



## Research article

## Investigation into co-gasifying Indian coal and biomass in a down draft gasifier – Experiments and analysis



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## ABSTRACT

Gasification is an energy efficient and environmentally clean process to generate heat and electricity, and biomass and coal have found wide usage as fuels. In India, biomass gasification has received significant attention, while, coal gasification has been less studied due to its lower reactivity and the potential difficulty in handling arisen due to high ash contents of domestic coals. In the current study, coal and biomass were co-gasified in a downdraft reactor, and the challenges originating due to the varying thermo-physical properties of both the fuels: like density, volatile fraction, ash content, etc. to achieve an engine quality gas are addressed. A fundamental study was undertaken and the fuels for flaming and glowing times were characterized. Further, the overall conversion time was estimated.

Gasification studies were conducted using an open top downdraft gasification system of 10 kg/h capacity, with different fuel blends, and varying reactants (air, air + steam), and it was observed that the fuel blend with higher percentage of coal generated severe clinker due to ash fusion. Steam was found beneficial in increasing the carbon conversion, reducing clinkers and also improving gas quality. The best performance was achieved with biomass to coal ratio of 85:15 on weight basis. With 94% carbon conversion and 65% cold gas efficiency, the present study successfully establishes the optimum operating conditions for stable operation with multi-fuel feed.

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## 1. Introduction

In view of increased concern about limited availability of fossil fuels and high level of air pollutions, energy efficient technologies are gaining importance, and gasification being highly efficient and environment friendly technology has received significant attention [1]. Gasification makes use of carbon based feedstocks to generate a combustible gas known as syngas which can be used as a fuel for electricity generation, thermal application, combination of both or for the production of chemicals. Coal and biomass are the most common feedstocks, while, the use of various other organic materials such as plastics, municipal solid waste, refinery waste, etc. have also been attempted [2].

Usage of coal has received broad attention because it is the most abundantly available fossil fuel while biomass is a renewable source of energy [3]. Conventionally, biomass or coal is gasified separately, and the individual technology has reached maturity. However, research is progressing towards further improvisation of the overall process and the technology, and many researchers working towards achieving this goal. While, some others have focused on co-gasification of coal and biomass as it is found to be advantageous over biomass or coal gasification alone [4–10].

Biomass gasification generates higher level of tars as its structure is more complex than coal, while coal gasification results in higher SO<sub>x</sub> and NO<sub>x</sub> attributing to higher percentage of inherent sulfur and nitrogen [11]. Besides, CO<sub>2</sub> emission is also higher in coal gasification while biomass has CO<sub>2</sub> neutral cycle [5]. Use of biomass with coal is considered to be important in terms of improved overall reactivity of coal, for biomass having higher volatile matter would enhance the heterogeneous reaction rates. Their co-blending could be an attractive option from economic, environmental and social points of view in lowering carbon footprint on the environment [12].

In general, low inorganic matter present in biomass could be an added advantage during co-gasification with coal. However, if the presence of mineral matters having low ash softening point is high, it can also be detrimental as it can act as a flux for ash fusion. The two fuels being potentially very different in many respects, including composition and reactivity [13], co-gasification may result in many process problems. Ignition, carbon conversion, ash fusion are some of the important issues that need attention. As far as Indian coal is concerned ash fusion phenomenon could be a major barrier because Indian coals are characterized with high ash, and co-firing/gasification may significantly lower the ash melting temperature and consequently ash particle may deposit on heat transfer surfaces [14]. Operating conditions and gasifier configurations are, however, two important parameters by which ash deposition can be minimized.

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Among the different configurations, fluidized bed systems have received wide attention while the fixed bed system for co-gasification has rarely been studied [6–10]. This is because the fluidized systems possess a major advantage of handling a wide variety of fuels with broad particle-size distributions, while the fixed bed configuration exhibits high carbon conversion efficiency and is best suited for small scale installations [15]. Fluidized bed configuration results in higher tar content due to the limited contact between the char and the products of pyrolysis. Besides, in co-gasification, its fluidity might be affected by (i) agglomeration of the low melting point ash present in the biomass and (ii) varied density between biomass and coal [8].

Many researchers have studied the co-gasification phenomenon in fluidized bed system, with different types of biomass and coals, and the parameters controlling the performance of the gasifier have been identified. Temperature, biomass to coal ratio, steam to fuel ratio, air to fuel ratio and types of biomass/coal are the most widely studied parameters and they are found to have significant influence on gasifier outputs: gas composition, gas yield, heating value, efficiency, etc. The major findings reported in the literature pertaining to coal–biomass co-gasification are summarized in Table 1.

It is observed from Table 1 that the type of fuel and the fuel blend have a strong influence on the gasifier performance. For low grade coal, addition of biomass improves the overall reactivity, and hence, the better output. Lapuerta et al. [16] reported ~20% improvement in gasification efficiency when biomass percentage in the fuel blend is changed from 0 to 90. Pan et al. [6] observed improved performance in terms of heating value and carbon conversion when pine chips were added to two different types of coals: black coal, a low-grade coal (ash: 74.2%) and Sabero coal (ash: 34.6%), a refuse coal. McLendon et al. [7] studied sub-bituminous, bituminous/saw dust and sub-bituminous/sawdust blends in a high pressure fluidized bed system and observed marked differences in operation when sub-bituminous or bituminous coal was used alone. They observed improved transport properties when coals were blended with sawdust. Feroso et al. [4] reported improvement in H<sub>2</sub> production with coals having higher carbon content and better reactivity. They studied four different ranked coals (semi anthracite and bituminous from two different locations) with two different types of biomass (olive pulp and pine saw dust) and observed increase in CO and CO<sub>2</sub> with the carbon content of coals. Sub-bituminous coal resulted in higher H<sub>2</sub> than semi anthracite due to

higher reactivity. Vellez et al. [8] demonstrated the feasibility of co-gasifying coal with three different types of biomass (sawdust, rice and coffee husks) with biomass ratio up to 15%, and reported increase in H<sub>2</sub> production and decrease in energy efficiency with increase in biomass percentage. Further, they commented that the requirement of steam for getting similar gas composition is different with different biomass tested. Coffee husk needed lower steam flow rate than sawdust. In the same line, Li et al. [9] studied co-gasification of coal and pine saw dust, and observed that with increase in steam to carbon ratio, the combustibles concentrations first increase, reach a maximum and then decrease. Further, they reported that continuous stable operation could be achieved for biomass ratio not more than 33% by weight.

While the factors affecting co-gasification in fluidized bed gasification system are nearly established, the studies on fixed bed system are still scarce. So far, we could access to only one published report, where co-gasification of coal and biomass in a downdraft system is discussed [10]. Kumabe et al. [10] conducted this study with an aim to establish the operating conditions for generating gases to use for synthesis of liquid fuels, and reported higher biomass percentage is favorable for Dimethyl ether synthesis. Further, they observed increase in cold gas efficiency with increase in biomass content, and reported successful operation even with only coal. However, the ash content in the coal they used was only 1.1% and this low value might not have altered the system performance through clinker formation due to ash fusion which otherwise is expected to have a significant effect as is observed with higher ash contents biomass.

