**Thermochemical conversion of coal and biomass blends in a top-lit updraft fixed bed: experimental assessment of the ignition front propagation velocity**

**Abstract**. Co-thermochemical conversion of coal and biomass can potentially decrease the use of fossil carbon and pollutant emissions. This work presents experimental results for an unconventional fixed bed reactor called the top-lit updraft. In a top-lit updraft fixed bed reactor, the ignition front starts at the top and propagates downward while the gas product flows upwards. Here we assess the ignition front propagation velocity for the co-thermochemical conversion of palm kernel shell, one of the main byproducts of the palm oil industry, and high-volatile bituminous coal. Within the assessed range of the air superficial velocity, the process occurred under gasification and near stoichiometric conditions. Under gasification conditions increasing coal particle size decreased the ignition front velocity by around 26% regardless of the coal volume percentage. For the operation near stoichiometric conditions, increasing coal volume percentage negatively affected the ignition front velocity in direct proportion to the coal particle size. Additional experiments confirmed the linear dependence of the ignition front velocity on air superficial velocity within the assessed experimental range. Those results also confirmed a minor influence of coal volume percentage and coal particle size on the ignition front velocity for the lower level of air superficial velocity. Although the top-lit updraft still represents a relatively unexploited fixed bed reactor, it features an enormous potential for the co-thermochemical conversion of coal and biomass. Further steps in the development of this technology are the implementation of continuous solids feeding and variable cross-sectional area, as well as optimizing coal particle size to exploit its synergy with biomass.

**Keywords**: TLUD, combustion, gasification, front propagation, syngas, burning rate, biochar

**1. Introduction**

Fixed bed reactors for gasification and combustion of solid fuels are widespread at the laboratory and industrial scales [1], [2]. Typically, the ignition front establishes near the bottom, and the product gas flows either upward or downward. The focus in this work is on the top-lit updraft (TLUD) fixed bed reactor in which the ignition front starts at the top and then propagates downward. The product gas flows upwards through the bed of char and ashes that are left behind. Improved cookstoves take advantage of the TLUD operation mode to separate gasification from the combustion of the product gas with secondary air [3], [4]. TLUD cookstoves feature lower specific fuel consumption, use a wide variety of small-size biomass particles, and reduce pollutant emissions REF. Grate furnaces for (co-)combustion of biomass, coal, and solid waste also take advantage of the TLUD configuration. In a grate furnace, a moving or vibrating grate transports the solids, primary air enters from below, and combustion with secondary air occurs on top of the bed [5]–[7]. Here we assess the ignition front propagation velocity for the co-thermochemical conversion of palm kernel shell (PKS) and high-volatile bituminous coal (HVBC) in a TLUD fixed bed reactor.

The TLUD operation mode is also referred to in the literature as an inverted downdraft [8]–[10], reverse downdraft [11]–[13], and reverse combustion [14]. However, in an actual downdraft, the solids move downward towards the ignition zone. In the TLUD configuration, on the other hand, the ignition front propagates downward through a static solids bed. The TLUD concept dates as early as the 1980s when its capabilities as an improved biomass cookstove started to be explored [15]. Most of the published research on TLUD concentrates on the development of improved biomass cookstoves [3], [16]–[19]. Other TLUD-related applications are biochar [20], syngas [21]–[24], and combined biochar-syngas production [9], [25], [26]. Likewise, bench-scale experiments in TLUD fixed bed reactors provide fundamental data for the design and operation of grate furnace combustors for solid waste [7], [27], [28] and biomass [5], [29].

The co-thermochemical conversion of PKS-HVBC blends in a TLUD fixed bed reactor remains unreported according to the best of the authors’ knowledge. Coal is a conventional raw material for thermochemical conversion because of its abundant reserves. However, coal is of fossil origin, emits significant amounts of pollutants such as H2S, SOx, and NOx, and its reactivity is rather low. Biomass, on the other hand, is a renewable feed of relatively high reactivity. Nevertheless, biomass is less available than coal and shows seasonal variation. Processing coal-biomass blends allows overcoming, at least partially, the abovementioned disadvantages [30], [31]. Thermogravimetric analysis (TGA) of PKS-coal blends revealed enhancement of the thermal degradation kinetics [32]–[34]. PKS-coal co-gasification in a bubbling fluidized bed showed positive results in terms of improved bed uniformity and syngas quality [35], [36].

