Evaluation of the Energy Density for Burning Disaggregated and Pelletized Coffee Husks

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ABSTRACT: Coffee husks represent about 12 wt % of coffee grains, generating a significant impact on the environment because of its inadequate disposal. In Colombia, this waste presents an energy resource opportunity equivalent to over 49,106 TJ per year. However, several challenges related to this type of biomass, such as the moisture content, the irregular shapes, and the low bulk density, make its use difficult in current burners. Thus, in this paper, the combustion of coffee husk pellets was studied in detail to design a high-efficiency burner to produce energy for coffee drying. The pellets were prepared in a pelletizer with 15% moisture and 20% yield and burned in a bench-scale lateral reactor to determine the energy density. It was found that the combustion properties of coffee husk depend on the specifics of the pelleting process. The energy density values were $I_{v} = 0.789 \text{ MW/m}^3$ and $I_{g} = 0.007 \text{ MW/m}^3$, which could be used to design the combustion chamber for coffee husk burning.

INTRODUCTION

The use of biomass for the generation of thermal energy can contribute positively to a series of common political objectives, including increasing the use of renewable energies, reducing pollution emissions, and complying with environmental regulations. Additionally, it can encourage economic development in communities dependent on the agricultural and forestry sectors. Consequently, in countries whose economies are based on agriculture, the use of biomass energy could be a solution for the final disposal of this type of waste and contribute to the generation of energy from alternative technologies.

In Colombia, around 72 million tons of agricultural residual biomass are produced annually, of which 193,460 tons correspond to coffee husk, an energy opportunity equivalent to 49,106 TJ per year. In recent years, the studies related to coffee husk have increased, and some of these investigations are focused on the development of dense products for combustion applications. However, the aim of this study is to evaluate the coffee husk combustion.

Kang et al. investigated the combustion characteristics of spent coffee beans and wood pellets. In their study, they found that the energy potential of spent coffee beans was higher than that of wooden pellets because spent coffee beans have a higher hydrogen content. In addition, the authors evaluated the combustion in a 6.5 kWth boiler and quantified the combustion gases, obtaining concentrations of 17.8% $O_2$, 643 ppm $CO$, and 163 ppm $NO_x$. These values indicate that the combustion was incomplete; therefore, the authors concluded that it was necessary to optimize the design of the boiler so that the combustion would be carried out properly and pollution emissions reduced.

Limousy et al. carried out the evaluation of the combustion of wood pellets, spent coffee pellets, and a mixture of pellets of both biomasses. In their study, they found that the combustion of the spent coffee pellets generated higher $CO$ and $NO_x$ emissions than those of both the wooden pellets and the biomass mixture. Moran et al. investigated different mixtures of biomass pellets and municipal waste to obtain good combustion efficiency and lower emissions. Their study found that the optimal mixture contained 20% waste and 80% biomass with a greater than 1.6 air ratio. Verma et al. measured the $CO$, $NO_x$, $SO_x$, and $C_2H_4$ emissions of the combustion of various biomass pellets in a 40 kWth boiler, including wood, apple, grass, and sunflower seeds. They found that the main parameters that must be considered for the proper use of agro-pellets in small-scale combustion equipment were the ash content and the low melting temperature.

Additionally, Guo and Zhong studied the combustion of pellets of amento compounds, wood residues, rice, and coal residues by both thermogravimetric and fluidized bed analyses to optimize the oxidation processes. The authors found that the ideal mixing ratio of the composite pellets to coal was 30%:70%, respectively, resulting in minimal activation energy and a reduced amount of alkali metals that potentially cause slagging problems.
Furthermore, in the literature, it is possible to find studies focused on the determination of the ignition temperature of various biomasses at different heating rates. Magalhães et al. found that ignition occurred in the gas phase because of the content of volatile material, where the volatile low-density material caused ignition regardless of the rate of heating used. Riaza et al. analyzed various factors to determine the ignition temperature of biomass in the form of a pellet. This study considered the heating rate and other parameters such as particle sizes, operating temperatures, and oxygen concentrations, finding that the biomasses showed a greater susceptibility to autoignition compared to the lignite coals.