The ash contents in Indian coals have wide variations, mostly on the higher side (5–50%), and the current study is focused to address the issues of handling some moderately high ash content coals along with biomass in a downdraft reactor that had been well tested with various biomass in the recent past [3,17–22]. The unique feature of this reactor is that it has a dual air entry system, from top as well as through nozzles, and this results in low tar due to high retention time of gases at elevated temperature.

In this work, a variety of biomass was co-gasified with Indian coal and the performance of the gasifier was assessed with different fuel blends. Emphasis was given on the stabilization of the process, and the conditions for optimum operating conditions were evaluated aiming similar quality gas as that obtained in biomass gasification alone. Single particle analysis was carried out first, followed by the gasification studies, where the usability of high ash coal in the downdraft reactor is discussed.

**Table 1**

A summary of previous coal/biomass gasification studies.

Author/gasifier type	Fuel/combination	Remark	Ref.
Pan et al. 2000 Fluidized	<ul style="list-style-type: none"> <li>Black coal/pine chips</li> <li>Sabero coal/pine chips</li> <li>Biomass/coal ratio range: 100/0 to 0/100</li> <li>Sabero coal ash: 74.2%</li> <li>Black coal ash: 34.6%</li> </ul>	<ul style="list-style-type: none"> <li>Fuel blend influenced gas composition, heating value, efficiency, carbon conversion, etc.</li> <li>Improved performance with biomass addition.</li> <li>Minimum % of pine chips required to have improved thermal efficiency: Sabero coal: 40%, black coal: 25%.</li> </ul>	[6]
McLendon et al. 2004 Fluidized	<ul style="list-style-type: none"> <li>Sub-bituminous coal–ash: 8.9%</li> <li>Bituminous coal–ash: 6.8%</li> <li>Sub-bituminous coal/sawdust blend (85/15, 75/25, 65/35, % wt/wt)</li> <li>Bituminous coal/sawdust blend (75/25, % wt/wt)</li> </ul>	<ul style="list-style-type: none"> <li>Gas composition was affected by coal type and coal/biomass blend.</li> <li>Carbon conversion improved with increase in biomass ratio. 85/15 to 65/35 blend: 67% to 93%.</li> <li>Without biomass, operation with bituminous coal was not possible due to heavy clinkering.</li> </ul>	[7]
Vellez et al. 2009 Fluidized	<ul style="list-style-type: none"> <li>Sub-bituminous/rice husk</li> <li>Sub-bituminous/sawdust</li> <li>Sub-bituminous/coffee husk</li> <li>Biomass ratio range: 6–15%</li> <li>Coal ash: 15.4%</li> </ul>	<ul style="list-style-type: none"> <li>Higher biomass proportions resulted in increased H<sub>2</sub> but lowered energy efficiency.</li> <li>Sawdust resulted in better performance.</li> </ul>	[8]
Li et al. 2010 Fluidized	<ul style="list-style-type: none"> <li>Coal and pine sawdust</li> <li>Biomass ratio range: 0–33%</li> <li>Coal ash: 9.2%</li> </ul>	<ul style="list-style-type: none"> <li>Increased biomass ratio resulted in decrease in gasified carbon at the same equivalence and steam to carbon ratios.</li> </ul>	[9]
Kumabe et al. 2007 Downdraft	<ul style="list-style-type: none"> <li>Japanese cedar/Mulia coal</li> <li>Biomass ratio range: 0 to 1 (mole basis)</li> <li>Coal ash: 1.1%</li> </ul>	<ul style="list-style-type: none"> <li>With an increase in the biomass ratio, the conversion to gas on a carbon basis increased.</li> <li>Increase in biomass ratio resulted in lower H<sub>2</sub></li> </ul>	[10]

The article is arranged in the following order. Section 2 provides the details on the material and methods; Section 3 describes the single particle and packed bed analyses, Section 4 presents the results, and the conclusion is highlighted in Section 5.

## 2. Materials and methods

In this work, three different biomass: casuarina wood, coconut shell, agro-residue pellets were used in combination with two types of Indian coals, one with 12% ash and the other with 21% ash. For comparison, a variety of Indonesian coal was also used. Table 2 lists their thermo-physical properties. Moisture, volatile matter, ash content were determined through the proximate analysis following ASTM standard D7582, and the chemical compositions (carbon, hydrogen, oxygen, nitrogen and sulfur) were evaluated using Thermo Fischer Flash 2000 Elemental Analyzer. High heating values were estimated using a bomb calorimeter, make: Parr instrument.

### 2.1. Experimental setup: gasification system and instrumentation

Gasification experiments were carried out in a fixed bed open top downdraft reactor. Fig. 1 shows the details of the system components. The reactor is made of stainless steel with ceramic lining inside, and is coupled to a duct for exiting gas and is further connected to a cyclone and scrubbers. The generated gas is flared in a burner located next to the scrubber. A blower is used to provide the necessary suction to draw air from two sources, (i) an inlet nozzle, and (ii) from top of the reactor. About 60–65% of the air comes from the top and the rest from the side air nozzles. The advantage of this system over the classical closed top design where air entry is only through the nozzle is that the higher temperatures in the vicinity of the air nozzles results in better conversion of char particles. The dual air entry permits establishing a flame front moving towards the top of the reactor and is favors a high residence time for the gases at elevated temperatures, eliminating the higher molecular weight compounds [22]. Further, an effective screw based system is provided at the bottom for periodical removal of ash.

The various parameters that have been monitored during the experiment are: bed temperature, exit gas temperature, biomass consumption rate, ash/char extraction rate, gas flow rate, gas composition and pressure drops across the reactor, cyclone and scrubbers. Temperature measurements were carried out using K type thermocouples. Five thermocouples were inserted at an equal spacing of 100 mm along the length of the reactor and data were acquired using a high speed data acquisition system (IOtech, PDAQ 56) in every second. Gas flow rate was measured using a calibrated venturimeter, and biomass consumption using a strain gauge based weighing balance with least count: 1 kg. An online gas analyzer (SICK Maihak: S715 Extractive gas analyzers) with measurement range for CO/CO<sub>2</sub>/H<sub>2</sub>: 0–100% and for O<sub>2</sub>/CH<sub>4</sub>: 0–25% by volume was used for measuring gas composition, and data were

acquired at an interval of 0.5 min. Pressure differences at various locations were measured using U tube water manometers. In the later part of experiments, steam was used, and it was generated using an electric boiler at saturated condition, 0.2 MPa pressure, and further superheated to 600 K using a superheater.

