using LECO SC 632 Carbon and Sulfur Analyzer and oxygen percentage obtained by difference. The proximate and elemental analyses of all the feedstock samples used in this study are shown in **Table 1**. These feedstocks were then gasified in an autothermal moving bed gasifier operating at atmospheric pressure and varying O₂/steam ratios.

3. Auto-Thermal Moving Bed Gasifier: Design and Operation

A laboratory-scale gasification system (**Figure 1**) has been designed and constructed for gasifying the feedstock materials (blends of coal and biomass). The core of the system is an updraft gasifier, where pressure and temperature profiles are measured by a pressure transducer and a set of thermocouples, respectively. Coal/biomass is fed at the top of the gasifier by means of a quick-open flange. Air/oxygen and steam is fed at the bottom of the gasifier and its rate is measured by a rotameter. The design utilizes a single condenser wherein the hot outlet gas enters a cold zone controlled using a refrigerator maintained at 5°C so that unreacted water and other solids can be collected more efficiently ensuring that clean syngas is produced at the outlet of the gasifier. The air/oxygen is sent in through the middle of the reactor so that heat coming out of the reactor can be used to preheat the air/oxygen entering the reactor ensuring better use of waste heat.

The gasifier is 3 feet long cylindrical stainless-steel modular flange assembly having an internal diameter of 1.37 inches fitted with another stainless-steel tube of 0.075 inches thick on the inside to promote better heat transfer in the axial direction. An initial comparative study was also performed with an inner quartz tube of similar dimensions as that of the stainless-steel tube and the outlet product gas compositions were analyzed for the gasification of both coals at various oxygen/steam ratios. A schematic representation of both reactor designs is shown in **Figure 2**.

Table 1. Proximate and elemental analysis of feedstocks.

Feedstock	Proximate Analysis (As Received Basis)				Elemental Analysis (As Received Basis)				
	%Moisture	%Fixed Carbon	%VM	%Ash	%C	%H	%N	%S	%O
DECS-38 Sub-Bituminous Coal	22.01	39.66	34.58	3.75	56.82	3.95	0.98	0.44	12.36
DECS-25 Lignite Coal	34.91	27.32	30.05	7.71	42.80	2.99	0.61	0.47	10.50
Corn Stover	5.66	10.32	76.15	7.87	42.33	6.71	0.73	0.30	42.06
Switchgrass	4.87	9.35	83.62	2.16	45.76	8.09	0.32	0.08	42.87

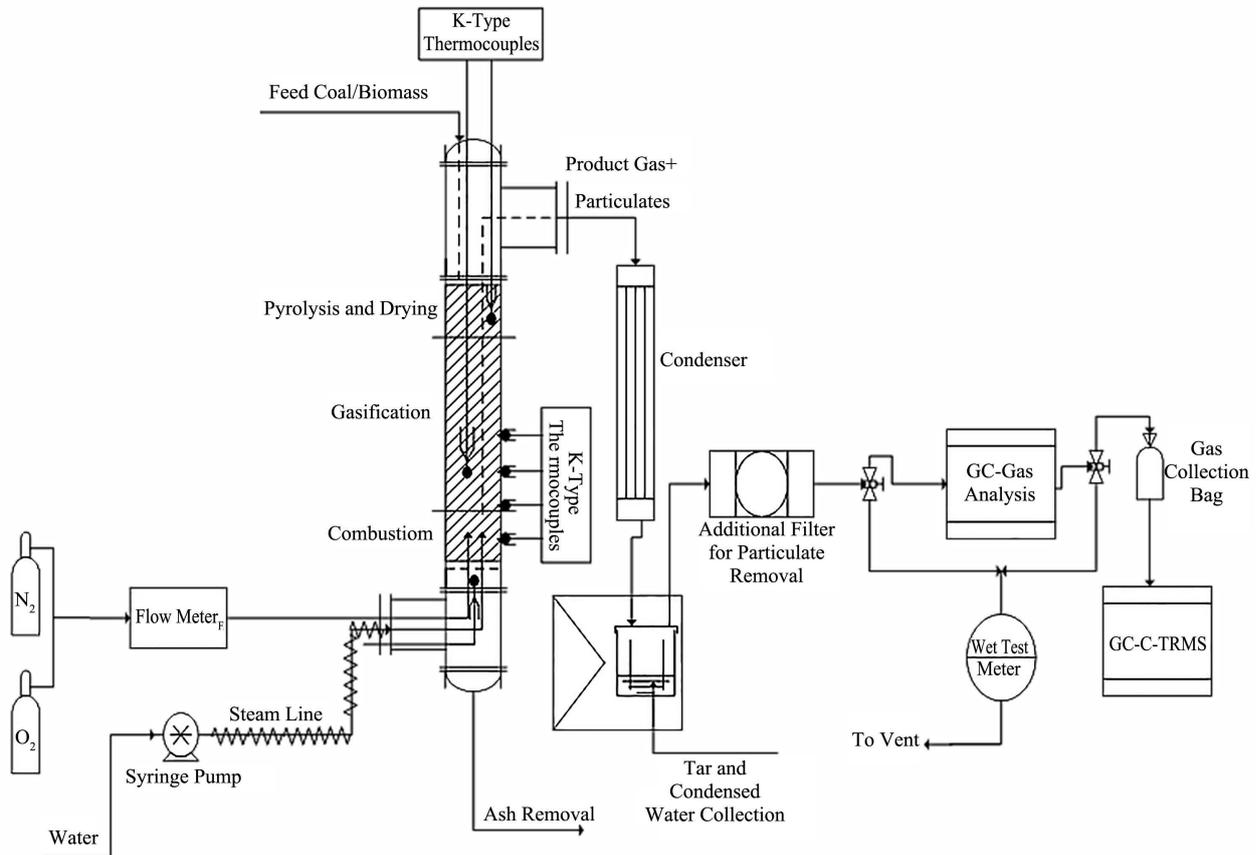


Figure 1. Schematic of the laboratory scale moving bed gasification system.

