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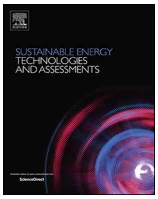

Mass, energy, and exergy analysis of the microgasification process in a top-lit updraft reactor: Effects of firewood type and forced primary airflow

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ABSTRACT

Four representative firewood species from some Colombian regions were evaluated in a top-lit-updraft (TLUD) reactor under gasification regimes. The effect of primary airflow on the process was studied at three levels (20, 30, and 40 l/min) using the firewood species with the highest fuel value index (FVI; 9.8 MJ/cm^3). The thermodynamic assessment of the microgasification process was characterized by means of response variables such as flame front velocity (V_{ff}), maximum reaction temperature (T_{max}), fuel/air equivalence-ratio (F_{rel}), mass yields (gas-Y_{gas}, char-Y_{char}, and tar-Y_{tar}), cold gas efficiency (CGE), chemical exergy efficiency (CEE), and irreversibility (I). With regard to the influence of the firewood type, the performance of the process was mainly affected by physical properties, such as bulk density and hardness, which had a positive effect on both F_{rel} and Y_{tar}, with a 95% confidence level. On the contrary, V_{ff}, Y_{char}, Y_{gas}, CGE, CEE, and I decreased when the bulk density and hardness increased. With regard to the effect of the airflow, V_{ff} and T_{max} increased from 7.9 to 14.0 mm/min and from 724.9 °C to 838.3 °C, respectively, because the process tended to lead to combustion; however, CGE and CEE tended to slightly increase with the airflow because the producer gas flow increased.

Introduction

Rural populations of developing countries use firewood as a source to satisfy their energy needs, i.e., cooking and heating [1,2]. According to the World Health Organization (WHO), about 3 billion people around the world use firewood, agricultural wastes, or coal for cooking their meals. The cooking process is generally performed on traditional cook stoves known as three-stone stoves [3]. Inefficient cooking systems that consume large amounts of fuel lead to high indoor air pollution with negative impacts on the health of particularly women and children [4,5]. Despite the social and environmental problems associated with the usage of firewood, its use in advanced systems (i.e., top-lit updraft -TLUD- biomass cook stoves) could be a solution for rural populations in terms of decreased emissions and increased efficiency [6,7].

The gasification process involves treating a carbon-based material (in this case, firewood) with a gasifying agent (i.e., air) to produce a gaseous fuel [8]. The gasification in TLUD reactors has been studied in the past decades for cooking applications. Grabow et al. [9] found that TLUD cook stoves produce combustion cleaner than that produced by three-stone and rocket cook stoves, decreasing the levels of indoor air pollution by 90% when operating with doors and windows opened. Njenga et al. [4] compared an improved gasifier stove with the traditional three-stone cook stove. The improved gasifier system saved 27%–40% of fuel, the cooking time decreased by 19%–23%, and the emissions were reduced between 40% and 90%. Tryner et al. [6] reported a thermal efficiency around 40% for five natural draft TLUD cookstoves. Obi et al. [10] characterized the performance of a TLUD cook stove using different biomass types and stated that the thermal efficiency increases by lowering the amount of ash in the fuel. Tyagi et al. [1] evaluated the performance of four improved cook stoves with the water-boiling test (WBT) and reported that the best energy and exergy efficiencies achievable were approximately 23% and 3.6%, respectively. Thus, cook stoves under gasification regimes can save energy and time during the cooking process among small-scale farmers and improve indoor air quality [4].

To understand the phenomenology of the TLUD microgasification process, researchers have been studying the effect of different process parameters. James et al. [11] studied the effect of biomass physical properties (particle size, moisture content, and packing factor) on the TLUD gasification process (in terms of gas composition and char and tar yields). The larger particles promoted tar formation, whereas the higher

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packing factor favored char production due to the higher amount of biomass involved in the thermochemical process. Porteiro et al. [12] reported that air mass flow is one of the most influential parameter affecting ignition propagation velocity under fixed-bed biomass gasification/combustion conditions. In this way, Kirch et al. [13] stated that the gasification efficiency could be improved and the emissions depleted by controlling the primary airflow fed to the process. Previous studies that focused on understanding the thermodynamic performance of TLUD microgasification process via mass, energy and exergy analyses are scarce, and most of these studies have analyzed TLUD cook stoves using protocols such as water boiling and cooking controlled tests (CCT) [6,14,15]. Thus, this work aims to perform a complete thermodynamic characterization of firewood microgasification in a TLUD reactor by evaluating the effect of firewood type and airflow on the gasification process because it is the main thermochemical transformation in TLUD biomass cook stoves [6,16].

The energy analysis in thermal systems allows us to quantify the energy distribution in the studied process (desired output, required input, and losses) and the first law of thermodynamics efficiency [17]. In a complementary way, exergy analysis, which is based on the second law of thermodynamics, enables the calculation of the useful work related with each energy form involved in the studied system [18]. Consequently, the degradation of the energy quality related to the entropy creation or exergy destruction (irreversibility) can be determined [19,20]. Thus, the exergy efficiency is a measure of the approach of the actual process to the reversible process, and can help designing more efficient energy systems by reducing the irreversibility [1,19,21]. In this study, the mass, energy, and exergy performance assessment of the TLUD microgasification process with regard to firewood type and forced primary airflow was conducted.