Two operation regimes for TLUD fixed bed reactors are distinguishable from a plot of the ignition front propagation velocity vs. air superficial velocity [13], [14]. First, the gasification regime with oxidization reactions in the gas phase and char reduction reactions in the solid phase. In the gasification regime, the solid phase temperature is lower than the gas phase temperature, and a diffusion-controlled flaming combustion model reproduces experimental observations [13]. Increasing air superficial velocity leads to the char oxidation regime in which char and gas-phase oxidation reactions simultaneously occur. In the char oxidation regime, the temperature difference between the solid and gas phases vanishes due to the simultaneous oxidation of volatiles and char. Additionally, the propagation velocity of the ignition front appears to follow a universal trend irrespective of the type of biomass, which is consistent with a diffusion-limited process [13].

The TLUD operation can generate synthesis gas, or syngas, with potential for thermal and electric power generation [21]–[23]. The char oxidation regime is attractive for thermal applications because the fuel converts entirely, and heat losses are minor. The ignition front propagation velocity thus emerges as a critical parameter for the operation and control of TLUD gasifiers and combustors. The TLUD concept has great potential for thermal and electric power production, particularly at a low scale in remote rural areas. Additionally, bench-scale TLUD experiments provide fundamental data for the validation of more accurate numerical models, and the design, operation, and optimization of grate furnaces. Nevertheless, the lack of experimental information on the ignition front propagation velocity hinders the development of TLUD-based biomass-coal co-conversion technologies. This experimental work contributes to closing that gap by assessing the effects of the air superficial velocity, coal particle size, and coal volume percentage on the ignition front propagation velocity.

**2. Experimental procedures**

2.1 Feedstock

This study uses palm kernel shells or PKS, one of the main byproducts of the palm oil industry. The particle size of PKS, according to sieve analysis, amounted to 4.9 ± 2.3 mm (mean and standard deviation) [37]. PKS is attractive for gasification due to its relatively high energy content and particle density. PKS was co-processed with HVBC in the sieve fractions 4.7-9.5 mm, 9.5-12.7 mm, and 19.1-25.4 mm [38].

2.2 Experimental setup

Figure 1 shows a schematic illustration of the experimental setup. The TLUD fixed bed reactor consists of a cylindrical tube with an internal diameter of 152.4 mm and a height of 900 mm. A fiberglass thermal insulation layer 25 mm thick surrounds the metallic tube. A 600 W blower (model STPT600-B3, Stanley) feeds ambient air into the gasifier via a 63.5 mm internal diameter pipe. Before entering the gasifier, air passes through a manual control valve and a air velocity flow sensor (model 8455, TSI). Four K-type thermocouples with a sensitivity of 41 µV/°C and a measuring range of -200-1350°C, were located inside the gasifier. The setup includes a data acquisition system (model USB 6341 BNC Pinout, National Instruments) acting as an interface between measurements and a computer.



**Figure 1** Schematic representation of the top-lit updraft fixed bed reactor setup.

2.3 Experimental conditions

The ignition front propagation velocity, , is given by Equation 1. Here represents the distance between consecutive thermocouples and the time required by thermocouple (corresponding to ) to reach 500 °C.

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 1 |

The experimental variables were air superficial velocity , coal particle size (taken as the average from the upper and lower sieve sizes) and coal volume percentage . Table 1 summarizes the operating conditions for the initial set of duplicated experiments. The total mass for the lower and higher levels amounted to 3.65 kg and 4.03 kg, respectively. Likewise, the respective mass percentages of coal for the lower and higher levels were 15% and 40%.

**Table 1** Experimental conditions for the initial set of duplicated experiments, where represents air superficial velocity, carbon mean particle size, and carbon volume percentage.

|  |  |  |  |
| --- | --- | --- | --- |
| Experiment | , ms-1 | , mm | , % v/v |
| 1-1 | 0.18 | 7.1 | 10 |
| 1-2 | 0.18 | 7.1 | 30 |
| 1-3 | 0.18 | 22.2 | 10 |
| 1-4 | 0.18 | 22.2 | 30 |
| 1-5 | 0.46 | 7.1 | 10 |
| 1-6 | 0.46 | 7.1 | 30 |
| 1-7 | 0.46 | 22.2 | 10 |
| 1-8 | 0.46 | 22.2 | 30 |

Table 2 summarizes the conditions for the second set of experiments which further evaluated the influence of and on .