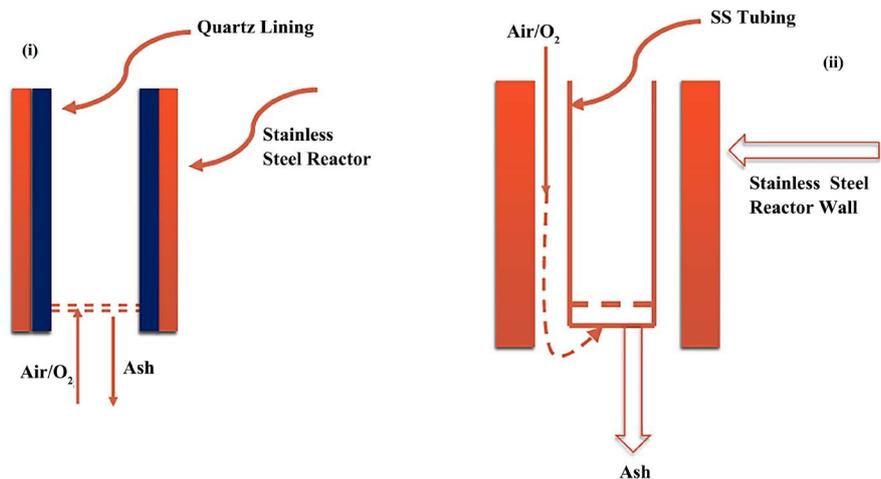


Figure 2. Schematic representation of the change in reactor design: (i) original design with inner quartz lining; (ii) modified reactor design with inner stainless-steel tube for better heat utilization.

The inner tube is fitted with a stainless-steel grate with apertures large enough to let the ash pass through but small enough to hold the feed material. The grate is connected to a mechanical rotary linear feed-through to periodically remove ash. The bottom zone, under the grate, has another cylindrical stainless-steel

flange with a height of about 5 inches to collect and then discharge the ash produced in the process. The grate at the bottom of the gasifier is used not only for holding the solid particles together but also as an oxidant distributor. The oxidant, fed at the bottom of the reactor, flows along the channels and exits through the small holes along the grate, so it is distributed across the whole section of the gasifier. At the bottom, a small tube allows the use of pre-heated steam to enter the bed. Temperature profiles along the gasifier axis are measured by a set of K-type thermocouples placed within a steel protective tube.

The feeding system is constituted by a conical chamber enclosed in a quick-open flange about 5 inches in height. As stated earlier, the product gas stream flows through a condenser maintained at 5°C where the condensed liquids flow down the tubes and capture the solid particles entrained by the gas. At the bottom, the liquid phase is discharged and collected for further analysis. Condensers, wet scrubbing, packed bed, and cartridge filters constitute the gas-cleaning system, which though not optimized, guarantees a gas sufficiently clean for gas-chromatographic analysis (GOWMAC Auto System GC equipped with thermal conductivity detector (TCD) and a packed column). Gas sampling and analysis are carried out at selected times during the whole duration of the tests.

There are two possible operation modes of the gasifier, corresponding to a constant or a variable bed height. In the first modality, after ignition, the bed height is brought to the desired value and maintained constant. This is achieved by feeding the solid material at proper time intervals. Therefore, because of variations in the oxidant flow rate, the oxidant-to-fuel ratio will also vary, given that the fuel feed rate is the adjustable variable to control the (constant) bed height. The feeding process is an important aspect in the operation of fixed-bed gasifiers. The rate of feed consumption is essentially dependent on the intrinsic reactivity and the rate of oxidant supply. Sufficient feed can be added to keep the bed height at a constant value. However, as the rate of feed consumption increases with the oxidant flow rate, the feeding frequency should also be properly adjusted. In particular, a limit is expected at very high flow rates, when the feeding frequency becomes so high that a semi-continuous procedure is no longer possible. The rate of feed consumption can also be adjusted by choosing a proper rate of solid discharge at the grate, but this may be problematic for small-scale systems. Indeed, frequent solid discharge causes significant heat loss (the discharged solid is at an elevated temperature), with the introduction of instabilities in the gasification process.

In the second modality, gasification tests can be made for different oxidant-to-fuel ratios, thus allowing the bed height to vary. For instance, after the selection of the oxidant flow rate, the fuel feed rate can be varied and, consequently, the bed height will also vary. However, it can be understood that there is again a limit at very low fuel feed rates, when the continuous operation approaches the behavior of a batch system and the processes of drying/devolatilization, on one side, and gasification/combustion, on the other side, tend to become uncoupled.

The first step in the gasification process is the ignition of the bed. This is caused by adding small amounts of externally heated coal particles onto the grate while supplying the oxidant at low flow rates of approximately 100 ml/min to 150 ml/min. The feed material is then added onto the heated coal particles and the oxidant flow rate is increased, thus causing ignition of the bed. Once the bed is ignited, pre-heated steam enters the bed through the grate at the bottom. Experiments have been performed with varying oxygen flow rates ranging from 150 ml/min to 650 ml/min and varying steam flow rates of 150 ml/min to 1600 ml/min. Apart from varying the oxygen to steam ratio, tests have also been performed with varying oxygen partial pressure on DECS-38 sub-bituminous coal.

4. Results and Discussion

4.1. Gasification with Varying Oxygen/Steam Ratio

4.1.1. Quartz Insulation

The gasification of DECS-38 sub-bituminous coal was first carried out in the moving bed gasifier using internal quartz insulation with varying oxygen to steam ratios. The oxygen flow rate was maintained constant at 650 ml/min while the flow rates of steam were varied from 0 to 1625 ml/min. The average composition of the product gases and the calculated energy efficiency values are provided in **Table 2** and **Table 3** respectively.