Moreover, studies have been carried out to determine the ignition temperature of varying mixtures of coal and biomass to utilize the waste material through co-combustion, reduce the ignition temperature, and reduce the generation of NOx. In these investigations, geometric methods from the thermogravimetric analysis (TGA) and differential thermogravimetry (DTG) graphs are mainly used. In other works, biomasses such as bagasse, bamboo, pine, olive, flower peel, almond peel, and olive residues were studied, and the ignition temperatures between 290 and 320 °C were calculated. However, these studies did not analyze the differences in the reactivity of the biomasses and the technical implications for the design of the combustion chamber.

In the literature reviewed, there are no reported works on the development of biomass pellet combustion equipment, and generally, the designers use design parameters obtained from coal combustion studies but are not from biomass combustion studies. Therefore, we will show a complete study of coffee husk combustion by analyzing the main differences between the combustion of the aggregate and disaggregated material, the combustion time residence, and the effect of pelleting on the combustion process.

## RESULTS AND DISCUSSION

The maximum temperature of the coffee husk during combustion was 751 °C for the disaggregated material form and 761 °C for the pellet form (see Figure 1). These values are higher than the furnace set temperature as a consequence of the exothermic reactions that characterize the oxidation of organic materials.

The heating rate can be observed in Figure 1; the differences may be due to the ignition temperature of the coffee husk (280 °C), as will be discussed later. When this temperature was exceeded, the disaggregated material exhibited both greater oxidation rate and higher production of carbon dioxide as compared with the pelleted material because of the distribution of the original material where the layer of coffee husk is more joined.

It can also be seen in Figure 1 that with the completion of the combustion process, as indicated by the CO2 concentration reducing close to zero, the temperature of the disaggregated material was recorded to be at the oven temperature. Because of the thermocouple being uncovered, it may have directly recorded the oven temperature. On the other hand, the thermocouple was inserted inside the pelleted sample. In this case, the recorded temperature was lower than the oven temperature after completion of the combustion process. This may be the result of the pellet reduced temperature because of secondary endothermic reactions (see Figure 2).

Figure 2 shows that, initially, endothermic reactions occur due to the humidity present in the material, and subsequently, exothermic reactions occur due to the oxidation of the material. At 20 min of combustion, the results indicate that the biomass had only partially oxidized. At 60 min of combustion, an endothermic peak indicates possible secondary reactions after oxidation of the coffee husk, which are distinct from the endothermic reactions because of the initial drying process. These secondary reactions occurred at 120 °C.

On the other hand, the adiabatic flame temperature was determined by an energy balance of heat capacity variation with respect to combustion gas temperature. The flame temperature results were determined under stoichiometric conditions and with 40% excess air, which is the recommended value found in the literature for solid fuels. Under stoichiometric conditions, the flame temperature was 1827 K (1624 °C), and under excess air conditions, the temperature was 1400 K (1127 °C). With a higher percentage of excess air, the volume of the combustion gases will increase, and therefore, the flame temperature will decrease. Table 1 shows the proximate and ultimate analyses of coffee husk.

The ignition temperature of the material was determined using graphical analysis of the thermogravimetric study of the sample, following the methodology of Li et al. For the tests in the TGA, a heating rate of 10 K/min was defined as reported in the literature. The graphical method consists of (1) drawing a vertical line at the point of maximum mass loss rate (point P), (2) drawing a tangent line at the intersection (point Q) of the mass loss curve (TGA in Figure 3), (3) drawing a tangent line on the first stage (drying) on the TGA curve, and (4) finally, drawing a vertical line at the intersection (point R) of the lines drawn from steps (2) and (3), indicating the ignition temperature on the base axis (see Figure 3). On the basis of this methodology, it was determined that the ignition temperature of the coffee husk is 280 °C, which is within the range of ignition temperatures reported for different biomasses in the literature.