Methodology

The microgasification process of a TLUD gasifier was studied using four representative firewood species from some Colombian regions to analyze the effect of the biomass type on the process. In the second experimental stage, the firewood species with the highest quality as a solid biofuel, quantified by the fuel value index (FVI; MJ/cm^3), was selected to analyze the effect of the primary airflow on the gasification process. Three levels of airflow (20, 30, and 40 L/min) were analyzed. The gasification process was thermodynamically characterized by means of the flame front velocity (V_{ff}), fuel/air equivalence ratio (F_{rel}), average maximum temperature (T_{max}), and cold gas efficiency (CGE) [22]. The estimation of irreversibility (I) associated to the TLUD microgasification process and the mass balance of three products (gas, char, and tar) as functions of the experimental factors considered in this work (see Section "Thermodynamic characterization of the TLUD gasification process") provided new contributions to the knowledge on the process.

Experimental setup

A laboratory facility with a TLUD gasifier (Fig. 1) working at atmospheric pressure was used for the thermodynamic analysis. This reactor was selected because it was comparable with a TLUD cook stove operating only with primary airflow [16]. Useful and fundamental parameters, such as firewood consumption rate, maximum reaction temperature (T_{max}), and biochar production can be obtained under controlled conditions. The producer gas composition (concentrations in vol.% of H_2, CO, CO_2, CH_4, O_2, and N_2) was determined by gas chromatography using a MicroGC Model 3000 (Agilent), which had a thermal conductibility (TCD) detector, a molecular sieve column (5 A of 10 m × 0.32 mm) with Argon as the carrier gas, and a plot U column (8 m × 0.32 mm) with Helium as the carrier gas. The experimental setup was described in detail by Lenis et al. [23].

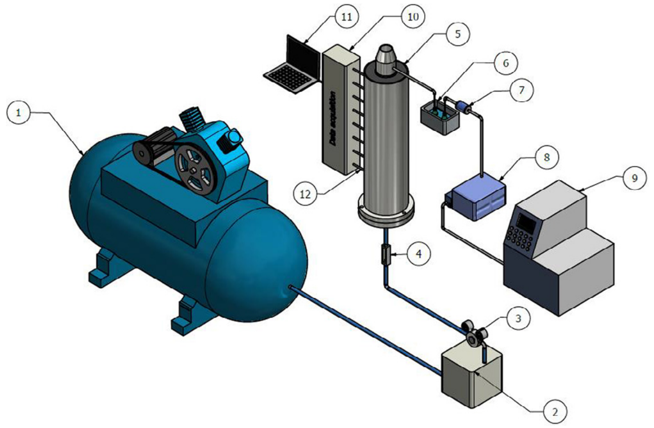

Fig. 1. Experimental setup: 1. reciprocating compressor, 2. plenum, 3. flow regulator, 4. rotameter, 5. Top-lift updraft (TLUD) reactor, 6. gas conditioning, 7. filter, 8, vacuum pump, 9. gas chromatograph, 10. data acquisition system, 11. computer, and 12. K-type thermocouples.

Characterization of firewood species

Representative firewood species from some Colombian regions used for cooking tasks [24] were employed as feedstocks. Debarked logs with ~15 cm of diameter and ~70 cm of length were chipped under the same conditions (i.e., engine speed and aperture of teeth) with a Bandit 95XP chipper, and the wood chips were sieved and classified into size groups between 4 and 20 mm. The samples were dried in sunlight for one week. The firewood species analyzed herein were *Cordia alliodora* (Nog), *Guazuma ulmifolia* (Gua), *Eucalyptus grandis* (Euc), and *Pinus patula* (Pat).

The firewood samples were characterized by proximate and ultimate analyses, lower heating value (LHV_{bms}), thermogravimetric analysis (TGA), bulk density, hardness, and particle size, as summarized in Table 1. Proximate analysis was conducted using a TGA Q50 instrument according to a modified ASTM D 5142-04 standard method [25]. The ultimate analysis was performed using a CHNSO (LECO) Truspec microapparatus according to the ASTM D 5373-08 method. Fiber analysis of the raw biomass was conducted according to the van Soest method [26] to determine the cellulose, hemicellulose, and lignin contents. The heating value was determined using a bomb calorimeter (6100 compensated jacket calorimeter, Parr Instrument Company) following the ASTM E144-14 standard method. The test was repeated three times for each sample. LHV was calculated based on the higher heating value (HHV) using Eq. (1), proposed by Quaak et al. [27].

$$LHV_{db} = HHV_{db} - 2260 \times M_{db} - 20300 \times H_{db} \quad (1)$$

where HHV_{db} (kJ/kg) is the HHV by dry basis, M_{db} is the moisture content of the sample (%), and H_d is the hydrogen content (wt% by dry basis).

The reactivity analysis was conducted using a TG50 instrument under constant nitrogen flow (60 ml/min) from 25 °C to 600 °C at a heating rate of 10 °C/min, and ~10 mg of each firewood sample was used, similar to the method adopted by Poletto [28]. The reactivity was estimated from the thermograms using the model suggested by Ghetti [29]. The complete physicochemical characterization of these firewood species as solid biofuels was presented in detail by Díez and Pérez [24].

Thermodynamic characterization of the TLUD gasification process

The performance of TLUD gasification at a laboratory scale was