**Table 2**. Experimental conditions of the second set of experiments. Experiments 2-1 and 2-3 were single runs, while Experiment 2-2 was duplicated.

|  |  |  |  |
| --- | --- | --- | --- |
| Experiment | , ms-1 | , mm | , % v/v |
| 2-1 | 0.18 | 11.1 | 20 |
| 2-2 | 0.32 | 11.1 | 20 |
| 2-3 | 0.46 | 11.1 | 20 |

2.4 Setup operation

Figure 2 shows pictures of the TLUD fixed bed reactor setup and the feedstock. A typical experiment started by filling the chamber with a PKS-HVBC blend reaching a fuel column of around 440 mm height. Introducing the thermocouples sequentially as the solids level rose, helped to avoid the formation of empty pockets. Subsequently, increased gradually until reaching the set point. The data acquisition process started once stabilizes. Finally, a layer of particulate solids soaked in mineral diesel was added at the top and then ignited with a torch lit.

|  |  |
| --- | --- |
|  |  |
| a) | b) |
|  |  |
| c) | d) |

**Figure 2** Top-lit updraft gasifier setup. a) Gasifier and thermocouples location; b) computer screen during data acquisition; c) Palm kernel shell (PKS); d) High volatiles bituminous coal (HVBC).

**3. Results and discussion**

3.1 Feedstocks composition

Table 3 shows that the most salient differences between PKS and HVBC stem from their carbon (C) and oxygen (O) contents. HVBC has around 1.4 times more C than PKS, but its O content is less than half than that of PKS. HVBC contains more sulfur (S) and almost no nitrogen (N) when compared to PKS. However, for both PKS and HVBC S and N together represent less than two percent on a dry-ash-free basis (dafb).

**Table 3** Elemental composition on a dry-ash-free basis (dafb), proximate analysis on a dry basis (db), and higher heating value (HHV) of the feedstock. VM represents volatile matter, and FC fixed carbon.

|  |  |  |
| --- | --- | --- |
| Analysis/parameter | Palm kernel shell, PKS | High volatile bituminous coal, HVBC |
| C, % wt dafb | 53.8 | 74.6 |
| H, % wt dafb | 6.13 | 6.07 |
| N, % wt dafb | 0.88 | 0.05 |
| S, % wt dafb | 0.11 | 1.91 |
| O, % wt dafb | 39.0 | 17.4 |
| Molar H/C ratio | 1.36 | 0.97 |
| Molar O/C ratio | 0.54 | 0.18 |
| VM, % wt db | 81.6 | 33.7 |
| FC, % wt db | 14.6 | 45.4 |
| Ash, % wt db | 3.78 | 20.9 |
| HHV, kJ/kg db | 21073a | 25781b |

aGaur and Reed correlation [39], bMason and Ghandi correlation [40]

On a dry basis, HVBC contains around three times more fixed carbon (FC) than PKS, but its volatile matter (VM) content is less than half than that of PKS. FC relates to the yield of char produced during the devolatilization process. FC is mostly carbon but contains minor quantities of H, O, N, and S, which do not drive off with the gases. FC is the combustible residue left after VM distills off. A feedstock with high VM content ignites easily and is highly reactive in combustion applications. The VM content is naturally high for many types of biomass; however, its contribution to the higher heating value (HHV) is relatively low due to its high O content. Finally, HVBC contains more than five times ash compared with PKS. Ash could melt and agglomerate, which exacerbates air channeling and can finally block the passage of gases.

3.2 Temperature profiles

Figure 3 shows how temperature varies with time at each thermocouple location during a typical experiment. The propagation of the ignition front reflects in a sudden temperature increase reaching maximum values of around 1000 °C. The calculation of via Equation 1 is sensitive to differences in both the slope of the vs. curve and the time interval - (corresponding to and ). Figure 3 indicates that temperature in the range 300-600 °C could serve as a reference to calculate .