The results of the combustion tests are presented in Figure 4, where the primary coffee husk pyrolysis stage and subsequent oxidation of the char can be distinguished.

The drying stage is the first stage of the biomass combustion process. However, in the present experiments, this stage was not detectable due to the low moisture content of the samples (~ 9.5%). Inserting the sample holder into the oven at 700 °C resulted in a high rate of drying, causing the water to evaporate and be forced out of the particle before devolatilization. With the drying of the sample, its temperature increases causing...
decomposition and the release of volatiles. The flow of volatiles out of the sample during devolatilization does not allow oxygen to reach its pores, resulting in pyrolysis.

The presence of $H_2$, $CO_2$, $H_2S$, $O_2$, $C_2H_6$, $CH_4$, $C_2H_4$, $CO$, and $C_3H_8$ species was measured using a gas chromatograph during the devolatilization stage as the oxygen concentration decreased, as well as during the subsequent char oxidation stage where the carbon monoxide on the sample surface reacted with the oxygen, generating carbon dioxide.

The pyrolysis stage lasted 3 min for the disaggregated material and 7 min for the agglomerated material. This difference occurs due to the fact that the pelleted material has a layer of the coffee husk joined together by means of mechanical interlocking, causing the material to oxidize more slowly. On the other hand, the disaggregated material has more space between layers of coffee husks, allowing the reaction to proceed more rapidly.

The resulting char, which forms at the end of the devolatilization process, is highly porous because of the spaces generated by the volatiles escaping the sample during the previous stage. Because of this porosity, air can diffuse into the sample during this stage. The resulting char oxidation times...
were 16 min for the disaggregated material and 21 min for the agglomerated material.

The sample power release rates per unit of volume and area were calculated using the oxidation times of the experimental tests, as well as the volume and area projected by the sample in the horizontal oven as determined before inserting the sample into the kiln. $I_v$ and $I_a$ were calculated using eqs 1 and 2. The results are presented in Table 2. The energy of the material was calculated using a lower calorific value of 15.8 MJ/kg, which does not depend on the geometry of the sample material, because the low heating value is an intensive property of the material.

The specific power corresponds to 0.3732 MW/m³ of the chamber for the disaggregated material and 0.7895 MW/m³ of the chamber for the agglomerated material. This indicates that the pelletized coffee husk could release more power in a fixed volume than the disaggregated material because there is more material in the pellet form than in the disaggregated form in the same volume, which implies more available energy for releasing in the combustion process. These differences between the pelletized and disaggregated materials are only due to the difference in space required for the combustion inside the combustion chamber because the HHV is the same for both cases.

To obtain a given power output requirement, the necessary combustion chamber volume for burning coffee husk in a disaggregated form is 2.1 times larger than that for pellets. Additionally, the bulk density of the pelletized material (614 kg/m³) is nearly three times greater than that of the disaggregated material (213 kg/m³). Consequently, the volume occupied by the agglomerated material is almost one-third that of the disaggregated material, indicating that equipment operating with coffee husk pellets could be more compact. Regarding the power release rate per unit of the grid area, the energy density of the pellets is three times higher than that of the disaggregated material. Consequently, combustion equipment for the pelletized material can be designed with three times smaller grid areas.

The specific power per unit volume of the disaggregated coffee husk used in this work was found to be below the range of $0.47−9$ MW/m³, as reported by other authors for other solid fuels.20,22 The specific power per unit of grid area was also found to be below the range of $0.74−1.7$ MW/m² for bituminous coal in a fixed grid, as reported by other authors.20,22 These discrepancies in specific power are mainly due to the thermal properties of the compared fuels, such as calorific value and density, which result in the superior energy performance of fossil fuels, such as coal. The discrepancies can also be attributed to the various combustion stages that occur, considering that devolatilization occurs as the first stage, followed by oxidation of the char at a later stage. The reaction rate depends on the stage of the combustion process, which leads to the varying reactivity of each stage. Biomass fuels may possibly be more reactive than fossil fuels during the devolatilization stage because of the easy oxidation of the gaseous compounds, providing energy for the combustion of char.