Table 2. Average composition of product gases obtained during gasification of DECS-38 sub-bituminous coal with varying oxygen to steam ratios.

Feedstock Weight, g	Average Composition of Product Gases, %							
	H ₂ O:O ₂	H ₂ :CO	CO:CO ₂	(H ₂ + CO):CO ₂	H ₂ %	CO%	CH ₄ %	CO ₂ %
75	0.00	0.14	0.90	1.02	5.39%	39.52%	1.43%	44.02%
115	1.00	0.37	0.78	1.07	12.35%	33.57%	1.35%	42.93%
110	1.50	0.48	0.72	1.08	15.09%	30.26%	1.31%	42.16%
85	2.00	0.81	0.49	0.88	17.31%	21.36%	1.58%	41.81%
235	2.50	0.91	0.47	0.90	18.23%	20.12%	1.29%	40.78%

Table 3. Calculated energy efficiency during gasification of DECS-38 sub-bituminous coal with varying oxygen to steam ratios.

H ₂ O:O ₂	Max H ₂ :CO	Max CO:CO ₂	Energy Input (KJ)	Energy Output (KJ)	Efficiency %
0.00	0.15	1.03	1504	378	27.9%
1.00	0.55	0.82	2614	953	42.9%
1.50	0.59	0.74	2499	1067	49.8%
2.00	0.90	0.46	1990	676	40.4%
2.50	1.20	0.46	5437	1922	40.4%

Once the composition of the product species is obtained, the gross heating value of the gases and the energy conversion efficiency of the gasifier can be calculated using the following equations [24] [34].

$$\text{GHV}_{\text{gases}} = \sum_i \text{GHV}_i X_i \quad (4.1)$$

where, GHV_i is the gross heating value in kJ/m^3 and X_i is the mole fraction of the fuel gases, $i = \text{CO}$, CH_4 and H_2 .

$$\eta_{\text{gas}} = \text{GHV}_{\text{gases}} / \left[N_{\text{fuel}} * \text{GHV}_{\text{fuel}} + N_{\text{steam}} * 18 \{ \lambda + 4.18(373 - 298) \} \right] \quad (4.2)$$

where, N_{fuel} and N_{steam} correspond to the moles of fuel and steam supplied, respectively, to the gasifier and λ is the enthalpy of vaporization. GHV_{fuel} is the gross heating value of the fuel in kJ/kg and η_{gas} is the energy conversion efficiency.

Figures 3-5 describe the results obtained during the gasification of sub-bituminous coal for varying steam to oxygen ratios. As seen from Figure 3, the increase in the amount of steam fed to the gasifier at constant oxygen flow rate (increased atoms of hydrogen supplied to the gasifier) results in an increase in the hydrogen percentage and a decrease in the percentage of carbon monoxide and carbon dioxide. The amount of methane produced should also increase with the steam supplied to gasifier. However, as the amount of methane produced during all the experiments was less than 2%; it was difficult to establish a trend for methane using the obtained data. When experiments were performed with steam to oxygen ratio above 2.5 in the non-externally heated moving-bed gasifier, the combustion zone at the bottom of gasifier was extinguished in a very short period. Increasing steam flow rates to higher values imply decreasing the oxygen supplied to the gasifier.

Thus, the exothermic reaction heat is not sufficient to maintain self-sustained

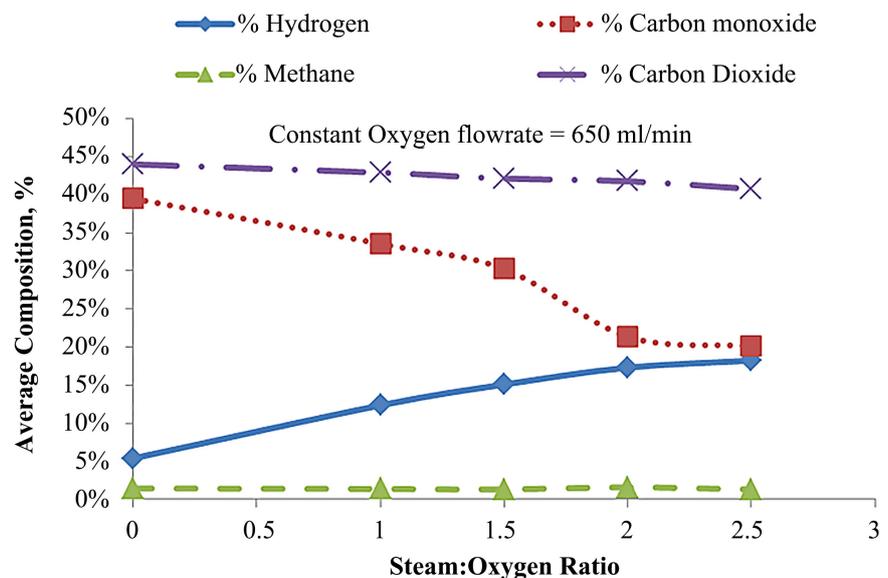


Figure 3. Average compositions of the product gases obtained during gasification of sub-bituminous coal with varying steam/oxygen ratios.

