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EFFECT OF FUEL MOISTURE AND AIRFLOW RATE ON COMBUSTION CHARACTERISTICS OF COCONUT SHELL IN A FIXED BED

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Abstract. *This work evaluates the influence of air flow rate and fuel moisture on the combustion characteristics of the coconut shell and verifies the economic feasibility of performing a pre-treatment of drying before burning. Therefore, experiments were carried out in a fixed bed reactor using grinded coconut shell. Before the experiments, the biomass characterization was performed through the proximate analysis, following the procedures of ASTM D1762-84. To prepare the biomass, 12.5 and 4mm sieves were used to standardize the fiber size. Then, the combustion experiments were carried out in the reactor. Flow rates of 100, 130 and 160% of theoretical air were used, and for the moisture analysis, the samples that dried for 1 and 2h in the oven were compared with the samples without pre-drying. The results showed that the air flow rate available for combustion has an important effect on maximum temperature, residual mass and flame front propagation velocity. Increasing flow rate from 100 to 130% leads to an increase on bed temperature as well as on propagation velocity, unlike what happened when flow rate was increased to 160%. Residual mass was reduced with the increasing of air flow rate on all studied values. Regarding the coconut shell moisture, only the increase on propagation velocity for drier samples was observed. Bed temperature and residual mass showed no significant variation.*

Keywords: *residue combustion, biomass, coconut shell, fuel moisture, airflow rate*

1. INTRODUCTION

In the last decades, a growing increase in the emission of gases of greenhouse effect occurred mainly due to the great consumption of fossil fuels for generation of energy. According to Höök and Tang (2013), 62% of the global emissions of greenhouse gases made by humans in 2008 are CO₂ emissions from fossil fuels. According to the US Environmental Protection Agency, EPA (2015), the concentration of carbon dioxide in the atmosphere has increased from about 315 ppm in the year 1950 to almost 400 ppm in 2015, exceeding 400 ppm in the year 2016.

Because of this growing concern about the emission of greenhouse gases, there is a need to obtain sources of energy with less dependence on fossil fuels in order to reduce the impact on the environment. Thus, in recent years, there has been a large increase in the use of biomass as a renewable raw material around the world (Cutz, *et al.*, 2016). The International Energy Agency's IEA (2016) renewable energy statistics show that 72.8% of the renewable energy produced in the world in 2014 comes from biofuels.

Coconut shells are considered one of the biomasses with the highest energy potential (Raveendran, *et al.*, 1995). The latest survey by the Food and Agriculture Organization of the United Nations (FAO) in 2013 shows that Brazil is the fourth largest producer of coconut in the world with a production of 2,890,286 tons. According to Rosa, *et al.* 2001, the shell of the green coconut represents about 80% to 85% of the gross weight of the fruit. Due to the immense amount of residues generated by the production and consumption of coconut in Brazil, a great problem with coconut shell discarding is originated, since the volume occupied by this residue is large and hardly has its volume reduced because of its high hardness. In addition, the shell has a long decomposition time, reducing the lifetime of the dumps (Silva, 2014).

An alternative to reduce the environmental impacts generated by the inappropriate disposal of coconut husks is the reuse of this residue, such as mulch, due to its high moisture retention, which can contribute positively to the fertilization of the crops, which may cause changes in soil properties (MATTOS, *et al.*, 2011). Thus, the use of coconut shell for energy generation represents a great alternative for the destination of these residues, promoting less environmental impact and still providing a source of extra income to the producer.

However, fuel properties and process conditions, such as fuel type and moisture, particle size, air flow rate and preheating affect the combustion characteristics, causing changes in the reaction rates, heat generation and transfer and therefore, several studies on the combustion of biomass have been carried out in the last decades (Zhao, *et al.*, 2008).

2. METHODOLOGY

Coconut shell samples were collected at a local company that crushes these residues to be used as mulch in their plantation. Before starting the combustion experiments it was necessary to perform the preparation and characterization of the biomass.

The samples were cut manually using scissors as shown in Fig. 1a. Sieves of 12.5 (Fig. 1b) and 4 mm (Fig. 1c) were used for greater uniformity in the particle size of the samples. The final samples was characterized as shown in Fig. 1d.



