Net carbon-di-oxide conversion and other novel features of packed bed biomass gasification with O₂/CO₂ mixtures

V.M. Jaganathan⁎, S. Varunkumar
Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600 036, India

A R T I C L E   I N F O

Keywords:
O₂/CO₂ gasification/combustion Biomass Universal flame propagation CO₂ conversion

A B S T R A C T

Biomass thermo-chemical conversion under O₂/CO₂ conditions is experimentally investigated to establish its CO₂ conversion potential. Packed bed configuration with counter-current flame propagation is chosen for this purpose and three different fuels are used (agro-residue pellets, coconut shells and wood pellets). For oxidizer streams containing 20, 25, 30, 40 and 50% O₂ (v/v) (rest CO₂) steady flame propagation is established at different superficial velocities and the following quantities are measured — temperature along the reactor, mass consumption rate and exit gas composition. Corresponding reference experiments with O₂/N₂ mixtures are performed for comparing the net CO₂ conversion. The propagation regimes, similar to earlier studies with air, fall under the following two categories — (1) gasification — volatile oxidation accompanied by char reduction and (2) char oxidation dominated — simultaneous char and volatile combustion. Invoking equilibration of volatile oxidation under gasification conditions, a new procedure is established to estimate the net CO₂ conversion (NCC). In general, NCC is significant around the volatile stoichiometric point (ϕv = 1) and falls off on either side as the oxygen mass flux is decreased or increased. NCC is zero in very rich regime i.e. when ϕv ≫ 1 due to low bed temperatures and also when ϕv < 1 due to char oxidation. Maximum NCC of 627 g/kg of biomass is observed with 30% O₂/70% CO₂ (v/v) case at ϕv = 0.96 for agro residue pellets. Cold gas efficiency (ηc) is as high as 85% for the maximum NCC case. Enhanced gasification efficiencies of O₂/CO₂ cases as compared to corresponding air cases is due to the additional conversion of CO₂ to CO (predominantly C + CO₂ → 2CO). The difference in the fraction of char left over with CO₂ and N₂ cases is consistent with this observation. Corrected fuel flux (CF), proposed to address these variations in fuel heating value, oxygen fraction in the oxidizer etc., is shown to exhibit universality with respect to oxygen mass flux and fuel type.

1. Introduction

Syngas from biomass gasification is typically used for power generation (0.1–1 MW usually). Charcoal synthesis, process heating etc., are some of the other applications of biomass gasification. In all these systems, air is used as the oxidizer. The possibility of sustainable synthesis of fuels and fine chemicals has rekindled research efforts in catalytic polymerization of syngas. Due to stoichiometric constraints of these polymerization reactions, specific H₂/CO ratio is expected (H₂/CO = 2 for Fischer–Tropsch, for instance). This is usually achieved by catalytic water gas shift reaction upstream of the main process. It is also possible to tailor the syngas composition by replacing the inert N₂ in the air with CO₂ and steam. Flexible H₂/CO₂ ratio along with easy separation of CO₂ are advantages associated with this approach. Also, the range of biomass conversion rates achievable in the counter-current configuration is around 50–70 g/m²s (universal propagation limit with air) as shown in [1]. Under optimal gasification conditions, product gas composition (% v/v) is CO – 20%, H₂ – 15%, CH₄ – 1.5%, CO₂ – 10% and rest N₂, with a heating value of 4.5 MJ/kg [2]. Therefore more than half of the volume of product gases is inert (taking up 28% sensible enthalpy [3]) and by replacing N₂ with reactive components like CO₂ and steam, the energy density of the product gas can be increased significantly. Also, much higher fuel fluxes than the limiting value of 50–70 g/m²s (with air) can be achieved by varying the O₂/CO₂/steam ratio. Given that the technology for air separation is well matured and with emerging technologies like Chemical Looping Air Separation (CLAS), O₂ extraction from air will be economically viable in near future [4–6].

Understanding the dynamics of gasification in a canonical configuration is essential for reactor design. Counter-current flame propagation mode in a packed bed offers one such with the following advantages — (1) fuel flux, as a function of superficial velocity (U) exhibits...
universal characteristics with distinct regimes (gasification and combustion) as shown in [1] with air as the gasification medium (also with O₂/CO₂ as shown in the current work), (2) tar fraction in product gases under counter-current configuration is much less compared to co-current (updraft) systems [2,7] and hence a preferred configuration for downdraft gasifiers, small (cooking) and medium scale (industrial heating) systems, (3) also flame propagation in these practical configurations is analogous to packed bed systems with a coordinate frame fixed to the unburnt fuel [3,8], and (4) single particle models developed using packed bed systems can be extended to fluidized bed configurations as well [9,10]. The current work is motivated by these considerations. In this paper, the thermo-chemical conversion characteristics of biomass with O₂/CO₂ mixtures in a counter current reactor are reported. Effect of steam will be a part of future work.

1.1. Earlier works

A number of studies have been carried out to explore CO₂ reuse in gasification/combustion systems using biomass and coal. Lab scale TGA/DTA studies with different types of biomass/coal in atmospheres of CO₂ and O₂/N₂/H₂O mixtures covering a range of heating rates (1–100 °C/min) and maximum temperatures (700–1400 °C) have been reported – see for instance [11–16]. Drop tube reactor (DTR) is another technique with which the reactivity of biomass and coal (powdered to few hundred μm diameters) in O₂/N₂/H₂O/CO₂ atmospheres have been studied at very high heating rates of the order of 10⁴ K/s (see for instance [17–20]) as compared to TGA/DTA.

A few other works were done in fluidized beds (FB), for instance Nilsson et al. [21] and Kramb et al. [22] performed experiments with dried sewage sludge and birch wood of particle sizes from 1–5 mm and 14 mm equivalent spherical diameter respectively, with nitrogen based de-volatilization and subsequent gasification of char under various N₂/CO₂/H₂O fractions at 800–900 °C. The main aim of these experiments is to explore kinetics of char-CO₂ reactions and to estimate Arrhenius parameters. Similar results are reported for coal particles by Bu et al. [23].