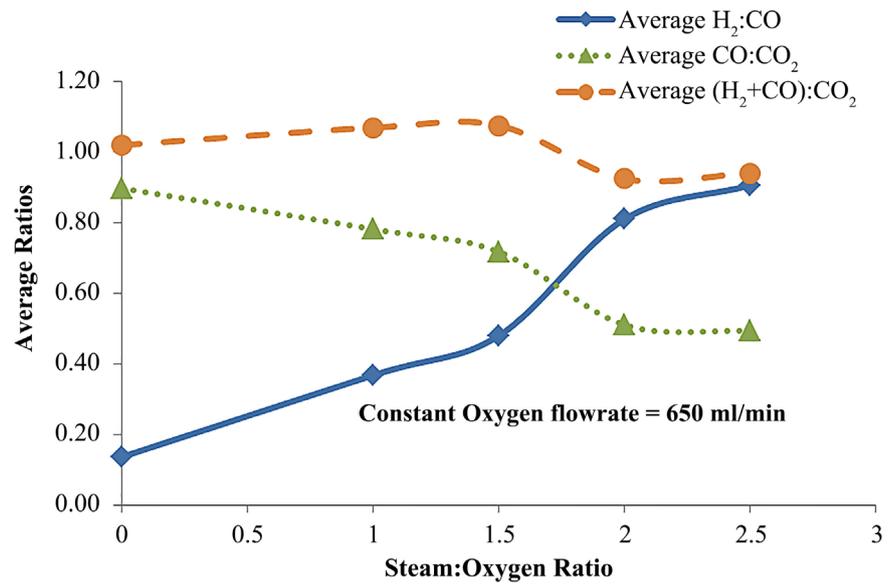


Figure 4. Average ratios of the product gases obtained during gasification of sub-bituminous coal with varying steam to oxygen ratios.

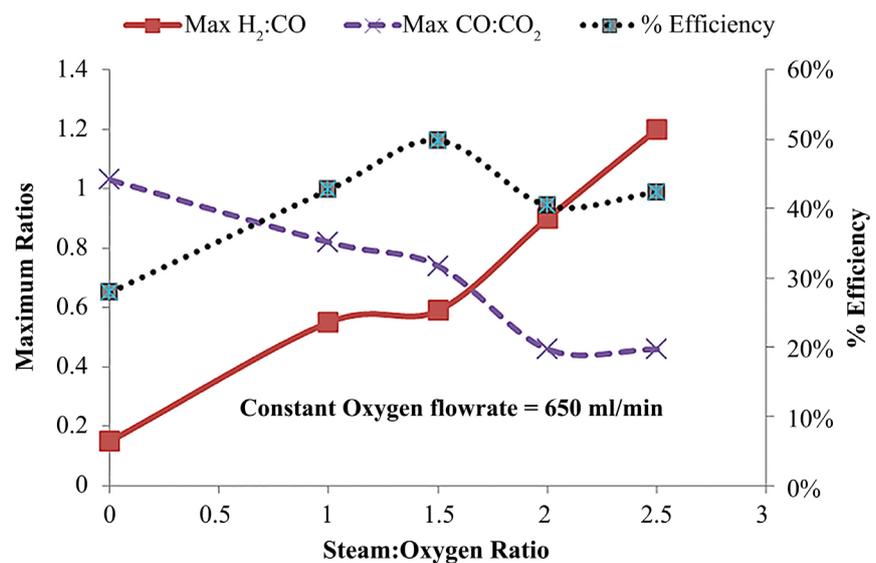


Figure 5. Maximum ratios of the product gases and efficiency obtained during gasification of sub-bituminous coal with varying steam to oxygen ratios.

reaction. **Figure 4**, using the data from the same experiment, shows that the ratio of carbon monoxide to carbon dioxide in the product stream decreases with an increase of steam supplied to the gasifier. Similarly, the ratio of syngas produced to the amount of carbon dioxide produced, increases up to a certain value of steam to oxygen ratio (Steam:O₂ = 1.5) and then decreases. This is due to the reason that the production of carbon monoxide diminishes with increasing steam ratio. It can be observed from **Figure 5** that the energy conversion efficiency, as described in Equation (4.2), increases up to a steam ratio of 1.5 and then decreases with higher steam ratios. The highest energy conversion efficien-

cy obtained is approximately 50% at a steam ratio of 1.5. The efficiency decreases for steam ratios above 1.5 since the exothermic zone at the bottom of the bed is either no longer available or that the endothermic zone is much more prevalent at higher steam ratios.

4.1.2. Stainless Steel Reactor: Gasification of Coal Feedstocks

As stated earlier, a comparative study on the effectiveness of using inner stainless-steel tubing in place of quartz tubing was performed at various oxygen/steam ratios for DECS-38 sub-bituminous coal. This was done to improve the heat transfer in the axial direction and thereby improve the useful product gas composition in the outlet gas and improve the overall efficiency of the gasifier. The product gas compositions and efficiency at various O₂/steam ratios for gasification of sub-bituminous coal are presented in **Table 4(a)** and **Table 4(b)**.

Clearly, with an increase in the concentration of steam in the gasifier the trends of the product gas compositions are similar to those obtained using an inner quartz lining. But, it must be noted here that the percentage of hydrogen generated at same operating conditions is much higher due to the increase in bed temperature (complete consumption of oxygen which was not achieved when using quartz insulation) and transfer of heat upwards in the axial direction and thus, better heat utilization which improved the overall efficiency by at least 20% when the steam concentration was at its maximum in the gasifier.

Table 4. (a) Average composition of product gases obtained during gasification of sub-bituminous coal at varying O₂/steam ratios in the stainless-steel moving bed gasifier; (b) Average ratios of desired product gases and calculated energy efficiency during gasification of sub-bituminous coal at varying O₂/steam ratios in the stainless-steel moving bed gasifier; (c) Average composition of product gases obtained during gasification of lignite coal at varying O₂/steam ratios in the stainless-steel moving bed gasifier; (d) Average ratios of product gases and energy efficiency during gasification of lignite coal at varying O₂/steam ratios in the stainless-steel moving bed gasifier.