Figure 1. a) Cutting process of the sample; b) 12.5 mm sieve; c) 4 mm sieve; d) final sample after preparation

To perform the biomass characterization, a proximate analysis was performed based on ASTM D1762 - 84, which presents test methods for the determination of moisture, volatile matter and ash in wood charcoal. The materials and tools used to perform the analysis were: muffle furnace VulcanBox 3-550PD, analytical balance Shimadzu AUY220, desiccator, blue silica gel as desiccant, porcelain crucibles with lid and pliers.

The reactor used for combustion was constructed by Deoclecio and Santos (2016) and its schematic design is shown in Fig. 2. It consists of a stainless steel tube (610 mm long, 63 mm internal diameter and 73 mm external diameter) connected to an exhaust pipe at the bottom and closed at the top with a screw cap. The air inlet is at the top.

To supply the cell with the biomass, it was necessary to remove all the thermocouples and to add the samples gradually, compacting them during the process. As the biomass level exceeded the height of a thermocouple, it was inserted into the reactor and then more biomass was added and compacted. After filling the bed completely, a layer of about 1cm of charcoal was added to start the combustion.

The ignition of the biomass was done with an oxyacetylene torch through the hole in the reactor cap. The air injection was made with a 2 HP Schulz PraticAir compressor and maximum pressure of 8 bar. Two rotameters were used for flow rate measurement, one with a scale of 1 to 10 standard cubic feet per hour, and another with a scale of 10 to 100 SCFH and the flow control was done by the needle valve present at the outlet of the compressor.

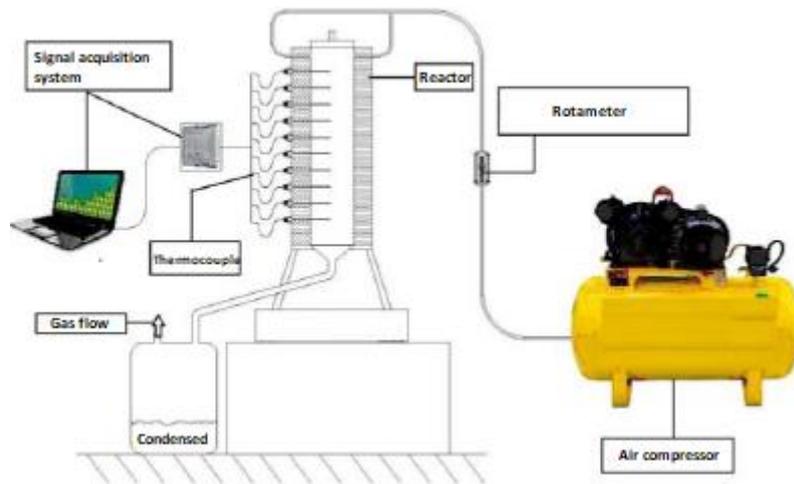


Figure 2. Schematic drawing of the experimental apparatus

The temperature measurement is done by 10 type K thermocouples equally spaced in 50 mm along the reactor. Two Arduino Mega 2560 boards were used to read the temperature measurements made by the thermocouples. The interface between the thermocouples and the Arduino boards was made with the MAX6675 modules.

Gas exhaust is made by a copper tube at the bottom of the reactor, where a high temperature resistant hose is connected. The gases then pass through a washing system where the condensate is trapped and the gases flow through another hose to the fume hood, an equipment that exhausts the gases to the external environment. The complete experimental apparatus is shown in Fig. 3.

To vary the moisture content of the samples a fixed amount of 300g of coconut shell will be placed in a stainless steel box and taken to the muffle furnace at 105°C. The drying times used will be 1 and 2h. Then a moisture analysis of the samples will be done following the ASTM D1762-84 standard.



Figure 3. Experimental apparatus

From the temperature profiles obtained for each airflow and fuel moisture experiment, the values of maximum temperature, residual mass on bed and ignition front propagation velocity are obtained. The maximum temperature is obtained by comparing the highest temperature peak in each thermocouple. The residual mass on bed is obtained by weighing the unburned material after each experiment and comparing it with the initial mass before combustion,

presenting the result in percentage of the initial mass. The ignition front propagation velocity is calculated through Equation 1.

$$V_f = \frac{e}{t} \quad (1)$$

Where, V_f is the ignition front propagation velocity [mm/s], e is the space between the thermocouples [mm] and t is the time required to go through the thermocouples [s].