Sandeen et al. [24] conducted experiments in a downdraft gasifier (10 kg/hr of casuarina wood chips) by systematically replacing N₂ with 15, 12 and 8.5% CO₂ maintaining 21% O₂ and a minimum bed temperature of 800 °C. Important features of this work are, (1) maximum CO₂ conversion of up to 55% at 15% CO₂ case, (2) carbon balance with an accuracy of ±20% is reported, and (3) CO₂ conversion efficiency is calculated as the ratio of the difference between CO₂ released from O₂/CO₂ case and air case to that of inlet CO₂ supplied in corresponding O₂/CO₂ case. It is important to note that even in the air gasification case there will be char reduction due to CO₂ generated by volatile oxidation. This is not accounted for in the calculation of CO₂ conversion in [24]. As shown later, CO₂ conversion with air can be substantial (220 g/kg of biomass). Annamalai et al. [25] have done experiments with updraft gasifier of mesquite fuel using air, air/steam and O₂/CO₂ (79% CO₂/21% O₂ by volume) mixtures in a batch type gasifier in co-current mode (oxidizer and flame moving in same direction). In this work, CO concentration up to 32% (v/v) is reported, which is attributed to CO₂ conversion to CO through Boudouard route at an equivalence ratio of 2.7 and hence the fuel value of the exit gas is higher in O₂/CO₂ cases as compared to corresponding air/steam and air cases. However, the bed is co-current and hence the volatile products interaction/reduction with char is limited in the above case as compared with countercurrent mode. Also as discussed earlier (refer Section 1), updraft gasifiers are not optimal for gasification due to excessive tar in the exit gas. Prabowo et al. [26] worked on pyrolysis and gasification of rice straw with mixtures of H₂O/CO₂/O₂/N₂ in a lab scale downdraft gasifier at varying proportions and temperatures from 750 to 950 °C in a electrically heated furnace with and without O₂. Maximum thermal efficiency of 60% was observed in 60% CO₂ fraction rest being O₂ (8.3%) and N₂ (31.7%) case at 950 °C. Experiments with oxygen are limited to 8.5% (v/v), wherein CO₂ conversion has been reported. It is also important to note that in any practical biomass gasification/combustion systems, external heating with high fractions of CO₂ (more than 80 to 100%) are of limited use.

Labijani et al. [27] worked on microwave enhanced fixed bed gasification of oil palm shell char. Activation energy of microwave induced gasification which operates at a heating rate of 1400 °C/min (similar range of fixed and fluidized beds) was found to be 74 and 36 kJ/mol for base case and catalytic microwave heating case respectively as against 250 kJ/mol by conventional (TGA/DTA) heating methods. Moreover, TGA operates at lower heating rates, DTR at very high heating rates, whereas practical systems like fixed bed/fluidized bed operate in between 700 and 7000 °C/min and hence reaction rate constants have fundamentally different dependencies on temperature which are manifested from Arrhenius parameters [27]. Also, most of the studies of TGA/DTR and FB were aimed at obtaining kinetic parameters to study the intrinsic reactivity of fuel (mostly char) with pure or mixture of N₂/O₂/CO₂/H₂O with external heating. On the other hand, fixed bed biomass combustion systems are self-sustained with volatile oxidation followed by char reduction. Intrinsin kinetics of volatile oxidation (releases 70% of total heat [3] and drives flame propagation) is of less relevance in these configurations, as it is limited by oxygen diffusion to the flame [1,28].

A few modeling works on CO₂ based conversion of carbonaceous
feedstock were studied [11,15,19,29] of which works of [19,29] are based on thermodynamic equilibrium/Gibbs free energy minimization technique. Other models are based on rate of change of surface area of char $S(X)/S_0$ (random pore model and grain model are extensively used for this purpose in literature) to estimate the reactivity of char under various atmospheres.

In summary, effect of CO$_2$ in thermo-chemical conversion route for carbonaceous feedstock is widely studied in controlled atmospheres like TGA/DTA/DTR. The main aim of these studies (including few FB and modeling works) was to explore the reaction kinetics of char when the reacting atmosphere is replaced with CO$_2$ either partially or totally. The heating rates and hence the rate constants arrived at, are different for practical combustion systems as compared to conventional heating methods (TGA/DTA/DTR); this limits the application of these works to practical gasification systems. Reported observations on CO$_2$ conversion are either qualitative [25,26] or does not account for the reduction of CO$_2$ from volatile oxidation [24]. In the current work, these issues are addressed using a combination of experiments and analysis; a new procedure for accurately estimating CO$_2$ conversion is developed. Using the corrected fuel flux (CFF) the universality of flame propagation in packed beds is shown to be valid for O$_2$/CO$_2$ cases also. The rest of the paper is organized as follows – (1) experiments, (2) CO$_2$ conversion, (3) results and discussions, (4) modified universal flame propagation behavior and (5) conclusion.

2. Experiments

The principal aim of the study is to determine the CO$_2$ conversion potential of biomass in counter current flame propagation mode. Net CO$_2$ conversion (NCC, g/kg of biomass) is defined as follows

$$NCC = \frac{m_{CO_2,g} + m_{CO_2,ex} - m_{CO_2,exit}}{m_b}$$

(1)

where $m_b$ is mass of biomass (kg), $m_{CO_2,g}$ is the mass of CO$_2$ (g) released through volatile oxidation, $m_{CO_2,exit}$ is the mass of CO$_2$ fed in O$_2$/CO$_2$ experiment (g) and $m_{CO_2,exit}$ is the mass of CO$_2$ in exit gas (g). It is important to note that even in air cases, CO$_2$ released from volatile oxidation participates in reduction reactions to produce CO and the amount is substantial (details later). For air and other O$_2$/N$_2$ cases, the second term on R.H.S of the equation is zero. Experiments to determine the NCC were conducted in the setup shown in Fig. 1. This setup is similar to that used by Varunkumar [3]. Three fuels were used in the current work – two pellets (Oorja agro-residue based and wood) and coconut shells. Relevant properties of the biomass used are listed in Table 1.

Table 1. Properties of biomass – Proximate and Ultimate Analysis.

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Pellets1 (Agro-residue)</th>
<th>Pellets2 (Wood)</th>
<th>Coconut Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m$^3$</td>
<td>1150</td>
<td>1260</td>
<td>1200</td>
</tr>
<tr>
<td>Size, mm</td>
<td>8 dia, 15–20 length</td>
<td>9 dia, 10–40 length</td>
<td>664</td>
</tr>
<tr>
<td>Bulk density, kg/m$^3$</td>
<td>630</td>
<td>75</td>
<td>370</td>
</tr>
<tr>
<td>Proximate Analysis**</td>
<td>45.7</td>
<td>49.6</td>
<td>52.7</td>
</tr>
<tr>
<td>Volatile content, %</td>
<td>66</td>
<td>75</td>
<td>71</td>
</tr>
<tr>
<td>Char, %</td>
<td>13.5</td>
<td>13.5</td>
<td>17.7</td>
</tr>
<tr>
<td>Ash content, %</td>
<td>10</td>
<td>4</td>
<td>1.3</td>
</tr>
<tr>
<td>Moisture content, %</td>
<td>10.5</td>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td>Ultimate Analysis*</td>
<td>46.12</td>
<td>43.4</td>
<td>41.2</td>
</tr>
<tr>
<td>O (%</td>
<td>1.43</td>
<td>0.5</td>
<td>0.08</td>
</tr>
<tr>
<td>N (%</td>
<td>1.43</td>
<td>0.5</td>
<td>0.08</td>
</tr>
<tr>
<td>C %</td>
<td>45.7</td>
<td>49.6</td>
<td>52.7</td>
</tr>
<tr>
<td>LCV (MJ/kg)**</td>
<td>15</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

* – dry ash free basis; ** – as received basis; * obtained from an external laboratory.