### 2.2. Analyses of experimental results

The gasifier performance was assessed upon: higher heating values (HHV) cold gas efficiency and carbon conversion efficiency. HHV is calculated using the following equation:

(i)

$$\text{HHV}(\text{MJ}/\text{kg}) = \frac{\text{CO}(\%) \times 283 + \text{H}_2(\%) \times 242 + \text{CH}_4(\%) \times 795}{\text{MW}_{\text{mix}} \times 100}$$

“%”: volumetric percentages of the product gas and “MW<sub>mix</sub>”: tmixture molecular weight.

(ii) Cold gas efficiency ( $\eta_c$ ) is calculated as follows.

$$\eta_c = \frac{\text{product gas flow rate (Nm}^3/\text{h)} \times \text{HHV of gas (MJ/m}^3\text{)}}{\text{solid fuel flow rate (kg/h)} \times \text{HHV of solid fuel (MJ/kg)}}$$

Carbon conversion to gas  $X_1$  is calculated based on the gas analysis data.

(iii)

$$X_1(\%) = \frac{Y \times (\text{CO}(\%) + \text{CO}_2(\%) + \text{CH}_4(\%)) \times 12}{22.4 \times C(\%)}$$

“C (%)”: mass percentage of carbon obtained in the ultimate analysis of coal. “Y (%)”: dry gas yield.

(iv) Carbon conversion to char is calculated as

$$X_2(\%) = \frac{\text{Carbon in residual solid}}{\text{Carbon in fuel}}$$

Carbon in residual solid was estimated using elemental analyzer.

## 3. Single particle and packed bed analyses

The current study involves two different aspects; the first one is directed towards single particle burning behavior of fuels, while the second aspect involves co-gasification of coal and biomass in the open top downdraft system. Single particle analysis gives an insight to the conversion timescale which is important to know a priori as the physical-chemical properties of coal and biomass are different, and biomass undergoes early decomposition due to weak covalent bonds and higher content of oxygen than coal [13,23]. Earlier studies conducted in this

**Table 2**  
Solid fuels characterization.

Sample	Moisture as received (%)	Ash (%) dry basis	Volatile (%) dry basis	C	H	N	S	O	Particle density (kg/m <sup>3</sup> )	Bulk density (kg/m <sup>3</sup> )	HHV (MJ/kg)	Mean particle size (mm)	Empirical formula
				(%)	(%)	(%)	(%)	(%)*					
Moisture and ash free basis													
Indian coal (type I)	8	21	30	53.2	3.2	3.2	0.42	39.9	1535	750	18.2	3–5	CH <sub>0.74</sub> O <sub>0.56</sub> N <sub>0.05</sub> S <sub>0.003</sub>
Indian coal (type II)	10	12	37	68.6	3.8	2.3	0.57	24.6	1362	730	22.5	3–5	CH <sub>0.67</sub> O <sub>0.27</sub> N <sub>0.03</sub> S <sub>0.003</sub>
Indonesian coal	33	3	29	–	–	–	–	–	890	460	–	–	–
Wood (casuarina)	10	<1	81	44.4	6.3	0.60	–	48.8	610	340	17.5	10–15	CH <sub>1.7</sub> O <sub>0.82</sub> N <sub>0.01</sub>
Coconut shell	10	<2	80	40.5	6.5	0.60	–	52.3	850	330	16.9	10–15	CH <sub>1.9</sub> O <sub>0.97</sub> N <sub>0.001</sub>
Agro-residue pellets	10	12	60	42.5	5.7	51.6	–	0.20	1280	450	16.3	Dia: 8, length: 18	CH <sub>1.6</sub> O <sub>0.91</sub> N <sub>0.004</sub>

“–” data not available.

\* By difference.

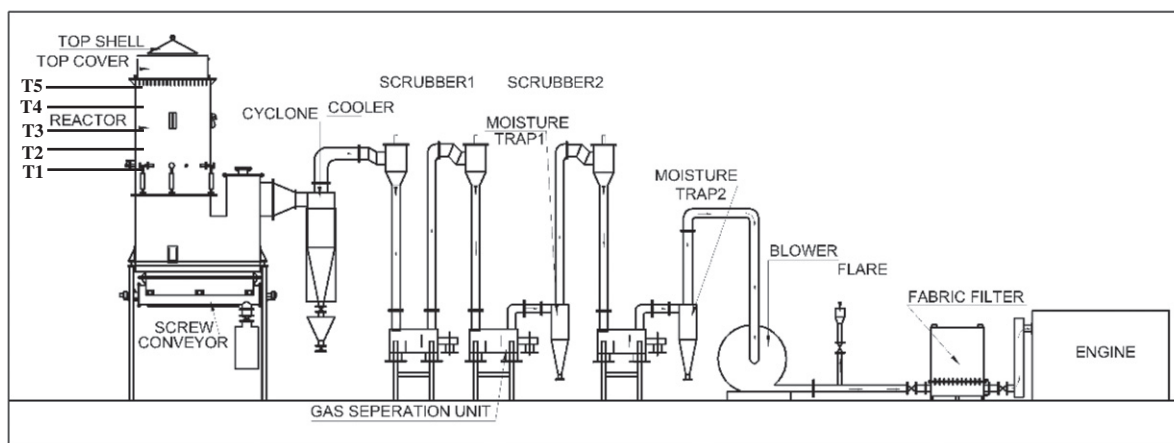


Fig. 1. Schematic of the gasification system with all the elements [22].

laboratory demonstrate that the feedstock size for a gasifier can be predetermined with single particle study that can well simulate the two important processes of gasification (i) pyrolysis and (ii) char combustion, and correlation can be obtained between the particle size and conversion time scale [24,25].

Pyrolysis encompasses issuance of volatile matters and char combustion invokes oxidation, reduction reactions. Box 1 summarizes the major reactions encountered in gasification.

During pyrolysis, a front moves inward of the fuel particle and as a result gases are issued from the surface and further combusted in the gas phase with a flame enveloping the particle (Fig. 2). In the next phase, the flame terminates when the pyrolysis front reaches the center and the oxidizing agents diffuse to the surface of the porous char and heterogeneous chemical reactions starts, leading to consumption of carbon leaving behind residual ash [25]. This phase is known as glowing combustion due to the radiating nature of fuel.

Practically, flaming time is defined as the time span corresponding to ignition of the sample to the time of quenching of flame, and the glowing time is the time taken by the char particle to completely oxidize. Unlike biomass, char burning is an important phenomenon in coal as it has high carbon content and the char conversion time in coal is much longer. Char combustion rate under diffusion limited conditions is very slow [11]. It has been established that pyrolysis is a diffusion limited process, and it has an important bearing on the conversion time scale, with time for conversion of  $\sim d_0^2$ , where  $d_0$  is the initial diameter of the particle.  $d^2$  law prevails both in the flaming and glowing combustion regimes [26]. In co-gasification, effective conversion of both coal and biomass char is important and the types of fuel has a significant effect on different output parameters such as gas composition, carbon conversion, cold gas efficiency, tar yield, calorific value, and emission

[27]. Besides, stability of the system is also affected by different ranked coals [4].