The ignition front propagation velocity is calculated between each thermocouple and then the average velocity are calculated. The time required to go through the thermocouples is the time difference between the peak temperature of a thermocouple and the peak of the previous thermocouple. With these results, the mean and standard deviation of the experiments for each value of airflow rate and fuel moisture will be calculated, and the non-standard values of the other experiments will be discarded. When one of the results is discarded, a new experiment will be done. Thus graphs of the average of each result will be plotted as a function of the airflow rate and fuel moisture and a comparative study will be done between them.

3. RESULTS

3.1 Proximate Analysis

Analyzes were performed on 8 samples of coconut shell and the averages and standard deviations of the results were calculated. The final result of the proximate analysis is presented in Table 1. Comparing the results obtained experimentally with the values verified in the literature is possible to observe that, in general, the results are similar, which validates the analysis performed.

Table 1. Coconut shell proximate analysis obtained experimentally

Properties	Average (% dry basis)	Standard deviation
Moisture	10,8	1,5
Volatile Matter	73,3	1,6
Ashes	1,1	0,1
Fixed Carbon	25,6	1,6

It is also possible to observe that the amount of volatile matter and fixed carbon present is very high, which is favorable for the combustion because they contribute to the calorific power of the biomass. In addition, the ash content obtained is very low, which also favors combustion, since only a small amount of the coconut shell is inert and will not contribute to its burning. The low ash content is also an economic advantage as it means less material to be discarded.

3.2 Bed temperature profile

Figure 4 shows the bed temperature profile at 10 different measuring points which are 50 mm apart each. By evaluating the temperature profiles obtained it is possible to observe that, once the burning has started, the ignition front propagates downward, reaching the thermocouples. Temperatures begin to rise to a value just below 373K and remain for a few seconds. This is because at this temperature the vaporization of the moisture present in the fuel is occurring, and the heat generated is being used for the phase transformation of the water. Once the fuel moisture has been released, there is a rapid increase in temperature to their respective peaks, which reach values up to 773K.

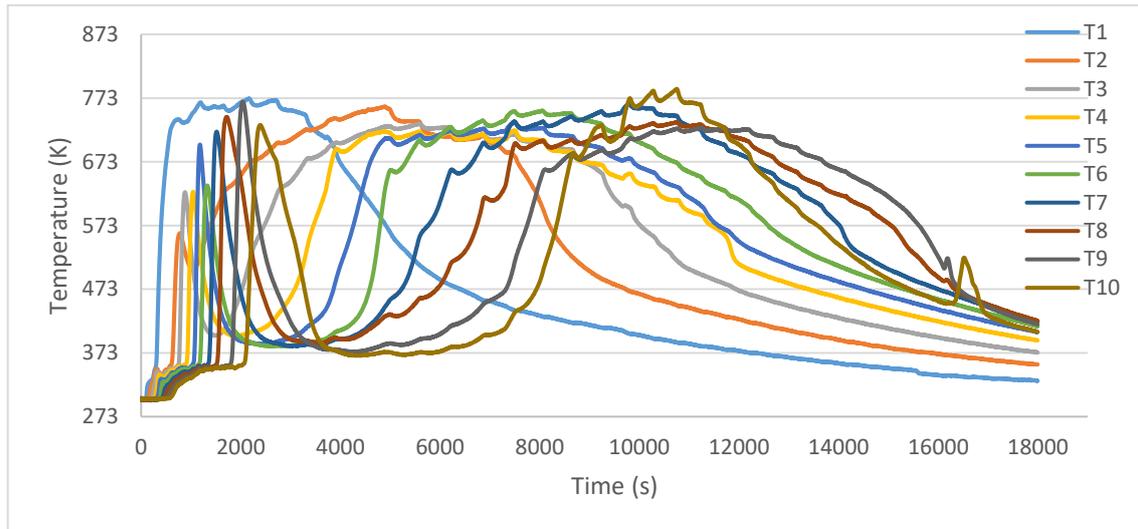


Figure 4. Bed temperature profile of coconut shell combustion

At that moment the devolatilization of the biomass is occurring, where the volatile matter is burned, which causes this rapid increase of temperature, and only the fixed carbon remains in bed. The first thermocouple exhibits a different behavior from the others because of the interference of the top layer of charcoal used to initiate the ignition, since it has a higher heating value than that of the coconut shell. The following temperature drop is due to the loss of heat from the exhaust gases.