Table 1. Experiments are carried out in a cylindrical stainless steel reactor SS310 grade of 108 mm diameter and 500 mm length. Perforated grate with 5 mm holes is placed at a distance of 50 mm from the bottom. Three different oxidizers were used, namely, (1) air, (2) O$_2$/CO$_2$ mixtures and (3) O$_2$/N$_2$ mixtures. List of oxidizer combinations used along with the notation used for referring to these cases is listed in Table 2. For each oxidizer, experiments were conducted to cover a range of superficial velocities – usually covering the overall equivalence ratio $(F/O)_{actual}/(F/O)_{stoichiometric}$ range of relevance to gasification (5–1.4). The lower equivalence ratio limit for gasification (say 1.4 for instance) usually coincides with the volatile stoichiometry point (complete combustion of volatile hydrocarbons) i.e. $\phi_i = 1$, as decreasing the equivalence ratio beyond this value leads to char oxidation. Most of the cases are repeated more than two times to check for repeatability and reproducibility of results. The oxidizer (O$_2$/CO$_2$ or O$_2$/N$_2$) gases are supplied from a bank of high pressure cylinders (99.9% purity). Electric heaters are used at CO$_2$ cylinder exit to avoid freezing of CO$_2$. Gas flow rate is regulated using mass flow controllers (one for each gas). The component gases are allowed to mix in a long pipe (4–5 m) and thorough mixing is ensured at reactor inlet using a portable gas analyzer.

![Fig. 1. Schematic of the experimental setup.](image-url)
Biomass is loaded in the reactor and ignited from the top using some kerosene soaked cotton over the bed. After ignition, the flame propagates from the top of the reactor to the grate till all the volatiles are driven off and this is called as flaming mode. After flaming mode, char mode starts which can also be observed by the change of slope of the mass loss curve (refer Fig. 2a). Reactor is quenched with N₂ at the end of flaming mode. All experiments were carried out at ambient pressure and the reported $\dot{m}_{\text{ox}}$ (mass flux of oxygen) values were calculated using flow rates at standard conditions (1 atm and 298 K).

2.1. Instrumentation

Estimation of CO₂ conversion in a packed bed counter current configuration requires the following parameters (1) fuel flux, (2) oxidizer flux, (3) bed temperature, (4) composition of exit gases, (5) fixed

Table 2
Experimental nomenclature.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Oxidizer</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air</td>
<td>PA, CA and WPA</td>
</tr>
<tr>
<td>2</td>
<td>25% O₂/75% CO₂</td>
<td>P25C and C25C</td>
</tr>
<tr>
<td>3</td>
<td>30% O₂/70% CO₂</td>
<td>P30C, C30C and WP30C</td>
</tr>
<tr>
<td>4</td>
<td>40% O₂/60% CO₂</td>
<td>P40C and C40C</td>
</tr>
<tr>
<td>5</td>
<td>50% O₂/50% CO₂</td>
<td>P50C</td>
</tr>
<tr>
<td>6</td>
<td>25% O₂/75% N₂</td>
<td>P25N</td>
</tr>
<tr>
<td>7</td>
<td>30% O₂/70% N₂</td>
<td>P30N</td>
</tr>
<tr>
<td>8</td>
<td>40% O₂/60% N₂</td>
<td>P40N</td>
</tr>
</tbody>
</table>

P – Agro-residue pellet; C – Coconut shell; WP – Wood pellet.
* All % on volume basis.

Fig. 2. Fuel mass loss and $T_{p6}$ variation with time for PA case at $V_i = 4.2$ cm/s.
carbon left at end of flaming mode and (6) fuel characterization. In this section, details of instrumentation used in the current work are explained. The reactor is mounted on a weighing balance (30 kg capacity and 1 g accuracy) interfaced to a computer with RS-232 to record the mass loss rate. Bed temperature is measured using six ungrounded R-Type thermocouples (1.5 mm bead size) placed at regular intervals (75 mm) along the length of the reactor; the temperature data was recorded using Agilent Benchlink data logger at a sampling rate of 3.3 Hz. Flow rates of gases, as mentioned earlier, is controlled by MCR series Alicat mass flow controllers (1% full-scale accuracy). Typical mass loss rate of the fuel with scaled time is shown in Fig. 2a. At same $V_s$ (4.2 cm/s), the fuel consumption rate per unit cross-sectional area or fuel flux $m_f^* = 1/A_x \times dm/\text{d}t$ is nearly same (28.3 g/m²s for Varunkumar [3] and 28.9 g/m²s in the current work). The x-axis label refers to the normalized time and the normalization procedure is given below. Irrespective of the reactor size, the fuel flux ($m_f^* = 1/A_x \times dm/\text{d}t$) is the same for the same superficial velocity ($V_s$). However, the reactor area ($A_x$) and the initial biomass loaded ($m_0$) are different in the current work and [3]. To account for these differences, the instantaneous mass was scaled with the initial mass and this leads to the following scaled equation,

$$m_f^* = \frac{d(m/m_0)}{d(A/A_0/m_0)}$$

Therefore, if $m/m_0$ is plotted against the scaled time ($t/A_0/m_0$), the mass loss data from the two experiments will collapse on to the same curve (as seen in Fig. 2a). Figure 2b shows the variation of bed temperature with time. Peak bed temperature ($T_{pb}$ herein), a rough indicator of bed operational regime i.e. stoichiometry, is the averaged temperature between the gas and condensed phase (reported $T_{pb}$ is an average of maximum values measured by thermocouples T1 to T6). The

![Diagram](image-url)
peak bed temperature is later used in the energy balance calculation for estimating sensible enthalpy. Propagation rate calculated from the temperature data (Fig. 2b) is consistent with mass loss data (Fig. 2a) and earlier literature [3].