(a)

Material	Operating Conditions			Average Product Gas Compositions				
	Air	O ₂	Steam	Steam:O ₂	H ₂ %	CO%	CH ₄ %	CO ₂ %
	ml/min	ml/min	ml/min					
DECS-38 Sub-Bituminous Coal		650	0	0	12.85%	32.96%	3.50%	41.71%
		650	325	0.5	20.53%	31.27%	3.21%	41.69%
		650	650	1	24.39%	26.13%	3.09%	41.68%
		650	1300	2	26.65%	21.63%	2.53%	42.66%
	1400	300	0.00	0	4.94%	5.90%	0.00%	13.92%
	1400	300	150	0.5	5.27%	5.48%	0.00%	13.83%
	1400	300	300	1	5.95%	5.01%	0.00%	13.68%
	1400	300	600	2	7.35%	4.48%	0.28%	13.51%

(b)

Material	Operating Conditions			Average Ratios of Product Gases			Efficiency %
	Air	O ₂	Steam	H ₂ :CO	CO:CO ₂	Syngas/CO ₂	
	ml/min	ml/min	ml/min				
DECS-38 Sub- Bituminous Coal		650	0.00	0.39	0.79	1.10	47.2%
		650	325	0.66	0.75	1.24	45.9%
		650	650	0.93	0.63	1.21	53.6%
		650	1300	1.23	0.51	1.13	58.3%
	1400	300	0.00	0.84	0.42	0.78	19.6%
	1400	300	150	0.96	0.40	0.78	21.0%
	1400	300	300	1.19	0.37	0.80	23.1%
	1400	300	600	1.64	0.33	0.88	23.9%

(c)

Material	Operating Conditions			Average Product Gas Compositions				
	Air	O ₂	Steam	Steam:O ₂	H ₂ %	CO%	CH ₄ %	CO ₂ %
	ml/min	ml/min	ml/min					
DECS-25 Lignite Coal		650	0	0	12.40%	35.73%	2.39%	45.97%
		650	325	0.5	16.14%	34.43%	1.95%	46.37%
		650	650	1	20.81%	27.58%	1.73%	45.47%
		650	1300	2	25.83%	22.03%	0.95%	45.90%
	1400	300	0.00	0	4.37%	7.65%	0.00%	14.95%
	1400	300	150	0.5	6.45%	7.45%	0.00%	14.72%
	1400	300	300	1	8.20%	6.98%	0.00%	14.80%
	1400	300	600	2	11.37%	5.60%	0.00%	14.20%

(d)

Material	Operating Conditions			Average Ratios of Product Gases			Efficiency %
	Air	O ₂	Steam	H ₂ :CO	CO:CO ₂	Syngas/CO ₂	
	ml/min	ml/min	ml/min				
DECS-25 Lignite Coal		650	0.00	0.35	0.78	1.05	58.1%
		650	325	0.47	0.74	1.09	55.2%
		650	650	0.75	0.61	1.06	58.8%
		650	1300	1.17	0.48	1.04	61.9%
	1400	300	0.00	0.57	0.51	0.80	31.1%
	1400	300	150	0.87	0.51	0.94	35.9%
	1400	300	300	1.17	0.47	1.03	41.7%
	1400	300	600	2.03	0.39	1.19	52.1%

Also, unlike the quartz insulation where the efficiency increased only until a certain point and the maximum steam/O₂ ratio that could be utilized was 1.5, in

this experimental set-up, the efficiency increased steadily until a steam/O₂ ratio of 2:1. Apart from this, the ratios of H₂/CO, CO/CO₂ and syngas/CO₂, which dictate the quality of the product gas, are markedly higher as compared with the previous experimental set-up. Hence, the current experimental set-up was utilized for analyzing the product gas trends during the gasification of various blends of coals and biomass materials. Once it was established that utilizing an inner stainless-steel lining improves the overall energy efficiency of the gasifier and quality of syngas produced, the process was repeated for the gasification of lignite coal. The product gas compositions and energy efficiency at various O₂/steam ratios for gasification of lignite coal are presented in **Table 4(c)** and **Table 4(d)**.

4.1.3. Stainless Steel Reactor: Blends with Corn Stover

Corn Stover was blended with both coals at various percentages, the maximum composition being 30% by weight of corn stover. Blending higher concentrations of corn stover (>30% by weight was not feasible) resulted in the reactions inside the gasifier being extinguished due to low temperatures achieved at the bottom of the gasifier. The blends of both coals with corn stover were gasified at various O₂/steam ratios and air/steam ratios and the product gas trends were analyzed accordingly. **Table 5** and **Table 6** provide an insight into these compositions and

Table 5. Average composition of product gases and energy efficiency obtained during gasification of blends of sub-bituminous coal and corn stover at varying O₂/steam ratios in the lab scale stainless steel moving bed gasifier.

Material	Operating Conditions			Average Product Gas Compositions				Average Ratios of Product Gases			$\eta_{\text{gas}}\%$		
	Air ml/min	O ₂ ml/min	Steam ml/min	Steam:O ₂	H ₂ %	CO%	CH ₄ %	CO ₂ %	H ₂ :CO	CO:CO ₂		Syngas/CO ₂	
90% SB + 10% CS		650	325	0.5	19.4	31.9	6.79	43.29	0.61	0.74	1.19	48.5	
			650	650	1	23.2	26.6	6.18	43.69	0.87	0.61	1.14	51.1
			650	1300	2	26.1	22.2	5.46	43.13	1.18	0.51	1.12	53.3
		1400	300	150	0.5	4.54	3.36	0.00	13.91	1.35	0.24	0.57	20.5
		1400	300	300	1	6.57	5.45	0.07	14.17	1.21	0.38	0.85	44.6
		1400	300	600	2	7.83	6.18	0.17	14.59	1.27	0.42	0.96	48.2
80% SB + 20% CS		650	325	0.5	13.8	25.3	6.01	48.17	0.54	0.53	0.81	20.3	
			650	650	1	15.6	22.5	5.94	47.43	0.69	0.48	0.81	32.4
			650	1300	2	24.4	20.1	5.83	47.11	1.21	0.43	0.82	37.1
		1400	300	150	0.5	4.59	4.74	0.11	13.50	0.97	0.35	0.69	23.1
		1400	300	300	1	7.23	5.92	0.00	13.80	1.22	0.43	0.95	47.1
		1400	300	600	2	7.45	6.11	0.00	13.73	1.22	0.45	0.99	50.4
70% SB + 30% CS		650	325	0.5	12.1	18.1	5.08	56.67	0.67	0.32	0.54	21.0	
			650	650	1	14.2	15.7	4.29	56.79	0.91	0.28	0.53	25.0
			650	1300	2	16.9	13.0	4.00	56.17	1.29	0.23	0.53	28.6
		1400	300	150	0.5	4.34	3.25	0.00	14.86	1.33	0.22	0.51	25.3
		1400	300	300	1	7.18	5.28	0.00	15.44	1.36	0.34	0.81	41.3
		1400	300	600	2	8.91	6.21	0.00	15.13	1.44	0.41	1.00	43.5