After the passage of the ignition front, a char burnout front begins, doing a complete burning of the remaining fixed carbon after devolatilization, which causes the temperature to rise again, reaching a new peak. As the fixed carbon is being burned, only the ashes remain in the bed, and the temperatures in each thermocouple begin to fall rapidly.

This behavior differs from that of other biomasses such as corn straw studied by Zhao, *et al.*, 2008 and simulated municipal solid waste studied by Sun, *et al.*, 2016 and Liang, *et al.*, 2008 wherein only one peak temperature is formed and then the temperature falls to room temperature without forming another peak. This can be explained by the fact that the coconut shell has a fixed carbon content higher than that of these other residues, while these have a larger volatile matter content, making the first temperature peak, related to devolatilization, larger and predominates on the burning of fixed carbon.

However, a similar behavior was observed by Putri, *et al.*, 2017, Ryu, *et al.*, 2006 and Yang, *et al.*, 2003, in which, after the first flame front, a further increase in bed temperature is noticed. This occurs, because once all the moisture and volatile materials inside the solid fuel have been burned out, only the char burning happens, accentuated by the availability of all the oxygen that is fed, increasing the bed temperature.

3.3 Influence of airflow rate

Fig. 5 shows the effect of the air flow at the maximum temperature. With the increase in air flow from 100% to 130% of theoretical air, it is possible to notice an increase of almost 373K in the maximum temperature reached. Since the combustion reactions do not occur uniformly over the bed, a theoretical air flow rate of 100% does not guarantee complete oxidation of the fuel, so with the increase in flow to 130%, more oxygen is available in the bed, causing the entire burn to occur. With an increase in airflow to 160%, the maximum temperature drops to 311K on average, since the available oxygen is more than sufficient for complete combustion to occur and this excess oxygen is incorporated into the exhaust gas, that its temperature decreases. Meng, *et al.*, 2017 only observed the increase in maximum temperature since the flow variation studied by them was from 22% to 110% of theoretical air.

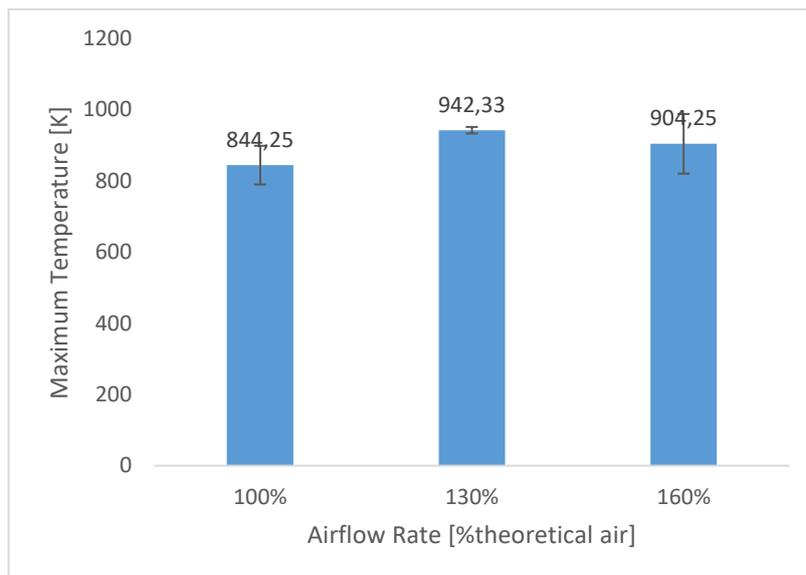


Figure 5. Influence of airflow rate on maximum temperature

Fig. 6 shows the influence of the flow rate on the residual mass in the reactor after combustion. It is possible to observe in the graph a tendency of reduction of unburned fuel with the increase of the air flow, presenting a reduction a little more than 1% between each value of flow, which is in agreement with the result of Meng, *et al.*, 2017. The explanation for this phenomenon is the increase in the flow, making more oxygen available inside the reactor, facilitating the reactions of oxidation of the fuel and, consequently, less unburned material remaining after the firing.