2.1.1. Measurement uncertainties
The weighing balance used has an accuracy of 1 g and with this, the scatter in measured fuel flux will be less than 0.3%. The thermocouples used are calibrated and reported with an uncertainty of ± 2 °C from the manufacturer. Fuel characterization instruments like proximate analyzer (0.1% accuracy) and bomb calorimeter (0.1–0.2% accuracy) have negligible uncertainty. The uncertainties associated with the flow parameters (like $V_f$ and $m_{\text{in}}$) are within 5%. The gas composition measured with GC has an error within 5%. This leads to a elemental and energy balance to ± 10%. Hence, the error in the estimated values (net carbon conversion, enhanced CO formation, corrected fuel flux, cold gas efficiency and volatile stoichiometry etc.) are within 10%.

2.1.2. Gas sampling
Gas sampling is done after the bed is ignited i.e. at least one layer of char bed is established. Sample gas of 0.5 slpm is sent to a NDIR based portable gas analyzer via condenser, moisture and dust filter, suction pump and mass flow controller to ensure there is no entrainment of air in the sampling line at any point of time. Position of the sampling tube is also adjusted to the vicinity of char bed as the char bed recedes down over time. Gases from the exit of portable analyzer are filled in gas bags (3 liter capacity) at regular intervals. Sampling intervals are chosen such that when each thermocouple i.e. from T6 to T1 reaches/ap-proaches peak bed temperature, one liter of sample gas (approx) is filled in the bag. Totally two bags are filled for each experiment and analyzed in a gas chromatograph (Perkin Claurus 680 GC with auto-sampler). Three to four GC runs are conducted for each bag to check the repeatability. Exit gas compositions from two bags are averaged to get the final reported composition. Hence the data from one single experiment is equivalent to that obtained from two similar experiments. Also to check the reproducibility of gas composition, few experiments are repeated and the errors are within ± 5% maximum for each gas eluted. Eluted gas peaks of FID and TCD columns of PA case at O2 flux of 12 g/m2s are shown in Fig. 3. In general, higher hydrocarbons like C6+, ethylene, propylene, ethane, propane and acetylene are found in considerable amount (totals to about 2%) in rich regimes (say $\phi > 2$). The components like CH4 and higher hydrocarbons (HHC) decreases as the bed transitions towards combustion regime.

Methane and HHC content in experiments with coconut shells is higher than pellets (about 5% maximum) in all the operating conditions. This is attributed to high volatile content and about 10% crude protein extractions and oil [2] in coconut shell (heating value around 18–22 MJ/kg), which enhances volatile heat release rate and shows higher fuel flux. Also, the surface area of coconut shell particles is higher due to its flat and curved geometry which promotes heat transport. Single particle experiments done by [30] on coconut shell also reports similar observation. Flame propagation of coconut shell with air case exceeds the universal propagation limit (110 g/m2s against the maximum of 80 g/m2s for other biomass fuels with air [1]) and hence the conversion characteristics of coconut shell is somewhat different from the universal characteristics exhibited by other biomass.

2.1.3. Experimental limits
The oxidizer oxygen fraction is restricted to 50% as a few experiments with 50% O2 showed excessive slag formation and damage to the reactor due to hot spots as the $T_p$ went beyond 1800 K. In coconut shell experiments the maximum O2 fraction is restricted to 40%. Beyond this, there was flame jump i.e. time taken for the axially positioned thermocouples to reach peak temperatures is faster owing to a flame propagation rate of 215 g/m2s corresponding to oxygen flux of 158 g/m2s but the leftover char is more than 5% (details later) which indicates incomplete conversion due to non-steady propagation; this regime is not investigated in the current work. Low oxygen fraction experiments i.e. when the ambient O2 % goes below 20 (20% O2/80% CO2) low propagation is observed in the order of 25 g/m2s and for experiments below these fractions of O2 the propagation is intermittent and steady flame front is not established and hence are not studied in this work. In agreement with [31], 20% O2 by volume (corresponds to 15% oxygen mass fraction for O2/CO2 case) is the least volume fraction for combustion to sustain and this is fixed as the lower limit. Hence the range of O2 fraction for all O2/CO2 experiments is restricted between 25 to 50% for pellets and up to 40% for coconut shells. The purpose of the O2/N2 experiments is to bring out the effectiveness of CO2 in the inlet stream on conversion. Fifteen sets of experiments are carried out in the current work. Firstly to validate the universal propagation behavior, air