Further combustion tests were carried out on a pilot scale. The quantities of comburent and fuel were determined based on the capacity of the feeding system. During 1 h testing runs, 1.2 kg of the disaggregated coffee husk was used compared to 1.6 kg of the agglomerated coffee husk. Figure 5 presents the results of the gas monitoring in the pilot tests.

The limiting reagent in both test cases was the coffee husk. The pollutant concentration increased during the feeding of the biomass and decreased once the material was consumed (Figure 8). The concentration of sulfur oxides remained low during combustion because of the very low sulfur content (0.05%) of the coffee husk. Sulfur dioxide can be produced by the decomposition of CaSO₄ at temperatures greater than 1200 °C21,25 however, in the present tests, the temperature of the equipment was well below this threshold. Nitrogen oxide emissions were around 180 ppm during the combustion of the material at a pilot scale.

The formation of NO is mainly due to the oxidation of nitrogen at temperatures below 1000 °C. The NO can be generated by both homogeneous and heterogeneous reactions.21,25 As the concentration of nitrogen in the biomass was very low (0.04%), the NO measured during the present tests was predominantly formed because of the process temperature. The difference between both results is mainly due to the disaggregated material reaches the combustion process and releases pollutant emissions more quickly than the pelletized material, which is due to the material distribution in the combustion chamber.

**CONCLUSIONS**

On the basis of experimental combustion tests, the flame temperature of the coffee husk was found to be 1624 °C, whereas the ignition temperature was found to be 280 °C, a value that is consistent with the ignition temperatures of biomasses reported in the literature. The pelletized material form increased the oxidation time compared to the disaggregated material because of the lack of surface area in the agglomerated form. The pelletized coffee husk required an average time of 21 min to fully oxidize, whereas the disaggregated form required an average time of 16 min.

This work presents the first known measure of the combustion characteristics of coffee husk in both its
disaggregated and pelleted forms, informing the design criteria of future coffee husk combustion equipment. The parameters of power released per unit volume and per unit area were calculated experimentally for coffee husk, resulting in $I_v = 0.3732$ MW/m$^3$ and $I_A = 0.0032$ MW/m$^2$ for the disaggregated material and $I_v = 0.7895$ MW/m$^3$ and $I_A = 0.0069$ MW/m$^2$ for the pelleted material. These values can facilitate the proper sizing of the combustion chamber. The methodology used in this research allows for the measurement of the parameters associated with the power released per unit of both volume and area for different biomasses, which are fundamental for the design of a suitable combustion chamber. It was determined that the combustion of the disaggregated coffee husk requires a combustion chamber volume and a grid area of 2.1 times greater than that required by the combustion of pelleted coffee husk for an equivalent performance characteristic.

EXPERIMENTAL SECTION

The adiabatic flame temperature and ignition temperature of coffee husk in both disaggregated and agglomerated formats were determined. The adiabatic flame temperature was measured in a combustion chamber by using an energy balance under stoichiometric conditions and with excess air. Samples were taken from the coffee husk to subject the material to elemental analysis and proximate analysis in EXETER brand model CE-440 using the ASTM D5373 standard and in TGA Linseis brand model STA PT-1600. The ignition temperature was determined by means of thermogravimetric analysis in TGA Linseis brand model STA PT-1600. The thermogravimetric analysis was performed with $13 \pm 0.01$ mg of samples at a heating rate of 10 K/min in an atmosphere of mixed N$_2$/O$_2$ (50/13 mL/min). The ignition temperature was determined from the mass loss curve by plotting the three segments with the most significant changes and contrasting with the curve of the mass loss derivative.