In the current work, the flaming and glowing combustion has been studied for fuels with sphere diameter between 5 and 20 mm, and having optimized the particle size, gasification experiments were conducted to obtain the throughput for the reactor with different biomass to coal ratios with the focus on ash fusion, consistent gas quality and related performance parameters.

The performance of the gasifier system was assessed considering two major aspects: (i) stability of the system and (ii) quality of gas. The quality of the producer gas depends on various factors: moisture and ash contents of the feed, particle size, percentage of fuel blend, amount of air/steam flow rate, position of air nozzle, reduction zone volume, etc. [28]. In the current study, in all experiments, sun-dried fuels were used with moisture percentage between 10 and 12%. Biomass to coal ratio was varied, and the gas quality was evaluated for four different fuel blends (biomass to coal to ratio: 75/25, 50/50, 25/75, and 85/15, % wt/wt). Fuel feed rate was maintained between 8 and 9 kg/h, and the average duration of the tests were between 8 and 8.5 h. Steam to carbon ratio was varied from 0.07 to 0.2 on mole basis. While air to fuel ratio was maintained between 1.8 and 2 with corresponding equivalence ratios: 0.30–0.35.

## 4. Results and discussion

### 4.1. Fundamental studies: flaming and glowing time

Prior estimating the flaming and glowing times, the typical ignition times for different coals and biomass were estimated, and the results are presented in Table 3. It is observed that the ignition time increases

### Box 1

Major gasification reactions.

				$\Delta H$ (kJ/mol)
Oxidation:	R(1)	$\text{CO} + 1/2\text{O}_2 \rightleftharpoons \text{CO}_2$	(Volatiles)	– 283
	R(2)	$\text{H}_2 + 1/2\text{O}_2 \rightleftharpoons \text{H}_2\text{O}$		– 241.9
	R(3)	$\text{C} + 1/2\text{O}_2 \rightleftharpoons \text{CO}$	(Char)	110.6
	R(4)	$\text{C} + \text{O}_2 \rightleftharpoons \text{CO}_2$		– 393.5
Reduction:	R(5)	$\text{C} + \text{CO}_2 \rightleftharpoons 2\text{CO}$	(Boudouard)	172.5
	R(6)	$\text{C} + \text{H}_2\text{O} \rightleftharpoons \text{CO} + \text{H}_2$	(Water gas primary)	– 131.4
	R(7)	$\text{C} + 2\text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + 2\text{H}_2$	(Water gas secondary)	90.2
	R(8)	$\text{C} + 2\text{H}_2 \rightleftharpoons \text{CH}_4$	(Methanation)	– 74.9
	R(9)	$\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$	(Water gas shift)	– 42.3
	R(10)	$\text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3\text{H}_2$	(Steam reforming)	+ 206
	R(11)	$\text{CH}_4 + \text{CO}_2 \rightleftharpoons 2\text{CO} + 2\text{H}_2$	(Dry reforming)	+ 247



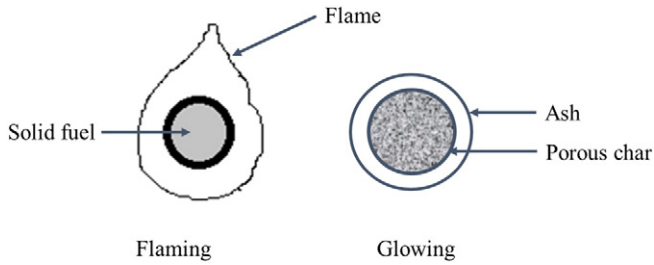


Fig. 2. Flaming and glowing.

**Table 3**  
Ignition, flaming and glowing times of solid fuels.

Fuels	Diameter (mm)	Ignition time (s)	Flaming time, $t_f$ (s)	Glowing time, $t_g$ (s)	Total time, $t_b$ (s)
Indian coal (type I)	5 ± 0.5	7	27	604	646
	7 ± 0.5	7	52	842	894
	10 ± 0.5	13	91	1684	1775
Indian coal (type II)	5 ± 0.5	5	48	403	430
	7 ± 0.5	5	64	791	855
	10 ± 0.5	12	121	1629	1750
Indonesian coal	10 ± 0.5	8	71	780	851
	15 ± 0.5	10	155	1580	1735
	20 ± 0.5	<30	260	3485	3745
Wood	7 ± 0.5	2	31	107	138
	10 ± 0.5	<5	72	189	261
	15 ± 0.5	5	116	477	593
Pellets	10 ± 0.5	6	74	525	599
	15 ± 0.5	8	125	1170	1295
	20 ± 0.5	<15	288	2041	2329

with the increase in particle diameter, and for coal, it is larger than the biomass. It must be indicated that wood spheres were easy to ignite using a spirit lamp while for the same equivalent diameter, coal spheres required a blow torch. The reason for higher energy requirement in the case of coal than biomass is found to be associated with higher density and thermal conductivity that results in higher internal and external resistances defined as  $((\rho c_p L_c^2)/k)$  and  $((\rho c_p L_c)/h)$ . ( $\rho$  : particle density,  $c_p$  : specific heat,  $L_c$  : characteristic length,  $k$  : thermal conductivity,  $h$  : heat transfer coefficient) respectively. For the same particle diameter, coal has almost 4 times higher external and internal resistances than biomass. Pellets having higher density than wood also exhibited the same trend as that of coal. Wood having lower density favoring higher diffusivity of oxidant was easier to ignite. The same is true for the Indonesian coal too.

High volatile matter in biomass results in longer flaming time than coal, and further the glowing time is larger than flaming time for all the fuels tested. It is observed from Table 3 that for the wood sphere and pellets, the glowing time is about 4 times higher than the flaming time, while for Indian coal type I, the same is higher by ~16 times and the type II by ~13 times. Indonesian coal shows ~10 times longer flaming duration. Higher glowing time in coals (both types) suggests that the heterogeneous char reaction being slower than the flaming process. In coal, the time required for glowing is far larger than that for wood. Apart from the higher carbon content and diffusional resistance for the reactant to flow, presence of high mineral matter in coal also prevents the access of oxidizing agent to the char and consequently the reaction time gets extended. Higher amount of ash could lead to the formation of char having low surface area due to filling up of pores by fusion of molten ash [29] and hence low reaction rate. Specific surface area and pore structure of char affect the transport of gaseous reactants and products [30].