<table>
<thead>
<tr>
<th>S.No</th>
<th>Details (inputs)</th>
<th>Values</th>
<th>S.No</th>
<th>Details(output)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Biomass loaded (g)</td>
<td>2484</td>
<td>24</td>
<td>Final H2 mass (g)</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>Volatiles (g)</td>
<td>1639</td>
<td>25</td>
<td>Final CO2 mass (g)</td>
<td>4708</td>
</tr>
<tr>
<td>3</td>
<td>Moisture (g)</td>
<td>248</td>
<td>26</td>
<td>Final HHC mass (g)</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>Fixed carbon (g)</td>
<td>335</td>
<td>27</td>
<td>Final H2O mass (g)</td>
<td>911</td>
</tr>
<tr>
<td>5</td>
<td>Ash (g)</td>
<td>248</td>
<td>28</td>
<td>C mass balance %</td>
<td>4.6</td>
</tr>
<tr>
<td>6</td>
<td>O2/CO2 %</td>
<td>30/70</td>
<td>29</td>
<td>H mass balance %</td>
<td>7.9</td>
</tr>
<tr>
<td>7</td>
<td>Total reaction time (s)</td>
<td>4759</td>
<td>30</td>
<td>O mass balance %</td>
<td>−1.6</td>
</tr>
<tr>
<td>8</td>
<td>Total O2 supplied (g)</td>
<td>1284</td>
<td>31</td>
<td>Volatile formula</td>
<td>CH3.55O1.64</td>
</tr>
<tr>
<td>9</td>
<td>Total CO2 supplied (g)</td>
<td>4118</td>
<td>32</td>
<td>Equivalence ratio $\phi$</td>
<td>1.68</td>
</tr>
<tr>
<td>10</td>
<td>Biomass left at end of reaction (g)</td>
<td>278</td>
<td>33</td>
<td>Volatile energy release (MJ)</td>
<td>25.2</td>
</tr>
<tr>
<td>11</td>
<td>Fixed carbon reacted (g)</td>
<td>305</td>
<td>34</td>
<td>$\Delta H_2$ (kJ/mol)</td>
<td>−342</td>
</tr>
<tr>
<td>12</td>
<td>Total reactant/product mass (g)</td>
<td>7596</td>
<td>35</td>
<td>CEA temperature (K)</td>
<td>1480</td>
</tr>
<tr>
<td>13</td>
<td>Iterated H2O fraction (final)</td>
<td>0.12</td>
<td>36</td>
<td>CEA CO mass (g)</td>
<td>1130</td>
</tr>
<tr>
<td>14</td>
<td>Dry product mass (g)</td>
<td>6684</td>
<td>37</td>
<td>CEA CO2 mass (g)</td>
<td>4864</td>
</tr>
<tr>
<td>15</td>
<td>CH ON S fractions</td>
<td>Table 1</td>
<td>38</td>
<td>CEA H2 mass (g)</td>
<td>25.6</td>
</tr>
<tr>
<td>16</td>
<td>$T_p$ (K)</td>
<td>1459</td>
<td>39</td>
<td>CEA H2O mass (g)</td>
<td>1575</td>
</tr>
<tr>
<td>17</td>
<td>Oxidizer mass flux (g/m2s)</td>
<td>125.2</td>
<td>40</td>
<td>CO enhancement (g/kg)</td>
<td>270</td>
</tr>
<tr>
<td>18</td>
<td>Fuel mass flux (g/m2s)</td>
<td>56.3</td>
<td>41</td>
<td>CO2 conversion (g/kg)</td>
<td>63</td>
</tr>
<tr>
<td>19</td>
<td>LCV of biomass (kJ/g)</td>
<td>15</td>
<td>42</td>
<td>Total sensible energy (kJ)</td>
<td>12378</td>
</tr>
<tr>
<td>20</td>
<td>Heating value of carbon (kJ/g)</td>
<td>32</td>
<td>43</td>
<td>Total LCV (kJ)</td>
<td>26732</td>
</tr>
<tr>
<td>21</td>
<td>$h_a$ (kJ/mol)</td>
<td>−190</td>
<td>44</td>
<td>Enthalpy of formation of reactants (kJ)</td>
<td>−52790</td>
</tr>
<tr>
<td>22</td>
<td>Final CO mass (g)</td>
<td>1821</td>
<td>45</td>
<td>Enthalpy of formation of products (kJ)</td>
<td>−62680</td>
</tr>
<tr>
<td>23</td>
<td>Final CH4 mass (g)</td>
<td>41</td>
<td>46</td>
<td>Energy balance %</td>
<td>4.7</td>
</tr>
</tbody>
</table>
experiments with agro residue based pellets, wood pellets and coconut shell (PA, WPA and CA) are done. Next set of experiments are carried out with different oxidizers (O2/CO2 mixture) under various fractions of O2 (P20C, P25C, P30C, P40C, P50C, C25C, C30C, C40C and WP30C cases) with agro residue pellets, coconut shells and few cases with wood pellets. Last set of experiments are done to compare the effect of CO2 with N2 for all O2/CO2 cases of agro residue pellets (P25N, P30N and P40N cases). In each case, the $V_{g}$ is varied until volatile stoichiometric range (few experiments are reported for combustion regime also) and hence more than 70 experiments are reported in the current work. Insights from these experiments are crucial to explain the fundamental behavior of flame propagation, CO2 conversion, gasification efficiency etc., which are explored in the current work.

3. CO2 conversion

In any biomass gasification system with air, the possible source of CO is through (1) partial oxidation of volatile carbon and (2) subsequent char reduction with CO2 and other gases formed during volatile oxidation. In O2/CO2 gasification, in addition to volatile CO2 (i.e. $\text{m}_{\text{CO}_2}$) reduction with char, there is a possibility of inlet CO2 reduction as well. This must be accounted in the NCC calculation (refer Eq. (1)). As discussed earlier, experiments reported in the current work are mostly restricted to gasification regime i.e. till volatile stoichiometry (few combustion cases are also reported). This is due to the fact that char will be inaccessible for reduction reactions in char oxidation regime. The general scheme of reaction is as follows – the fuel (volatile, fuel moisture and char) reacts with oxidizer (either O2/CO2 or O2/ N2 mixture) to give exit gases, water vapor, and char (if not fully reacted) as products. Ash is assumed to be non-reactive. A particular experimental case from P30C (O2 flux of 31 g/m2s) is taken to outline the procedure for estimation of CO2 conversion (NCC). Relevant parameters for computation are listed in Table 3. Each cell value of Table 3 is referred by # numeric, for instance, #1 refers to the value of the first cell which is 2484 g of biomass loaded.

![Gas composition and $T_{ph}$ variation with $\dot{m}_{ox}$](image)

Fig. 4. Gas composition and $T_{ph}$ variation with $\dot{m}_{ox}$; uncertainties in data smaller than marker size are not reported.
The total product mass is equal to the reactant mass which is the mass of the experiment is 7.5 cm/s.

\[ \Delta \text{value of } m_{\text{CO}} \text{ which are 56.3 and 125.3 g/m^2s respectively and increases, exit } m_{\text{m}} \text{.} \]

It is important to note that, if the operating mode is gas CO₂ concentration reduces and then increases, whereas CO follows 44) = 1123 g of C]. Summation of both gives the total input carbon of decreases with increasing m_v. (see below) which is estimated from carbon, hydrogen and oxygen balance for the gasification reactions (similar to Varunkumar et al. [32]). Input carbon sources

\[ \text{The oxidizer O}_2/\text{CO}_2 \text{ fraction } \Delta \text{fixed carbon reacted. Ultimate analysis of the biomass on dry ash free basis (refer to Table 1, where C, H and O % by mass are given) is taken to calculate the amount of carbon from fuel i.e. volatile and fixed carbon reacted ([#1–#3–#5] × 0.457 – ([#1–#5] = 878 g of C]). Carbon from the oxidizer stream is estimated from the amount of input } \text{CO}_2 \text{ [#9 × (12/44) = 1123 g of C]. Summation of both gives the total input carbon of the reaction [878 g + 1123 g = 2001 g of C]. Hydrogen sources are from fuel and moisture i.e. [(#1–#3–#5) × 0.0661 + 3 × (2/18)] = 159 g of H. Oxygen in the input is from fuel, moisture and oxidizer } [(#1–#3–#5) × 0.46 + #3 × (16/18) + #8 + #9 × (16/44)] = 5416 g of O. Dry composition of the exit gases from GC is converted to mass basis and their mass fractions (Y_i) are multiplied with #14 to get the mass of all gases in the exit stream on dry basis. The exit H₂O fraction is estimated by enforcing CHO balance. The carbon, hydrogen and oxygen error percentages after iteration for the example are 4.6, 7.9 and 1.6 % (#28, #29 and #30) respectively. For all the cases the CHO balance is within 10%. Wet composition of the exit gas is now known (#22–#27). Thus from the above procedure mass of outlet CO₂ on wet basis i.e. the third term of R.H.S of Eq. (1) is known (#25).