Table 6. Average composition of product gases and energy efficiency obtained during gasification of blends of lignite coal and corn stover at varying O₂/steam ratios in the lab scale stainless steel moving bed gasifier.

Material	Operating Conditions			Average Product Gas Compositions					Average Ratios of Product Gases			$\eta_{gas}\%$
	Air ml/min	O ₂ ml/min	Steam ml/min	Steam:O ₂	H ₂ %	CO%	CH ₄ %	CO ₂ %	H ₂ :CO	CO:CO ₂	Syngas/CO ₂	
90% LG + 10% CS		650	325	0.5	14.14	32.1	7.21	46.45	0.44	0.69	1.00	41.4
		650	650	1	17.73	27.2	6.03	46.20	0.65	0.59	0.97	49.4
		650	1300	2	20.19	21.6	5.81	46.05	0.93	0.47	0.91	58.3
	1400	300	150	0.5	6.30	8.00	0.00	13.66	0.79	0.59	1.05	35.9
	1400	300	300	1	10.87	8.62	0.00	13.26	1.26	0.65	1.47	57.2
	1400	300	600	2	13.83	9.81	0.00	13.01	1.41	0.75	1.82	64.6
80% LG + 20% CS		650	325	0.5	13.41	23.9	7.43	51.12	0.56	0.47	0.73	36.2
		650	650	1	16.43	20.6	6.22	51.94	0.79	0.40	0.71	42.3
		650	1300	2	18.78	18.1	5.19	51.74	1.04	0.35	0.71	48.0
	1400	300	150	0.5	6.64	8.38	0.00	12.71	0.79	0.66	1.18	37.5
	1400	300	300	1	11.94	7.73	0.00	13.33	1.55	0.58	1.48	52.8
	1400	300	600	2	13.98	6.14	0.00	13.48	2.28	0.46	1.49	61.1
70% LG + 30% CS		650	325	0.5	12.92	17.1	6.93	60.93	0.75	0.28	0.49	29.2
		650	650	1	15.18	15.1	6.51	61.17	1.00	0.25	0.50	34.5
		650	1300	2	18.01	12.3	5.06	61.11	1.45	0.20	0.50	38.4
	1400	300	150	0.5	5.22	5.69	0.00	14.76	0.92	0.39	0.74	29.1
	1400	300	300	1	12.03	12.9	0.00	11.65	0.93	1.11	2.14	64.1
	1400	300	600	2	13.73	14.0	0.00	14.34	0.98	0.98	1.94	66.5

the effect that addition of corn stover to coal had on the quality of gases produced.

For blends of both coals with corn stover (Table 5 and Table 6), it may be observed that with an increase in the inlet steam: O₂ ratio, the composition of H₂ in the outlet stream increases, composition of CO decreases while CO₂ remains constant in all experiments indicating that Boudouard reaction (Equation (1.4)), water gas reaction (Equation (1.5)) and water gas shift reaction (Equation (1.6)) are taking precedence. For instance, addition of 10% by weight of corn stover to pure sub-bituminous coal and varying the O₂: steam ratios from 2:1 to 0.5:1 results in a significant increase in the fraction of hydrogen in the dry product gas from approximately 19% to 26% while the percentage of carbon monoxide decreases from approximately 32% to 22% whereas the fraction of carbon dioxide remains fairly constant at approximately 43%. In other words, the ratio of H₂/CO increases with the addition of steam to the gasifier. This can be attributed to the fact that addition of excess steam to the gasifier lowers the temperatures which favor the conversion of char to CO and H₂ and the generated CO is converted to CO₂ and more H₂ through water gas shift reaction [35]. The gas compositions can also be compared by increasing the corn stover percentage in the blend, and

holding the O₂:steam ratio constant. An increase in corn stover percentage yields lower hydrogen and carbon monoxide while increasing the carbon dioxide yield in the product gas (Figure 6(a)). For illustration, at a steam:O₂ ratio of 2:1, the fraction of carbon monoxide decreases from 21% to 13%, hydrogen percentage decreases from 27% to 17% while carbon dioxide increases from 42% to 56% when corn stover is increased from 0% to 30% in blends with sub-bituminous coal. This observed effect is significant with confidence intervals greater than 95%.