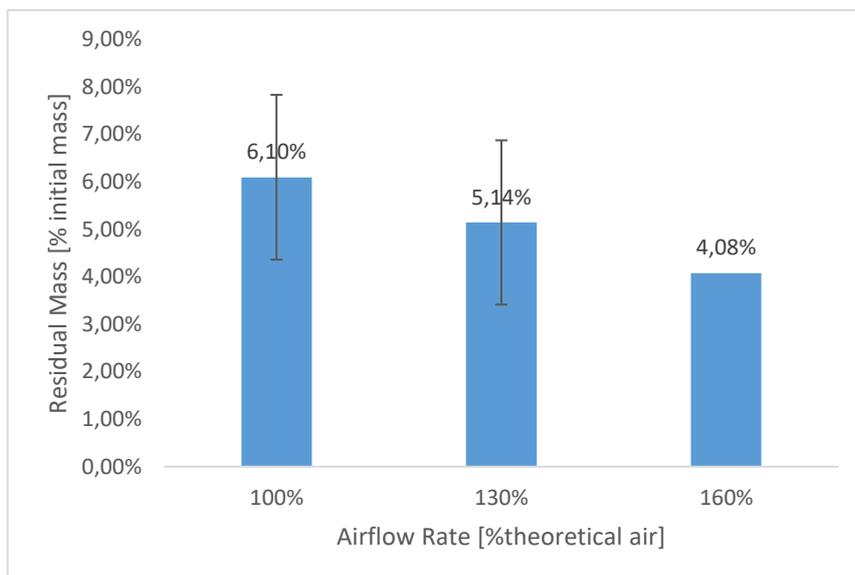


Figure 6. Influence of airflow rate on residual mass

Fig. 7 shows the variation of the propagation velocity of the flame front as a function of the air flow. With an increase in the air flow rate from 100 to 130%, an increase in propagation velocity greater than 57% is perceptible, but with a 130% increase to 160%, a reduction of about 23% in this value was observed. This happens, therefore, the increase of the flow provides the sufficient amount of O_2 for the oxidation of the coal and the reactions with the volatile materials up to a limit value. By exceeding this value, the heat dissipated by this high flow is greater than the heat generated in the lower bed layers, resulting in increased ignition time. Meng, *et al.*, 2017 observed only the tendency of increase in the velocity of propagation of the flame front because the maximum value of theoretical airflow studied by them was 110%.