\[ \text{3.3. Volatile equilibrium calculations} \]

Computation of volatile CO₂ (the first term in R.H.S of Eq. (1)), requires composition of volatile oxidation products. This is calculated with NASA CEA SP-273 code. Volatile oxidation in gasification regime is diffusion controlled [3], and hence equilibrium approach is appropriate to get the composition of volatile products. The inputs required for the calculation are equivalence ratio (ϕ_f) and enthalpy of formation of volatile biomass (ΔH_v). To calculate ϕ_f, the total C (difference between volatile and fixed carbon), H and O of volatile biomass consumed from the flaming mode are accounted and empirical formula is obtained (CH_{13}O_{16}.8, #31). It is important to note that, if the operating mode is very rich, some volatiles will be left unburnt and hence the volatile formula will vary and the method developed will address this. Oxidizer for the current case is a mixture of O₂/CO₂ and from this volatile stoichiometric F/O of 0.27 is computed. Actual F/O is the ratio of m_f (18) and m_e (17) which are 56.3 and 125.3 g/m^2s respectively and hence the actual F/O of 0.45 is obtained. Therefore equivalence ratio (ϕ_f) is 1.7. To calculate ΔH_v, total input energy i.e. heat released by volatile biomass is computed considering 5% surface heat loss [3] and the value is 25.2 MJ (#33 = (#19 × #1–#4 × #20) × 0.95). Molecular weight of the volatile biomass is 39.15 g/mol (from #31) and total volatile moles reacting is 47.7 from which ΔH_v value of −342 kJ/mol is computed (#34). Equivalence ratio (ϕ_f) and enthalpy of formation of volatiles ΔH_v is now known. With these inputs, equilibrium calculation is done with NASA CEA software. Exit gas mass fractions are multiplied with total product mass (#12) and individual mass of each gas is obtained as listed from #36 to #39 of Table 3. The ratio of the net positive difference of #37 (sum of volatile CO₂ and inlet CO₂) and #25 (outlet CO₂) to #1 (biomass loaded) gives net grams of CO₂ converted per kg of biomass loaded (NCC) which is 63 g/kg (#41). CO enhancement (ECM) i.e. fraction of CO in excess with CEA calculation (see below) which is attributed to Boudouard and water gas shift reaction route is 270 g/kg biomass (#40). (Table 4)

\[ \text{ECM } (\text{g/kg of biomass}) = \frac{(m_{\text{CO,outlet}} - m_{\text{CO,in}})}{m_b} \]

where m_{CO,outlet} is the mass of CO in exit gas and m_{CO,in} is the mass of CO at the end of volatile oxidation. Maximum CO enhancement is thought to occur when the total fixed carbon is reacted with volatile oxidation products. To obtain a theoretical limit for maximum CO attainable, volatile oxidation products (#36–#39) are equilibrated with total fixed carbon (#4) and compared with the experimental values. In experiments, CO is maximum near volatile stoichiometry and decreases on either side, CO₂ reaches minimum around the same point and increases on either side. Concentrations of H₂ is higher and H₂O is less as compared to equilibrium concentrations. A few cases show that the theoretical value is less than the actual. This is because of the fact that char reactions are rate limited and the system operates far from equilibrium.
3.4. Energy balance

Energy balance is mandatory to reassure C, H and O balance as discussed earlier and also to calculate the cold gas efficiency of the system. Energy balance of any combustion/gasification packed bed system with any fuel is as follows,

\[ m_{\text{vol}} [h_{\text{vol}}^0 + h_{\text{vol}}^s] + m_{\text{bio}} [h_{\text{bio}}^0 + h_{\text{bio}}^s] = m_{\text{char}} [h_{\text{char}}^0 + h_{\text{char}}^s] + \sum_{i=1}^{n} m_i [h_i^0 + h_i^s] \]

L.H.S of the above equation is the total input energy of the reactants and R.H.S is the total output energy from products, where \( m_{\text{vol}} \), \( m_{\text{bio}} \), \( m_{\text{char}} \), \( m_i \) are mass of oxidizer, biomass, unreacted carbon and ith component of exit gas, \( h_{\text{vol}}^0 \), \( h_{\text{bio}}^0 \), \( h_{\text{char}}^0 \), \( h_i^0 \) and \( h_{\text{vol}}^s \), \( h_{\text{bio}}^s \), \( h_{\text{char}}^s \) and \( h_i^s \) are their corresponding heat of formation at standard conditions (1 atm and 298 K), \( h_{\text{vol}}^0 \), \( h_{\text{bio}}^0 \), \( h_{\text{char}}^0 \) and \( h_i^0 \) refers to sensible enthalpy of oxidizer, biomass, unburnt carbon and exit gases respectively. Oxidizers used in the work are O\(_2\)/N\(_2\)/CO\(_2\) out of which O\(_2\) and N\(_2\) have enthalpy of formation as zero. Also, the sensible enthalpies of the reactants are zero (as reactants are at standard conditions i.e. 1 atm and 298 K). In product side, the enthalpy of formation of unreacted carbon \( h_i^0 \) is also zero. Moreover, the sensible enthalpy of unburnt carbon is small (less than 1% of total input energy) and hence neglected. Considering these factors the above equation is simplified as follows,

\[ m_{\text{CO}_2} h_{\text{CO}_2}^0 + m_{\text{bio}} h_{\text{bio}}^0 + \sum_{i=1}^{n} m_i [h_i^0 + h_i^s] \]

All the relevant properties are taken from JANAF thermo-chemical tables. Enthalpy of formation of biomass (\( h_{\text{bio}}^0 \)) on as received basis is calculated (refer to Table 3, #21) similar to the procedure described in Section 3.3. The sensible enthalpies of all exit gases are calculated at corresponding \( T_{\text{pa}} \) (refer Figs. 5–7). It is important to note that, \( T_{\text{pa}} \) of all O\(_2\)/N\(_2\) (including air case) cases is higher than corresponding O\(_2\)/CO\(_2\) case (refer Fig. 5) due to the higher heat capacity of CO\(_2\) as compared to N\(_2\) [25,23]. The mass of CO\(_2\), biomass and all exit gases for the illustrative case from P30C case at \( m_{\text{vol}}^{\text{PA}} \) of 31 g/m\(^2\)s are taken from Table 3. The difference between L.H.S (#44) and R.H.S (i.e. sum of #42 and #45) gives the percentage error in energy balance (#46). Energy is balanced within 5% error. The ratio of LCV (#43) to sum of LCV (#43) and sensible enthalpy (#42) gives the cold gas efficiency. In this case the cold gas efficiency is 68.4% (44/110) multiplied by 100 = 68.4%. Elemental and energy balance calculations were implemented in a spreadsheet (for case P30C at \( m_{\text{vol}}^{\text{PA}} \) of 31 g/m\(^2\)s the calculation sheet be downloaded from [33]). The same procedure is used to calculate the net CO\(_2\) conversion for all experiments (as listed in Table 2) of the current work.