For the same particle diameter, the Indian coal (type I) exhibits higher glowing but lower flaming time than type II coal, due to the lower volatile percentage. For the particle diameter of  $10 \pm 0.5$  mm, the Indonesian coal and pellets exhibit similar burn time when normalized it with density. Fig. 3(a) and (b) presents the density normalized flaming and glowing time of the selected fuels on log–log plots. It has been observed that for the same equivalent diameter, the normalized flaming time is nearly same for all the fuels studied, and the conversion time during flaming varies with diameter index 1.5 to 1.8, while, during glowing, the index ranges between 1.7 and 2. Table 4 shows the correlations between burn time and the fuel diameter obtained through curve fit.

In comparison to wood, the time taken by coal in glowing is higher. Shorter burn time in wood is attributed to its higher reactivity. The presence of high ash in coal prevents the access of oxygen to char for the oxidation and thus increase in burn time. The time scale for Indonesian coal and Indian coal type II is nearly same while wood exhibits the lowest conversion time for the same equivalent diameter as that of coal.

The rates of char conversion are mainly determined by surface area, surface accessibility, carbon active sites and additional catalytic effects created by the presence of inorganic matter [29]. Coal char having lower porosity and surface area ( $50\text{--}100 \text{ m}^2/\text{g}$  for coal char against  $200\text{--}300 \text{ m}^2/\text{g}$  for wood char, according to BET measurement) than wood char exhibits lower reactivity, and in order to have a similar conversion time scale, when co-gasified with wood, it is important to maintain the coal particle sizes lower than that of wood towards ensuring conversion process to be completed inside the reactor. It is to be mentioned that particle size is the only controlling parameter for a better conversion, since for a given mass flux, the residence time of the solids inside the reactor is fixed.

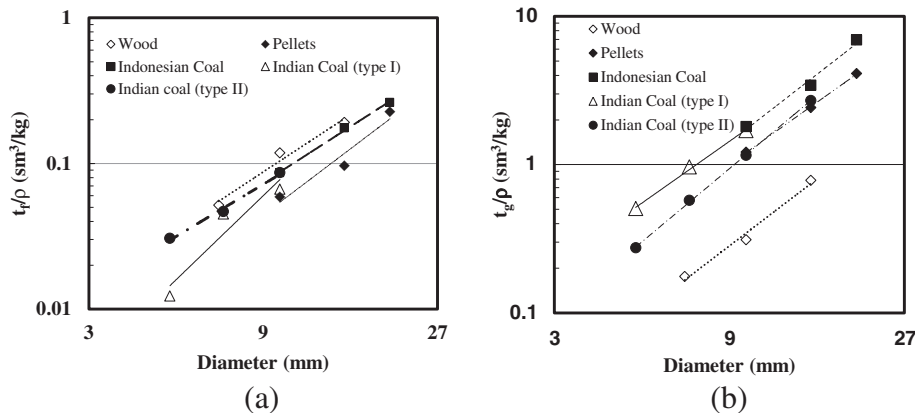


Fig. 3. Density normalized (a) flaming time (b) glowing time.

Based on the results presented in Table 4 and Fig. 3, it is possible to arrive at a particle size for the two different fuels having different properties for improved carbon conversion profile. For the reactor diameter chosen wood particle size of about 10 mm is found ideal based on the earlier studies [22]. The current study reveals that, in case of wood with equivalent diameter 10 mm, the coal particle size should be of ~3–5 mm so that the conversion time matches. Particle size has a significant influence on the gas quality [31–34]. Smaller particle size results in better conversion, while too fine particles might result in severe pressure drop across the bed, inducing channel burning [35].

In the current study, it was observed that with the increase in sphere diameter, the overall carbon conversion is affected. Formation of ash in the outer layer of the sphere due to the reaction at interface, and subsequent collapsing of pores due to ash fusion might lead to lower diffusion of oxidizer to the core leading to higher internal resistance as described before. Fuel blending also affects conversion process. The following section discusses the systematic strategy adopted to arrive at the optimum fuel blend.

#### 4.2. Gasification studies: optimization of various parameters

Initial experiments were conducted with three different fuel blends (biomass to coal to ratio: 75/25, 50/50, 25/75, % wt/wt), and the performance of these blends were compared with only biomass and coal too. Majority of the experiments were conducted with wood, while coconut shell has also been tested and the performance is reported towards the end of this paper. Fig. 4 compares the average gas compositions for the three different fuel blends mentioned above with only coal and biomass.

It is evident that the biomass gasification results in higher percentage of H<sub>2</sub>, CO and CO<sub>2</sub> than coal gasification, while CH<sub>4</sub> remain nearly same. The increase in H<sub>2</sub> with higher percentage of biomass is attributed to higher reactivity of biomass [6,36–38]. Biomass having higher oxygen, contributes higher CO<sub>2</sub> too [10,37,39]. Further, the presence of metal oxides in biomass char has a catalytic effect and might result in higher CO<sub>2</sub> and H<sub>2</sub> [40]. About 3% increase in CO<sub>2</sub> and H<sub>2</sub> is noted when biomass ratio changed from 25 to 75 (% wt/wt). However on prolonged run, clinker formation was observed in 75/25 blend, and hence, for further trials coal percentage was lowered to 15%. With 85/15 (% wt/wt) blend, stable operation was achieved although some minor clinkers were observed that did not impede the char and ash movement. The ash extraction screw could take out those clinkers without much difficulty. Fig. 5 compares the gas composition with biomass to coal ratio 75/25 and 85/15 (% wt/wt).

It is observed from Fig. 5 that when biomass to coal ratio changes from 75/25 to 85/15 (% wt/wt), the gas composition has not changed much; notable change (~3%) is observed only in the case of H<sub>2</sub>. Little clinkers were noticed, probably due to the high localized temperature (~1700 K) near the air nozzle due to higher mass flux, however it was successfully counteracted by introducing endothermicity by spraying of a regulated amount of water through the air nozzle, converting into steam during its path inside the reactor. The steam reaction with char being endothermic was expected to have two intrinsic benefits, reducing the average bed temperature thus countering ash fusion and enhancing the gas composition [41]. It was found that with water injection, the oxidation zone temperature came down to ~1400 K and H<sub>2</sub> production had risen by ~3%. The operations were modified using steam generated through an electric boiler and superheated to a

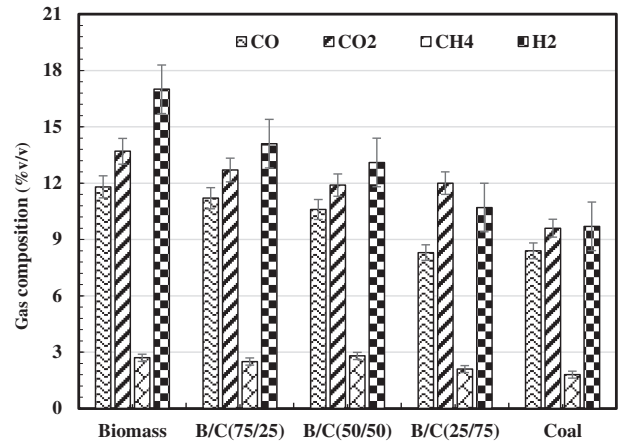


Fig. 4. Effect of fuel blend on gas composition with air gasification.

temperature ~600 K. The superheated steam supplied at the rate of 1.3 kg/h could maintain the condition favoring low clinkers.