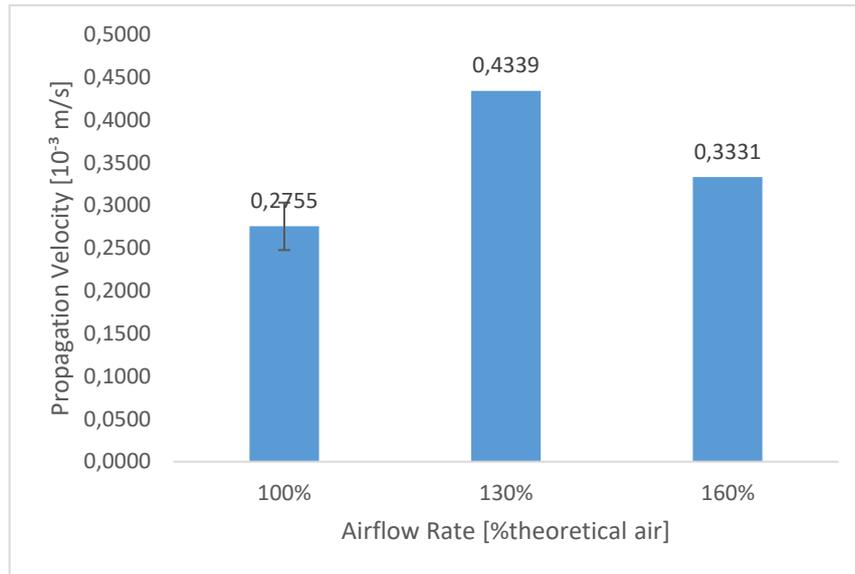


Figure 7. Influence of airflow rate on flame front propagation velocity

3.4 Influence of fuel moisture

Fig. 8 shows the maximum temperature as a function of the humidity of the coconut shell. In this graph, it was possible to observe that there is not a significant variation of the maximum combustion temperature with the reduction of the humidity of the coconut shell, since between the humidities of 10.8% and 4.8% there is a variation of only 300K. This result is different from that obtained by Liang, *et al.*, 2008 and Zhao, *et al.*, 2008, in which temperature variations as high as 473K and 493K were obtained, respectively. This difference occurs because the reduction of the biomass moisture after drying in this work is very small, only 6%, which does not affect significantly the results, which shows that the crushed coconut shell already presents a humidity low enough for the burning, while in the works of Liang, *et al.*, 2008 and Zhao, *et al.*, 2008 variations are made greater than 40% and 30%, respectively, which affects drastically the results.

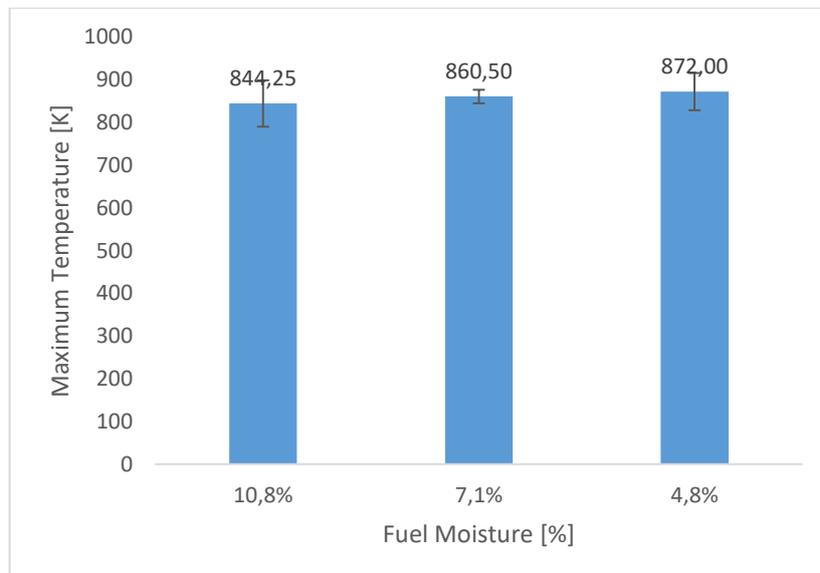


Figure 8. Influence of fuel moisture on maximum temperature

Fig. 9 shows the influence of coconut shell moisture on the residual mass after combustion. With the reduction of humidity from 10.8% to 7.1% there was a reduction of the mass of unburnt material of almost 1%, this can be explained as follows. According to Zhao, *et al.*, 2008, the oxidation of coal depends on three factors: amount of coal formed, amount of O_2 available and temperature. The drier fuel has a greater devolatilization rate, which increases the formation of coal and the consumption of O_2 for the burning of the volatile gases. However, the formation of more coal counteracted the

reduction of the O₂ available during devolatilization, causing the residual mass to decrease in the end. Reducing the humidity to 4.8%, it is possible to observe that there is not a significant change in the final mass, because the increase in the O₂ consumption generated by the faster devolatilization is balanced by the reduction of the availability of the same during this process, end the oxidation rate remains the same.