4. Results and discussions

The results of NCC, \( \phi _f \) and ECM variation with \( m_{\text{vol}}^{\text{PA}} \) for all cases as listed in Table 2 are shown in Figs. 8–14.

4.1. Volatile stoichiometry (\( \phi _f \)) and NCC

Net CO\(_2\) Conversion (NCC) for all cases is significantly higher around the volatile stoichiometry (\( \phi _f \approx 1 \)) i.e. the transition point of gasification to combustion as compared to either side of it. To elucidate the effect of oxidizer, the NCC of O\(_2\)/CO\(_2\) cases is compared to the corresponding O\(_2\)/N\(_2\) cases and the results are shown in Figs. 8–10. As can be seen, excluding air, NCC of O\(_2\)/N\(_2\) cases is less/negligible as compared to corresponding O\(_2\)/CO\(_2\) cases.

High CO\(_2\) concentration in O\(_2\)/CO\(_2\) cases, promote reactions of char with CO\(_2\), near volatile stoichiometry. This argument is further supported by enhanced char conversion of O\(_2\)/CO\(_2\) cases as compared to O\(_2\)/N\(_2\) cases as seen from Fig. 15 and hence, higher NCC is observed in O\(_2\)/CO\(_2\) than the corresponding O\(_2\)/N\(_2\) cases.

The question that now arises is, if O\(_2\)/N\(_2\) cases have lesser CO\(_2\) concentration than O\(_2\)/CO\(_2\) cases then why there is a substantial NCC in air cases? The answer is volatile stoichiometry. Except for air cases and P25N case, other O\(_2\)/N\(_2\) cases do not reach volatile stoichiometry (for the range of \( m_{\text{vol}}^{\text{PA}} \) studied). On the other hand, for cases operated in combustion regime i.e. \( \phi _f < 1 \), NCC is not observed (ref Figs. 8 and 10).

This is due to char participation in oxidation reactions.

Oxygen mass flux (\( m_{\text{vol}}^{\text{PA}} \)) X a function of \( V_i \) and oxygen fraction in the oxidizer stream along with \( \phi _f \) dictates volatile stoichiometry (\( \phi _f \)) and hence plays a crucial role in NCC. In any particular case if \( m_{\text{vol}}^{\text{PA}} \) increases, \( \phi _f \) decreases i.e. the operational regime of the reactor shifts from gasification to char oxidation dominated zone or in other words, the reaction front gets thinner. Further increase in \( m_{\text{vol}}^{\text{PA}} \) cools the stream and flame extinction happens [3,28]. This is also evident from the experiment that the variation of \( T_{\text{pa}} \), measured by thermocouples placed along the axial distance of reactor narrows down as \( m_{\text{vol}}^{\text{PA}} \) increases. Refer PA and P30C cases in the Figs. 5 and 6 respectively (for PA from ± 130 K to ± 30 K and for P30C ± 110 K to ± 20 K). This implies that the operational regime of the reactor shift towards equilibrium (around 40 g/m\(^2\)s for PA and 60 g/m\(^2\)s for P30C), a similar observation made by [3]. On the other hand, as discussed earlier, if the oxygen fraction is increased for same \( m_{\text{vol}}^{\text{PA}} \) and \( \phi _f \) are their corresponding values but \( \phi _f \) for high O\(_2\) fraction experiments (40 and 50% O\(_2\) cases). Steep slopes of \( \phi _f \) means faster volatile stoichiometric reach i.e. at low \( V_i \) and hence NCC also occurs at lower \( m_{\text{vol}}^{\text{PA}} \) as compared to higher O\(_2\) fraction experiments where NCC is reached at higher \( m_{\text{vol}}^{\text{PA}} \) as evident from Figs. 9 and 11. As discussed earlier, one another interconnected parameter with \( \phi _f \) affecting NCC and ECM is \( T_{\text{pa}} \). Surface reduction reactions of carbon with CO\(_2\) are predominantly a high temperature pathway and well pronounced above 1000 K [34]. High concentration of CO\(_2\) promotes char reactions as compared to inert N\(_2\) (refer Section 1.1) and hence char conversion is more prominent in O\(_2\)/CO\(_2\) cases than corresponding O\(_2\)/N\(_2\) cases. Volatile oxidation reaction as discussed earlier is diffusion limited and hence the char above flame front is available only for reduction reactions with volatile products.

In addition, the char conversion in all O\(_2\)/CO\(_2\) cases, excluding coconut shell is complete before volatile stoichiometry which implies that the char is only consumed by reduction reactions. Also, it is well known that the char steam reaction is enhanced in CO\(_2\) atmospheres [34]. At low temperatures i.e. below 1500 K, CO produced, in turn, reacts with steam through water gas shift reactions and promotes the formation of CO\(_2\) and H\(_2\) whereas at high temperatures (1500 K or more) CO
formation is enhanced as the equilibrium of water gas shift reaction shifts (CO + H₂O \rightleftharpoons CO₂ + H₂) towards the reactants along with Boudouard route. Hence, before volatile stoichiometry, zero/negative CO₂ conversion is observed and becomes positive when the Tₚₐ reaches 1500 ± 100 K or more for the all the cases reported in the current work. After volatile stoichiometry char gets oxidized and hence NCC is zero. Coconut shell exhibits universal propagation behavior like pellets and NCC is observed. However, as discussed earlier (refer Section 2.1.2), coconut shell exhibits different combustion characteristics like (1) high fuel flux than limiting value of 80 g/m²s with air, (2) low Tₚₐ as compared to agro and wood pellets, (3) high methane and other higher hydrocarbons in exit gas and very high cold gas efficiency (82% for...
C25C case at 99 g/m²s) (4) flame jump is observed beyond 40% O₂ fraction and (5) poor carbon conversion. Fuel flux obtained with coconut shell is as high as 246 g/m²s at an oxygen flux of 120 g/m²s for C40C case, but the corresponding char conversion was only 50%. Even with high fuel flux, the bed packing density is low (1.7 times lower than pellets) and hence the Tₚₑ rise is low and reaches 1500 K or more at higher mₓ, as compared to pellets. Similar to pellets, char conversion is more in O₂/CO₂ as compared to air case for coconut shell (refer Fig. 15), but the NCC occurs only at higher mₓ as compared to pellets due to slow Tₚₑ rise. The fixed carbon percentage on dry ash free basis is