Reduction of peak temperature is essential for clinker-free operation, and at the same time, the knowledge on reactivities of different oxidizing agents is vital. Dasappa [42] and Dasappa and Paul [43] have established a map showing the reactivities of different oxidizing agents viz., CO<sub>2</sub>, H<sub>2</sub>O, air and O<sub>2</sub> and observed that reactivity varies with oxidizing agent. Fig. 6 provides an insight into the typical reaction chemistry for different reactants in the case of wood char. It is observed that for a particular diameter, the lowest reactivity was recorded with 100% O<sub>2</sub> and the highest one was observed with CO<sub>2</sub>.

Steam reactions are temperature dependent. The primary water gas reaction becomes significant at temperatures 1373 K or upward, while the secondary water gas reaction begins and predominates between 773 K and 873 K. Water gas shift reaction is purely a gaseous reaction and takes place in the presence of un-decomposed steam [44,45]. Boudouard reaction becomes more dominant at temperatures greater than 1103 K [40]. In the current configuration, the water gas shift reaction was seen to participate more than any other reactions due to the lower oxidation and reduction zone temperatures maintained to avoid fusion of ash and thereby clinkering. Fig. 7 compares the gas compositions in air–steam and air gasification for biomass to coal ratio of 85/15 (% wt/wt).

Addition of steam is seen to improve the gas composition, especially H<sub>2</sub> concentration, which in the case of air gasification is ranged between 11 and 13%, while in the case of air–steam is 15–17%. CO<sub>2</sub> is also seen to improve in air–steam gasification, indicating major role of water gas shift reaction which is thermodynamically favorable at moderate

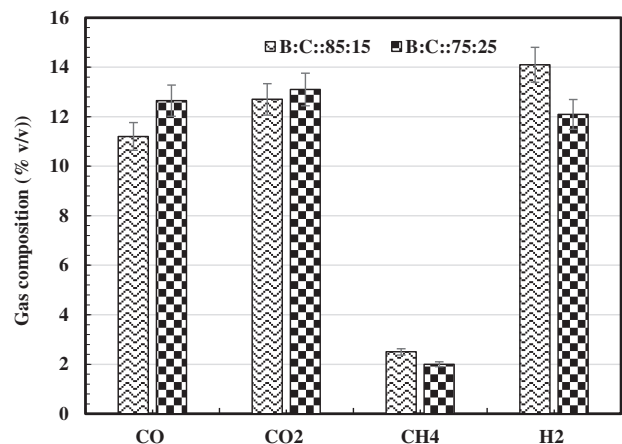


Fig. 5. Comparison of gas composition: biomass to coal ratio 75/25 and 85/15 (% wt/wt).

Table 4  
Correlations between burn time and particle diameter.

Indian coal (type I)	$t_f = 0.0022d_p^{1.5}$	$t_g = 0.0311d_p^{0.7}$	$t_b = 0.0211d_p^{0.8}$
Indian coal (type II)	$t_f = 0.0011d_p^{1.8}$	$t_g = 0.0122d_p^{0.0}$	$t_b = 0.0103d_p^{0.0}$
Indonesian coal	$t_f = 0.0021d_p^{1.6}$	$t_g = 0.0209d_p^{0.9}$	$t_b = 0.0094d_p^{0.0}$
Wood	$t_f = 0.0023d_p^{1.7}$	$t_g = 0.0044d_p^{0.9}$	$t_b = 0.0079d_p^{0.7}$
Pellets	$t_f = 0.0006d_p^{0.7}$	$t_g = 0.0213d_p^{0.9}$	$t_b = 0.0051d_p^{0.9}$

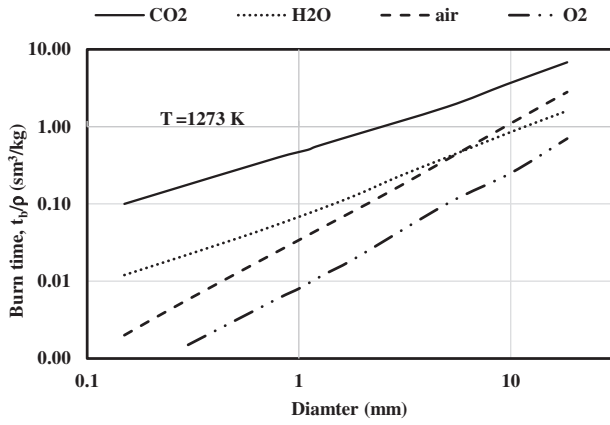


Fig. 6. Conversion time of wood char with different gaseous species [22].

temperature [8,36]. With the rise in temperature, CO<sub>2</sub> production is reduced due to an increase in the consumption during dry reforming of CH<sub>4</sub>/light hydrocarbons/tars (reaction: R(11) in Box 1) and Boudouard reaction (reaction: R(5), Box 1) [36]. The average temperature recorded in the reduction zone at present is 923–973 K. The current reactor being small with surface area to volume ratio higher, is impacting heat losses. At higher capacities however, the temperature profiles favors the char reactions and equilibrium calculations can well predict various parameters.

In the current study, the equilibrium calculations were carried out using a computer programme (Chemical Equilibrium with Applications: CEA) developed by NASA [46] for four different cases (biomass + air; coal + air; biomass + coal + air; biomass + coal + steam + air). Fig. 9 shows the result for biomass coal blend 85/15 (% wt/wt) with air and steam as oxidizer.

It is observed that the theoretical and the experimental results are different. H<sub>2</sub> and CO concentrations are higher, while CO<sub>2</sub> concentrations are lower than the experimental values. CH<sub>4</sub> concentration is found negligible. This difference suggests that the reactions did not reach equilibrium conditions, and this observation is similar to the observations reported by other researchers [36,47]. The equilibrium calculation incorporates 100% carbon conversion, while the same is not true in practical cases, and hence the difference always exists [4,10,36,47]. Further Dasappa [42] and Pinto et al. [36] reported that kinetics play an important role during gasification, especially the kinetics of heterogeneous char–gas reactions, which are characterized by lower reaction rates than those of the gas phase reactions and hence the equilibrium condition is affected. However, rise of temperature favors gasification

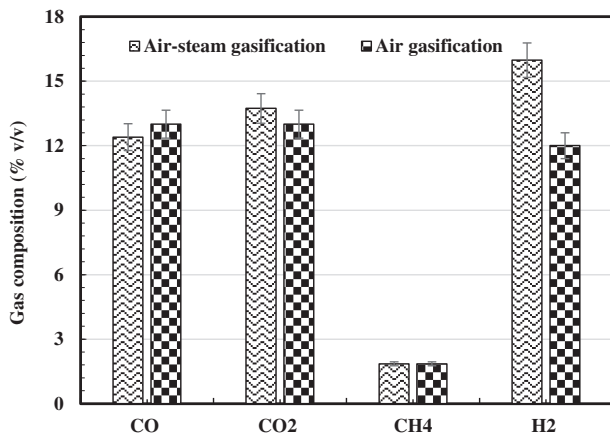


Fig. 7. Comparison of gas compositions in air–steam and air gasification for biomass to coal ratio 85/15 (% wt/wt).