**Figure 3** Typical temperature profiles for the top-lit updraft thermal co-processing of palm kernel shell (PKS) and high-volatile bituminous coal (HVBC). represents temperature, time, and superficial velocity.

Linear regression of the observed vs. profile in the temperature range 300-600 °C data showed correlation coefficients higher than 0.96 for all experimental runs. Figure 4 shows for 500 °C and values from the linear regression models. Similar calculations for 300 °C and 600 °C showed minor differences with that for 500 °C, so from now on we use 500 °C as the reference for calculating .

3.3 Results for the initial set of experiments

3.3.1 Ignition front propagation velocity

Figures 4 and 5 show the results for the first set of experiments listed in Table 1. Figures 4A and 4B correspond to a of 10% and values of 7.1 mm and 22.2 mm, respectively. Figures 4C and 4D show equivalent results for a of 30%. The vertical bars at each value correspond to for the thermocouple locations 1-2, 2-3, and 3-4. A visual inspection of Figure 4 reveals differences in with the axial position. These differences in are more evident for the higher and the lower levels (i.e., Figure 4C). A direct proportion characterizes the dependence of the maximum temperature on . Additionally, the maximum temperature features higher values for the lower level (i.e., Figure 4A and Figure 4B).

Figure 4 shows that for the lower level of the increment in lowered by around 26% for both levels (Figure A vs. Figure B, and Figure C vs. Figure D), but the increment in did not influence in either case (Figure A vs. Figure C, and Figure B vs. Figure D). Results are not conclusive when considering the influence of on for the higher level of due to the scattering of the data. Results for the higher level of indicate that increasing leads to around 10% higher for the lower level and 17% lower for the higher level. Finally, for the higher level of , the increment in lowered by around 14% and 35% for the lower and the higher levels, respectively.

The Biot dimensionless group (), given by Equation 2, represents the ratio of intraparticle conduction and interfacial convection time scales [41]. In Equation 4 represents the characteristic length scale, the convective heat transfer coefficient between the coal particle and the carrier gas and the thermal conductivity. Provided that intraparticle conduction limits the observed reaction rate. To evaluate , was calculated via the Ranz-Marshall correlation [42] with equal to . For the operating conditions in Table 1 varies in the range 2.4-6.3, and even if is reduced to a half, is still higher than one. The analysis of shows that for our experiments the thermal conversion of coal was always limited by intraparticle conduction. Additionally, the ratio of intraparticle conduction and interfacial convection time scales for the higher level was more than twice than that for the lower.

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 2 |

Our results for the effect of on are in agreement with previous experimental studies with biomass in TLUD fixed bed reactors [10], [43]–[47]. Section 3.1 already discussed the most salient differences in composition between HVBC and PKS. Those compositional differences, and the fact that HVBC is around 1.6 times denser than PKS, might be responsible for the observed effect of on . The negative impact of on , particularly at the higher value is consistent with the marked difference in VM between HVBC and PKS. Experiments with biomass showed that an increment in bulk density of the bed results in lower [48]–[51], which is also consistent with our results regarding the effect of . Finally, experiments with biomass fixed beds also showed that increasing particle size could cause canalization and stagnant zones [44], [52]. Those effects could explain the relatively high scattering of the date, especially in Figure 4C and Figure 4D.

**Figure 4**. Ignition front propagation velocity () and maximum temperature () as a function of air superficial velocity (). A) Coal volume 10% and coal particle size 7.1 mm; B) Coal volume 10% and coal particle size 22.2 mm; C) Coal volume 30% and coal particle size 7.1 mm; D) Coal volume 30% and coal particle size 22.2 mm. Error bars represent the difference between the average and individual values of duplicated experiments.

3.3.2 Calculated equivalence ratio

The equivalence ratio, , given by Equation 3, represents the actual air-fuel ratio () divided by the stoichiometric air-fuel ratio (). The calculation of requires the elemental compositions in Table 3, together with the mass percentages of PKS and HVBC given in section 2.3. The calculation of , on the other hand, necessitates the mass of converted fuel per unit time () together with the air mass flow rate (). The mass flow rate indicates, given by Equation 4, results from the product of , the cross-sectional area and the density of the bed .