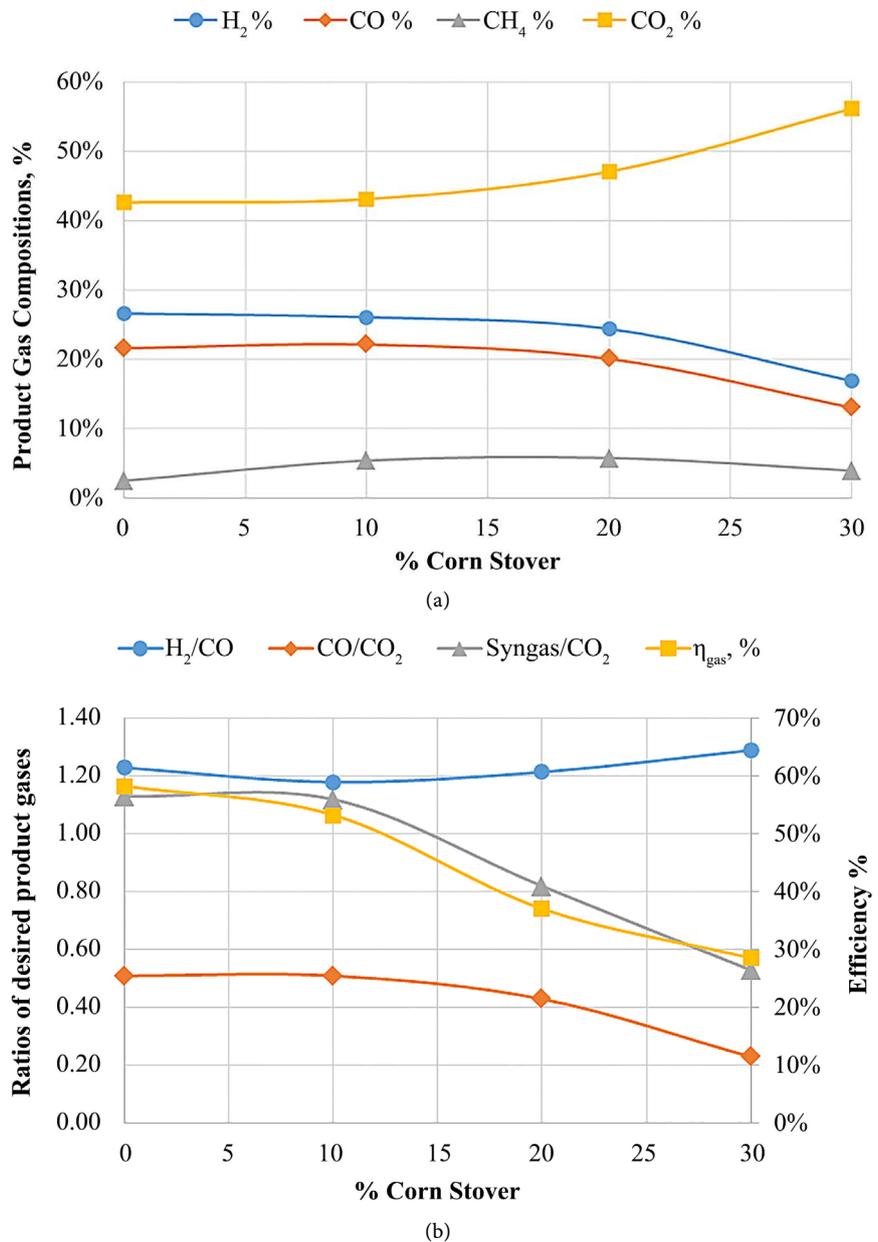


Figure 6. (a) Effect of increasing percentage of corn stover on the product gas compositions in its blends with DECS-38 Sub-Bituminous coal (Steam/O₂ = 2); (b) Effect of increasing percentage of corn stover on the desired product gas ratios and efficiency in its blends with DECS-38 Sub-Bituminous coal (Steam/O₂ = 2).

4.1.4. Stainless Steel Reactor: Blends with Switchgrass

The gasification of blends of both coals with switchgrass was also performed under similar conditions as that of corn stover and the results were compared for compositions and efficiencies obtained as shown in **Table 7** and **Table 8**.

Table 7. Average composition of product gases obtained during gasification of blends of sub-bituminous coal and switchgrass at varying O₂/steam ratios in the lab scale stainless steel moving bed gasifier.

Feed	Process Conditions			Ratio of Product Gases			Average Product Gas Compositions				$\eta_{gas}\%$	
	Air	O ₂	Steam	Steam/O ₂	H ₂ :CO	CO:CO ₂	(H ₂ + CO):CO ₂	H ₂ %	CO%	CH ₄ %		CO ₂ %
	ml/min	ml/min	ml/min									
90% SB + 10% SG		650	325	0.5	0.61	0.63	1.02	17.7	28.9	5.21	45.8	27.1
		650	650	1	0.89	0.53	1.00	21.7	24.3	5.75	46.0	30.4
		650	1300	2	1.15	0.49	1.05	26.3	22.8	4.69	46.6	53.5
	1400	300	150	0.5	0.96	0.28	0.55	4.15	4.32	0.00	15.4	17.3
	1400	300	300	1	1.15	0.28	0.61	5.04	4.38	1.18	15.4	25.7
	1400	300	600	2	1.50	0.26	0.65	6.19	4.12	1.78	15.9	29.8
		650	325	0.5	0.72	0.37	0.63	14.1	19.7	5.42	53.6	23.5
80% SB + 20% SG		650	650	1	1.01	0.32	0.63	16.6	16.4	4.50	52.1	30.7
		650	1300	2	1.22	0.28	0.62	18.1	14.8	4.65	53.57	33.3
	1400	300	150	0.5	0.73	0.23	0.40	3.01	4.14	0.00	17.6	16.4
	1400	300	300	1	0.92	0.25	0.47	3.96	4.33	0.70	17.5	24.8
	1400	300	600	2	1.05	0.26	0.53	4.87	4.65	0.00	17.9	28.9
70% SB + 30% SG		650	325	0.5	0.65	0.26	0.33	10.3	16.0	5.73	62.5	21.8
		650	650	1	0.82	0.23	0.43	11.8	14.5	4.28	62.0	26.8
		650	1300	2	1.31	0.16	0.46	13.0	10.0	4.78	63.4	28.3
	1400	300	150	0.5	0.43	0.32	0.46	3.19	7.43	0.00	23.1	14.8
	1400	300	300	1	0.64	0.29	0.47	4.61	7.21	0.00	24.9	22.1
	1400	300	600	2	0.71	0.29	0.50	4.98	7.01	0.00	24.1	27.7

Table 8. Average composition of product gases obtained during gasification of blends of lignite coal and switchgrass at varying O₂/steam ratios in the lab scale stainless steel moving bed gasifier.