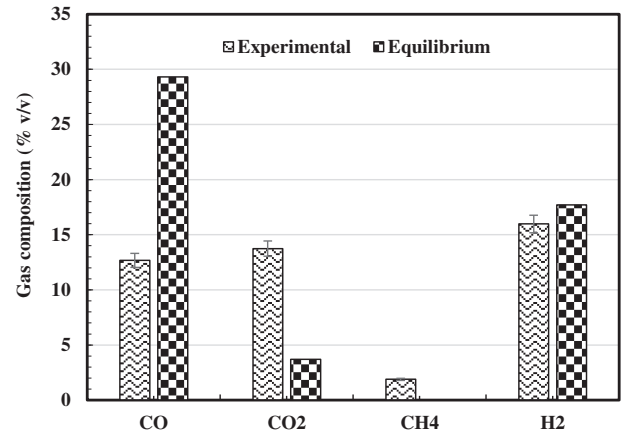


Fig. 8. Experimental and equilibrium gas compositions for biomass to coal ratio 85/15 (% wt/wt) in air–steam gasification.

reactions, and at such condition, the difference between the experimental and theoretical calculation diminishes [4,47].

Temperature is one of the most significant operating parameters, which affects the gasifier output: gas composition, gas, char and tar yields, heating value, carbon conversion, cold gas efficiency, etc. It has been reported by many researchers that higher the temperature better is the output. However, there is a limitation on how high the temperature for the gasification process can go up. It is because, high temperature result in production of undesirable gases such as NO<sub>x</sub> and also clinking due to fusion of ash. In the present case, as stated before, the second issue is more severe due to the high ash content of domestic coal but the use of open top gasification system ensured a uniform temperature across the reactor due to a wide reaction zone. Fig. 9 shows the temperature distribution inside the gasifier measured at five different locations (four above the air nozzle and one below, Fig. 1).

In the case of open top gasifier, the flame front moves towards the reactor top and the rate of propagation is primarily controlled by air mass flux, volatile fraction of fuel and the surrounding reaction environment of the particle. It is evident from Fig. 8 that the reaction front reaches the thermocouple placed at a height of 200 mm in 30 min, 300 mm in 55 min, 400 mm in 70 min and 500 mm in 95 min, respectively, and this gives the average local propagation rate of 0.17 mm/s which is found suitable for generating appropriate thermal environment inside the reactor for better quality of gas [23,46]. Fig. 10 illustrates the gas compositions measured over the entire run.

It is observed that for the first six hours of data collection, the average concentration of H<sub>2</sub>, CO, CO<sub>2</sub> is nearly constant. However, CO exhibits a distinct decreasing trend for the next one hour of operation,

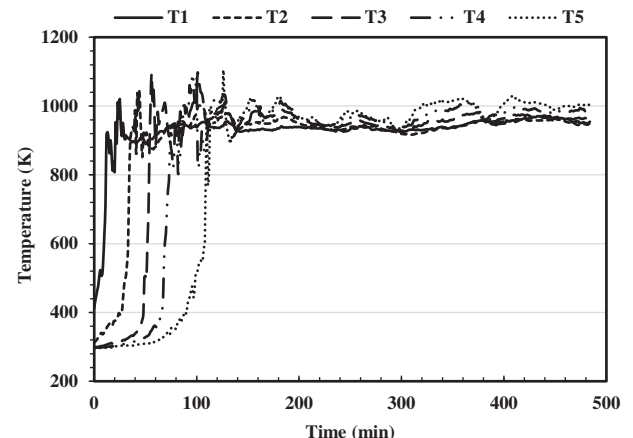


Fig. 9. Temperature distribution inside the gasifier in biomass coal ratio 85/15 (% wt/wt).

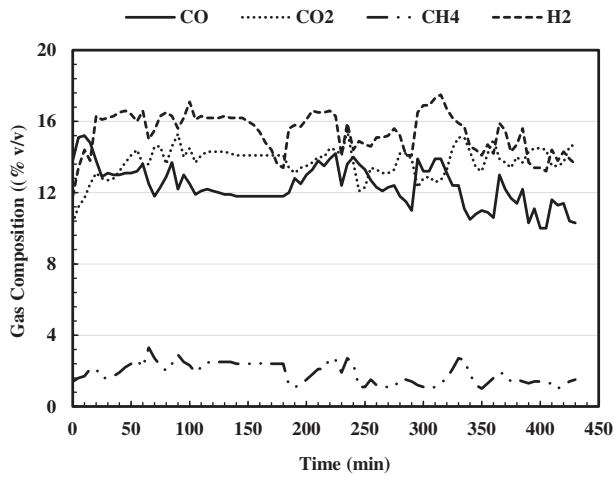


Fig. 10. Gas composition in air-steam co-gasification with biomass to coal ratio 85/15 (% wt/wt).

while  $\text{CO}_2$  and  $\text{H}_2$  remain constant. The decrease in CO concentration could be due to clinker formation allowing less surface area for reduction but needs further investigation. Figs. 11 and 12 show the compositions for wood and coal gasification respectively. In coal gasification, it is observed that CO and  $\text{H}_2$  are continuously decreasing, while for wood gasification they remain nearly constant. Larger clinkers in coal gasification is thought to obstruct the fuel flow and hence the gas quality. Table 5 compares the output parameters viz., gas yield ( $\text{m}^3/\text{kg}$ ), cold gas efficiency (%) carbon conversion (% gas and char) in co-gasification as well as coal and wood gasification systems. Tar being negligible has not been taken into account for the carbon calculation. The remaining carbon obtained through carbon balance in Table 5 is assumed to be in tar and ash.

It has been observed from Table 5 that the heating value of the product gas in wood gasification and 85/15 blend is nearly same. However, wood gasification results in higher heating value when it is operated with only air [16]. Introduction of steam with air has lowered the bed temperature and accordingly the fuel composition is affected. With coal alone, because of severe clinker formation, gas flow is affected and hence the heterogeneous reaction, resulting in low heating value. This finding is consistent with the results available in the literature [5, 37] Aigner et al. [37] correlated the reason for increased mass flow of the product gases with better carbon conversion in co-gasification. Seo et al. further [5] stated that the increase in gas yield with increase in biomass ratio is due to transfer of hydrogen radicals from biomass to coal that causes more decomposition of coal.