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 3 |
|  |  |  |
|  |  | Eq. 4 |

The parameter provides a first indication of the operating regime for the TLUD fixed bed reactor. For gasification, typically lies in the range 0.2-0.4 while values higher than one correlate with combustion. Note that greater than 0.4 may result in excessive formation of CO2 and H2O at the expense of CO and H2. Figure 5 reveals a direct proportion between and , which is consistent with a higher fuel consumption rate as increases. Additionally, these results confirm the potential of the TLUD setup to operate within a wide range of with PKS-HVBC blends.

For the lower level, Figure 5 shows that varies in the range 0.48-0.80. For these conditions, the TLUD fixed bed reactor operates in the gasification regime [13]. The gasification regime characterizes by volatiles oxidization reactions in the gas phase and char reduction reactions in the solid phase. Note that excessive formation of CO2 and H2O results in a synthesis gas of relatively low heating value. For the higher level, Figure 5 shows that varies in the range 0.89-1.1. For these experiments, the value indicates that the TLUD fixed bed reactor operates near stoichiometric conditions. Under those conditions, oxidation reactions may occur in both the solid and gas phases. Further increasing could finally cause cooling by convection and shift the process to fuel-lean conditions.

Increasing negatively affected while the opposite was observed for irrespective of the level in both cases. For the lower level of , Figure 5 shows that the increment in increased by around 35% for both levels (Figure A vs. Figure B and Figure C vs. Figure D). On the other hand, for the same level, the increment in yielded a 19% decrease in for both levels. For the higher level of the increment in decreased by around 9% for the lower level but featured an increment of 20% in for the higher level. Results are also contrasting when considering the influence of for the higher level of as it was the case with . In this case, increasing leads to 5% lower for the lower and 25% higher for the higher . Note that increasing leads to higher and eventually to higher , even if decreases.



**Figure** 5 Equivalence ratio () as a function of air superficial velocity (). A) Coal volume 10% and coal particle size 7.1 mm; B) Coal volume 10% and coal particle size 22.2 mm; C) Coal volume 30% and coal particle size 7.1 mm; D) Coal volume 30% and coal particle size 22.2 mm. Error bars represent the difference between the average and individual values of duplicate experiments.

3.4 Results for the second set of experiments

Figures 6 and 7 show the results for the second set of experiments listed in Table 2. Linear regression of the observed vs. data shows a correlation coefficient of 0.97. The value for the lower level differs by less than 8% with the corresponding values in Figure 4. This result is consistent with the observation that the influence of and on is minor for the lower level. On the other hand, for the higher level, the result is similar to the one for the higher and lower levels, but differs significantly with that for the higher .and levels.



**Figure 6** Ignition front propagation velocity and maximum temperature as a function of air superficial velocity, coal volume 20%, and coal particle size 11.1 mm. Error bars represent the difference between the average and individual values of duplicate experiments.

Figure 7 shows that increases by 36% when increases from 0.18 ms-1 to 0.32 ms-1, but remains constant with a further increase in to 0.46 ms-1. The for the lower level lies in between the corresponding result for the higher levels in Figure 5. The latter observation is also valid for the higher level, which is an indication of consistency for results in Figures 5 and 7.



**Figure 7** Equivalence ratio as a function of air superficial velocity, coal volume 20%, and coal particle size 11.1 mm. Error bars represent the difference between the average and individual values of duplicate experiments.

3.5 Outlook

Blends of small and large particles improved the stability of the ignition front and broadened the operation range [49]. The main reason is that for relatively small particles () intraparticle conduction does not limit their conversion rate, i.e., they release volatiles at a relatively high rate. Coal-biomass blends naturally benefit from the abovementioned effect due to their vast differences in VM. Besides, offers an additional degree of freedom to operate within a wide range of and optimize .

The batch operation mode of the TLUD fixed bed reactor limits their application range and deployment scale. A further step in the development of this technology is the continuous feeding of particulate solid fuel. An option to realize this idea is the combination of solids feeding screw and a second screw inside the reactor. The former delivers the feedstock near the bottom while the latter keeps the ignition front within certain axial positions. Ideally, ashes spill over the top of an inner tube and drop in an annular zone. To the best of the author's knowledge, a TLUD fixed bed reactor with continuous solids feeding remains unreported.