The study of the combustion of coffee husk was carried out by means of experimental tests in a lateral oven bench scale (see Figure 6). The tests were performed using 1.8 g of the sample material at a time. The reaction zone is 30 cm long, wrapped with electrical resistance for heating the quartz tube measuring 3.5 cm in diameter and 64 cm in length, where the material to be studied was placed. The sample was weighed before and after the test and was supported on a quartz sample holder with a diameter of 2.4 cm and a length of 13 cm. Preliminary tests were performed to ensure that the air flow used would exceed the friction losses in the line and traps without disturbing the sample. The flow of compressed air was set at 1.7 lpm, supplied by a tank lung connected to a piston-type compressor.

The process temperature was 700 °C as measured on the outer surface of the electrical resistance, whereas an internal thermocouple was used to monitor the temperature of the pellet or the disaggregated material (see Figure 7). The sample holder with the coffee husk was placed into the reactor once the oven reached the process temperature. After confirming the contact between the thermocouple and the sample material, the quartz tube was sealed, and the flowmeter valve opened to introduce the oxidizing atmosphere. The gases generated from combustion were passed through two stages of traps: (1) retaining the tar by direct contact with isopropyl alcohol and (2) followed by removing moisture by direct contact with silica gel. These samples were collected in Tedlar bags and analyzed in an Agilent MicroGC model 3000 gas chromatograph to quantify the presence of O$_2$, H$_2$, CH$_4$, CO, CO$_2$, and H$_2$S according to Valdés et al. and Montoya et al.

To measure the temperature of the pellet, a perforation was made to the agglomerated material using a 1 mm drill, where the tip of the thermocouple was inserted. Figure 7 shows the position of the thermocouple in the case of (A) the disaggregated material and (B) the pelleted material.

The energy velocity of the fuel was calculated using eqs 1 and 2, which relate the power per unit volume and area in the combustion chamber

$\frac{m}{t} \times PCI$ $\frac{m}{tA}$ $\times PCI$

where $I_v$ is the fuel empirical rate of power release per unit volume of the combustion chamber, $V$ is the volume of the combustion chamber, $m$ is the amount of material used, PCI is the lower calorific value of the fuel, $I_A$ is the empirical rate of energy release per unit area of the grid, and $A$ is the area of the grid. These factors were calculated using the experimental results of the combustion tests with agglomerated and disaggregated coffee husk combustion in the lateral oven.

The oxidation time of the disaggregated and pelleted materials was determined using the oxygen and carbon dioxide content of the combustion gases, that is, the end of combustion was defined as when the percentage of oxygen at the outlet was equal to its concentration in the input air and when the concentration of carbon dioxide was zero.

Additionally, the power release rate of the fuel per unit volume and area was calculated from the volume and area projected of the material in the oven, the volume projected was related with the length of the material inside the sample holder.

![Figure 6. Experimental assembly for the combustion of coffee husk pellets.](image)

![Figure 7. Thermocouple assembly inside the quartz tube. (A) Disaggregated material. (B) Pelletized material.](image)
and the area of the quartz tube, and the area projected was related with the length of the material inside the sample holder and diameter of the quartz tube. This values compared with the general values reported in the literature, this indicator allows to define the size of the combustion chamber easily.

Finally, pilot-scale tests were carried out to analyze the pollutant emissions generated during the combustion of both the agglomerated and disaggregated materials. Four experiments were carried out with 1.2 kg/h of pelletted material and disaggregated material, guaranteeing a flow of 200 lpm of a comburent, according to the feeding system of the reactor. Figure 8 illustrates the experimental setup.

![Figure 8. Experimental assembly at pilot scale.](image)

The comburent flow was provided by compressed air from a lung tank, controlled using digital flowmeter OMEGA brand reference FMA5400/SS500. Samples of combustion gases were collected and analyzed for O2, H2, CH4, CO, CO2, and H2S content using the previously mentioned gas chromatograph, as well as NOx and SO2 content using a Bacharach brand portable gas analyzer.

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**Notes**

The authors declare no competing financial interest.

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