---

**Fig. 12.** ECM variation with mₓ for P30C, P30N, C30C and WP30C cases; uncertainty ± 10%.

**Fig. 13.** ECM variation with mₓ for P40C, P40N, P50C and C40C cases; uncertainty ± 10%.

**Fig. 14.** ECM variation with mₓ for PA, P25C, P25N, CA, C25C and WPA cases; uncertainty ± 10%.

**Fig. 15.** Char conversion with mₓ in gasification regime; uncertainty smaller than marker size.

(V.M. Jaganathan, S. Varunkumar, Fuel 244 (2019) 545–558)

555
high for coconut shell (20%) and hence even with peak NCC of 406 g/m$^2$s at $m_{\text{ox}}^*$ of 120 g/m$^2$s with C30C case, 10% of char is left unconverted. Further investigations are needed to understand the behavior of coconut shell in packed bed reactors and this will be addressed in future work.

4.2. Cold gas efficiency ($\eta_c$)

Cold gas efficiencies ($\eta_c$) of all the experiments done in the current work are plotted in Fig. 16. Cold gas efficiency is defined as the ratio of energy value of the exit cold gas to the input fuel. In conventional gasification with air, even with the NCC of CO$_2$ available for reduction is less as compared to O$_2$/CO$_2$ cases and hence the cold gas efficiency of air cases is always lower than corresponding O$_2$/CO$_2$ cases. At maximum ECM, CO concentration is more and hence $\eta_c$ is also maximum at that point. As the bed operates in combustion regime, char gets oxidized and hence, fraction of combustibles in area exit reduces leading to decrease in $\eta_c$ (refer PA, P30C and CA cases). Also for coconut shell, as discussed earlier, $\eta_c$ as high as 82% for C25C case is observed and this is due to the presence of methane and HHC along with enhanced CO formation. However, this is to be further explored.

5. Modified universal flame propagation behavior

Uncorrected data showing the variation of $m_f^*$ with $m_{\text{ox}}^*$ for the cases of current work is shown in Fig. 17. In the current work, $m_f^*$ as such exhibits universal flame propagation behavior with $m_{\text{ox}}^*$ as observed by Varunkumar et al. [1], but for cases of high oxygen fractions (like 40% O$_2$ or more) and for fuels with higher calorific value like coconut shell (LHV 18–20 MJ/kg), $m_f^*$ exceeds the universal propagation limit with air (50–70 g/m$^2$s). Oxygen fraction and high heating value increases the volatile heat release rate and hence very high propagation rates (as high as 208 g/m$^2$s at a oxygen flux of 149 g/m$^2$s of P50C case) are observed. Hence for fuels with high heating values and when other oxyfuel burning modes are employed (like O$_2$/CO$_2$ and O$_2$/N$_2$), the universal propagation behavior needs modification. As discussed earlier, for peculiar fuels like coconut shell, high surface area aids better heat transport and enhances the fuel flux (as high as 246 g/m$^2$s at a oxygen flux of 120 g/m$^2$s for C40C case). Also, when O$_2$ fraction exceeds 40%, flame jump is observed coupled with very high temperature for the aforesaid reasons. Hence bed void age is also considered as one of the normalization parameters for correction of universal flame propagation behavior to account for the slightly different behavior of coconut shells – otherwise the variability of fuel flux ($m_f^* = \rho_f \phi_s$), with different biomass expected from the heat flux balance as explained in [1] is followed. Eq. (2) gives the Corrected Fuel Flux (CFF) which takes into account heating value H, oxidizer fraction in a stream $Y_{\text{ox}}$, stoichiometric coefficient (s) and bed density effects (in case of coconut shells).

$$\text{CFF} = \left( \frac{m_f^*}{m_{\text{ox}}^*} \right) \left( \frac{(H Y_{\text{ox}}/s)_{\text{ref}}}{(H Y_{\text{ox}}/s)_{\text{fl}}} \right) \left( \frac{\rho_{\text{fl}}}{\rho_{\text{ref}}} \right)$$

(2)

where H, $Y_{\text{ox}}$, s and $\rho$ represent heating value, oxidizer fraction, stoichiometric coefficient and bed density respectively. Suffixes (ref) and (a) represent reference and actual cases. Here agro residue based pellets with air as reactant is taken as reference here (it can be any fuel). Figure 18 depicts CFF or universal propagation rate which takes into account all the required parameters of normalization.

6. Conclusion

Fundamental studies of O$_2$/CO$_2$ gasification/combustion of biomass in a packed bed counter current configuration are carried out in this work. A new procedure for estimation of CO$_2$ conversion is developed. The salient features of this procedure are – (1) the importance of elemental and energy balance for accurate estimation of NCC is brought out and (2) the role of volatile CO$_2$ and its effect on estimated NCC is addressed for the first time to the best of our knowledge. NCC is evident from the experiments for all O$_2$/CO$_2$ cases and higher than corresponding air and O$_2$/N$_2$ cases. Presence of CO$_2$ in the inlet stream promotes char reduction reactions and when the operation regime shifts to near volatile stoichiometry ($\phi_v = 1 \pm 0.2$), where $T_{pb}$ is above 1500 K, significant NCC is observed. Enhancement of CO (ECM) increases the fuel value of the exit gas. The gasification efficiency of all O$_2$/CO$_2$ cases are higher than corresponding air cases and this is due to the reactive contribution of CO$_2$ unlike inert N$_2$ in air and O$_2$/N$_2$ cases. The study elucidates that O$_2$/CO$_2$ gasification is a promising route for both energy efficient power generation as well as CO$_2$ mitigation. With the development of air separation technologies and emerging techniques like CLAS (chemical looping air separation), oxy-fuel combustion is economical too. Moreover, use of CO$_2$ avoids cost implications of exhaust separation unit and hence promotes better carbon sequestration techniques and carbon negative power generation. Effect of fuel type, oxidizer and oxygen fraction on universal flame propagation behavior of biomass is addressed and a modified flame propagation behavior is proposed. This along with reported NCC and ECM values can be used to build efficient practical O$_2$/CO$_2$ gasification systems for small and medium scale power and heating applications.

Acknowledgments

We are thankful to our colleagues Mani Kalyani A, Vignesh C and...
Omex Mohan for technical assistance provided for conducting experiments.

References