Feed	Process Conditions			Ratio of Product Gases			Average Product Gas Compositions				$\eta_{gas}\%$	
	Air	O ₂	Steam	Steam/O ₂	H ₂ :CO	CO:CO ₂	(H ₂ + CO):CO ₂	H ₂ %	CO%	CH ₄ %		CO ₂ %
	ml/min	ml/min	ml/min									
90% LG + 10% SG		650	325	0.5	0.55	0.56	0.87	16.6	30.0	5.96	53.6	37.1
		650	650	1	0.72	0.46	0.80	17.5	24.4	5.62	52.5	50.7
		650	1300	2	0.82	0.43	0.78	18.3	22.3	4.82	52.0	59.0
	1400	300	150	0.5	0.78	0.40	0.72	5.75	7.33	0.00	18.2	30.3
	1400	300	300	1	0.84	0.37	0.68	5.91	7.01	0.00	18.9	33.1
	1400	300	600	2	0.88	0.38	0.71	6.08	6.9	0.00	18.1	38.0

Continued

		650	325	0.5	0.60	0.30	0.48	11.5	19.0	5.44	63.2	34.4
		650	650	1	0.94	0.24	0.46	14.4	15.3	4.00	64.1	36.7
80% LG + 20% SG		650	1300	2	1.23	0.20	0.44	15.6	12.7	4.51	64.0	46.5
	1400	300	150	0.5	0.72	0.25	0.43	3.29	4.55	0.00	18.4	24.1
	1400	300	300	1	0.70	0.38	0.65	4.37	6.24	0.00	16.3	34.9
	1400	300	600	2	0.72	0.44	0.76	5.15	7.18	0.00	16.1	39.7
		650	325	0.5	0.44	0.21	0.30	6.35	14.3	3.51	69.8	20.1
70% LG + 30% SG		650	650	1	0.67	0.18	0.30	8.53	12.8	3.00	70.9	21.9
		650	1300	2	0.78	0.16	0.29	9.13	11.6	3.00	71.1	25.5
	1400	300	150	0.5	0.59	0.22	0.34	2.02	3.44	0.00	15.8	14.6
	1400	300	300	1	0.58	0.23	0.36	2.48	4.30	0.00	18.9	19.0
	1400	300	600	2	0.59	0.26	0.42	2.96	5.00	0.00	18.9	23.0

Under similar experimental conditions, the product gas compositions obtained with switchgrass blends follow trends that are in comparison with corn stover blends. But it can be clearly observed that the overall energy efficiencies obtained are much lower than that of blends with corn stover. This is because a much higher fraction of carbon dioxide is generated during gasification of these blends. A possible reason for this could be the fact that removal of higher percentage of volatile matter from switchgrass during pyrolysis may be resulting in char with higher void fraction due to which the interaction with incoming steam is reduced, thereby, generating more carbon dioxide through combustion in the bottom zone of the gasifier.

5. Conclusions

The main objective of this work was to investigate the thermochemical conversion of blends of coal and biomass to create an alternative technology for offsetting the load on the usage of fossil fuels in producing energy. Gasification characteristics of the single fuels, as well as blended feedstocks, were evaluated with an emphasis on improving the producer gas composition. Based on the research work performed, some of the major conclusions and contributions are enlisted:

- 1) A laboratory-scale moving gasification system has been designed and constructed for the purpose of gasifying the feedstock materials. The efficiency and product gas compositions obtained reveal that utilizing an inner stainless-steel tubing better promotes heat transfer upwards in the axial direction when compared to utilizing quartz insulation. The trends of the product gas compositions are similar to those obtained using an inner quartz lining. However, the percentage of hydrogen generated at same operating conditions is much higher due to the increase in bed temperature (complete consumption of oxygen which was not achieved when using quartz insulation) and transfer of heat upwards in the axial direction and thus, better heat utilization which improved the overall efficiency

by at least 20% when the steam concentration was at its maximum in the gasifier. Also, unlike the quartz insulation where the efficiency increased only until a certain point and the maximum steam/O₂ ratio that could be utilized was 1.5, in this experimental set-up, the efficiency increased steadily until a steam/O₂ ratio of 2:1. In addition, the ratios of H₂/CO, CO/CO₂ and syngas/CO₂, which dictate the quality of the product gas, are markedly higher as compared to the experimental design utilizing an inner quartz lining.

2) Using a mixture of nitrogen and oxygen in the feed gas stream, the inlet gas stream flow rate of 1625 ml/min and oxygen percentage of 40% provides the highest energy conversion efficiency and a max CO:CO₂ ratio of approximately 3:1. The bed temperature range during the gasification of sub-bituminous coal was generally observed to be between 600°C and 800°C for the experiments with varying steam ratios and between 800°C and 1000°C for the experiments with varying oxygen partial pressures.

3) Using pure oxygen and steam in the inlet gas stream, energy conversion efficiencies greater than 50% were obtained for blends of both coals with corn stover at a steam to oxygen ratio of 2:1. Also, replacing pure oxygen with air as the gasifying agent greatly improved the H₂:CO ratios (greater than 2:1 in some cases) and overall efficiency in blends with corn stover. This is due to the fact that the addition of air at a much higher flow rate than oxygen promoted the heat transfer axially along the gasifier, resulting in better temperature distribution and hence, promoting the reaction char with steam. In contrast, blends with switchgrass are not very effective with respect to the overall gasification characteristics. This could be speculated to be because of the fact that no synergy and interactions exist in blends with switchgrass and addition of switchgrass to a coal source may not be very effective from the viewpoint of generating high quality producer gas for downstream operations (Fischer-Tropsch synthesis, etc.).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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