The incorporation of sections of the different cross-sectional area provides further flexibility to the aforementioned continuous TLUD operation. In a typical straight TLUD, increasing air superficial velocity shifts the operation regime from the gasification regime to the char oxidation regime. This result implies that syngas throughput cannot increase without changing its composition. A device with different cross-sections allows increasing syngas throughput while keeping its composition. The screw inside the device is essential for keeping the ignition front at the desired location. Finally, the composition of the gasses is essential to elucidate further the potential applications of biomass-coal co-conversion in TLUD fixed bed reactors.

**4. Conclusions**

Co-thermochemical conversion of coal and biomass could decrease fossil carbon usage, mitigate pollutant emissions while enhancing reactivity. This work presents an experimental investigation of this process in a to-lit updraft fixed bed reactor or TLUD. The work focused on the ignition front propagation velocity for thermal co-processing of palm kernel shell and high-volatile bituminous coal. Experiments within a wide range of experimental conditions shed light on the effects of the air superficial velocity, coal particle size, and volume percentage. The investigation used an in-house, designed, and built TLUD setup.

Results revealed differences in ignition front propagation velocity, , with the axial position. A direct proportion characterizes the dependence of the maximum temperature on air superficial velocity. Additionally, increasing the coal volume percentage negatively affected the maximum temperature reached in the TLUD fixed bed reactor. Results confirmed the potential of the TLUD setup to operate within a wide range of equivalence ratios with PKS-HVBC blends. For the lower air superficial velocity level, the calculated equivalence ratio varied in the range 0.48-0.80, i.e., the TLUD fixed bed reactor operated under gasification conditions. For the higher air superficial velocity, the equivalence ratio varied in the range 0.89-1.1, i.e., near stoichiometric conditions. This result indicates that, for the latter conditions, oxidation reactions may occur in both the solid and gas phases, and that further increasing the air superficial velocity could cause cooling by convection.

For the lower level of air superficial velocity, the increment in coal particle size lowered for both levels, but the increment in coal volume percentage did not influence . Results were contrasting when considering the influence of coal particle size on for the higher level of air superficial velocity due to data scattering. For the higher level of air superficial velocity, the increment in coal volume percentage lowered indirect proportion to the coal particle size. Additional experiments confirmed the linear dependence of on the air superficial velocity within the assessed experimental range. Those results also confirmed a minor influence of coal volume percentage and coal particle size on for the lower air superficial velocity.

The TLUD operation mode still represents a relatively uncharted fixed bed reactor. Its capabilities indicate that further and more frequent uses will come over the next decade. The TLUD fixed bed reactor shows excellent potential for the thermal conversion of solids fuel in the rapidly developing fields of energy and environmental engineering.

**Nomenclature**

|  |  |  |
| --- | --- | --- |
|  | Cross-sectional area | m2 |
|  | Biot number, |  |
| dafb | Dry-ash-free basis |  |
| db | Dry basis |  |
|  | Coal particle size | mm |
|  | Actual fuel-air ratio |  |
|  | Stoichiometric fuel-air ratio |  |
| FC | Fixed carbon | % wt |
| HHV | High heating value | kJ kg-1 |
|  | Convective heat transfer coefficient | W m-2 K-1 |
| HVBC | High-volatile bituminous coal |  |
|  | Characteristic length scale of a solid particle | mm |
|  | Air mass flow rate | kg s-1 |
|  | Fuel mass flow rate | kg s-1 |
| PKS | Palm kernel shell |  |
|  | Temperature | °C |
|  | Maximum temperature | °C |
|  | time | s |
| TGA | Thermogravimetric analysis |  |
| TLUD | Top-lit updraft |  |
|  | Ignition front propagation velocity | mm s-1 |
| VM | Volatile matter | % wt |
|  | Coal volume percentage | % v v-1 |
|  | Air superficial velocity | m s-1 |
|  | Distance between consecutive thermocouples | mm |
|  | Solid thermal conductivity | W m-1 °C-1 |
|  | Equivalence ratio |  |
|  | Bed density | kg m-3 |

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