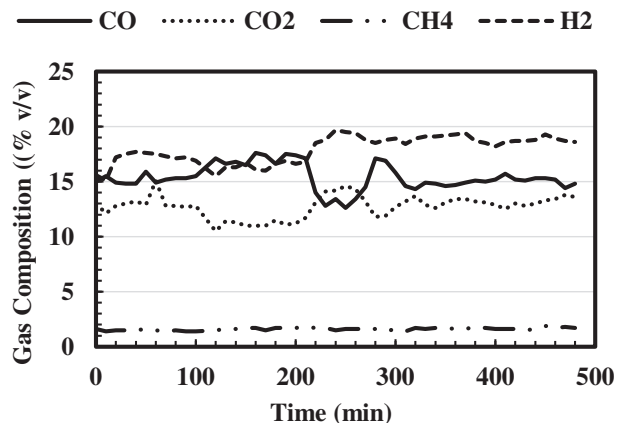


Fig. 11. Gas composition in wood gasification.

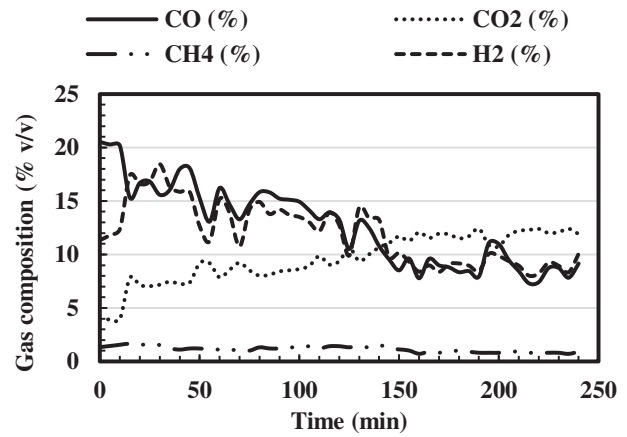


Fig. 12. Gas composition in coal gasification.

Cold gas efficiency is found to be higher in 85/15 blend than wood gasification alone. Air gasification, however, results in higher efficiencies in wood (~80%) [22]. The trend of increase in efficiency with the increase in biomass fraction in the mixture is reported by many researchers [4–6,12,16]. Kumabe et al. [10] observed an increase from 65% to 85% when biomass ratio was changed from 0 to 1. In the same line, Aigner et al. [37] reported 62% in co-gasification against 48% in case of coal alone. Combination of biomass and coal along with the gasification agent has provided a unified enhancement of operation, with the overall contribution on the performance improvement. The combined effect on the overall performance observed in the present case is similar to the observation made by Collot et al. [48]. High yield of gas and low char indicates a possible effect of synergy.

Carbon conversion to gas is found highest in case of biomass to coal ratio 85/15 (% wt/wt). In the current study, steam to carbon ratio of 0.20 is found beneficial for co-gasification as it improves  $\text{H}_2$  composition and reduces the problem of clinkering. The maximum flow that can be obtained with the current setup is 1.3 kg/h, and it suffices the requirement of good carbon conversion (94%) in 85/15 fuel blend. Higher carbon conversion in co-gasification is reported by many researchers and it is argued to be attributed to high contents of hydrogen and oxygen in biomass and also higher reactivity of biomass that causes an increase in volatile matter, which subsequently gets converted to free radicals and improves the gasification reactions [35].

#### 4.3. Preliminary experiments with coconut shell

In order to assess the feasibility of handling biomass other than wood in the same gasifier, coconut shell was tested. Operating conditions were maintained same as that of wood/coal gasification and the gas compositions data were acquired. Stability of the system was assessed by monitoring the temperature profiles within the reactor. Fig. 13 presents the gas composition with coconut shell/coal.

It is observed that with coconut shell there is not much change in gas compositions compared to wood/coal gasification (Fig. 10); CO slightly

Table 5  
Comparison of output parameters for wood, coal and wood/coal blends (85/15, % wt/wt).

Parameters		Wood	85/15	Coal
Input	Fuel flow rate (kg/h)	8	8	8
	Air flow rate (kg/h)	14.5	15.5	22.5
	Steam flow rate (kg/h)	1.3	1.3	1.3
	HHV (MJ/kg)	3.5	3.6	2.8
Output	Gas yield, $Y$ ( $\text{m}^3/\text{kg}$ )	2.5	2.9	3.2
	Cold gas efficiency, $\eta_c$ (%)	50	65	40
	Carbon conversion to gas, $X_1$ (%)	80	94	60
	Carbon conversion to char, $X_2$ (%)	17	5	36



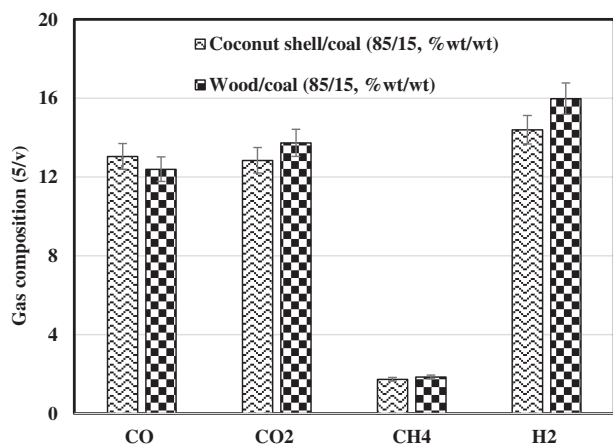


Fig. 13. Gas composition in coconut shell/coal co-gasification.

improves, while H<sub>2</sub>, CO<sub>2</sub> decreases, and CH<sub>4</sub> remains nearly same. This result is important because biomass availability is seasonal and site specific. Further, it indicates the possibility of co-gasifying other biomass with similar composition with coal, and that would increase the flexibility of fuel choice.

## 5. Conclusions

The present work demonstrates the feasibility of co-gasifying biomass with coal in a downdraft gasifier and following are the major conclusions.

- A continuous stable operation could be achieved when the coal percentage in the fuel blend is not more than 15% by weight. Increase in the coal percentage was found to result in more clinker formation due to ash fusion.
- The highest gasification efficiency obtained in 85/15 blend is 65%. Accordingly, the syngas yield and carbon conversion to gas are 2.9 Nm<sup>3</sup>/(kg fuel) and 94%, respectively.
- H<sub>2</sub> production is found to improve with steam addition. The highest percentage of H<sub>2</sub> recorded is 15%. It is found to decrease with the increase in coal percentage.
- Gasifier performance remains same with the bio-fuels having similar characteristic as that of wood. Coconut shell was tested, and the performance was found to be similar.
- Agro-residue pellets were characterized, and single particle analysis shows the scope for its uses in gasifier.

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