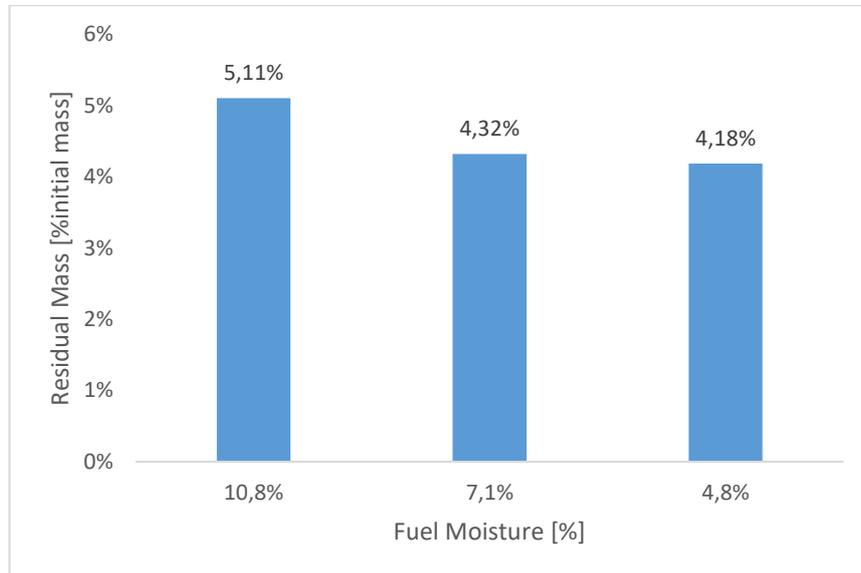


Figure 9. Influence of fuel moisture on residual mass

Fig. 10 shows the propagation velocity of the flame front as a function of the humidity of the coconut shell. It is possible to observe that with the reduction of the humidity there is a tendency of increase in the velocity of propagation of the flame front, with an increase of 50% of the speed of 10,8% to 4,8% of humidity. This is in accordance with the results of Liang, *et al.*, 2008 and Zhao, *et al.*, 2008, where the propagation velocities obtained were about 5 times higher between the highest and lowest values of moisture studied. This is because with a lower content of moisture in the fuel, less time is spent with the vaporization, causing the flame front to travel the bed more quickly.

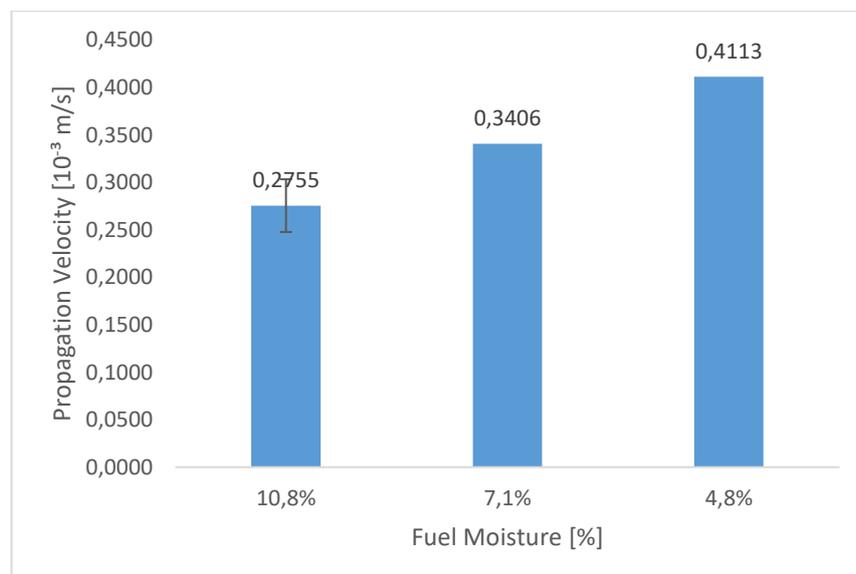


Figure 10. Influence of fuel moisture on flame front propagation velocity

4. CONCLUSIONS

At the end of this work it was possible to verify the behavior of the biomass of the green coconut shell during its burning for energy generation, and with that, to verify its viability for this purpose.

Among the analyzed parameters, the air flow available for combustion had an important effect on the maximum temperature, the residual mass and the flame propagation velocity. It was possible to notice in this work that the increase of the air flow brings positive effects to the combustion, however, that increase must not be undefined. It was verified that the theoretical air flow rate of 130% was the best result among the studied values, since it presented the highest combustion temperature and the highest velocity of the flame front propagation, although its residual mass was slightly higher than that obtained for the 160% flow rate. In this way, it can be seen that there is a limit for the increase of the flow during the firing.

In relation to the moisture of the coconut shell, an increase in the speed of propagation of the flame front with the drier samples was observed. It was concluded that pre-drying is not feasible economically, since there were no significant variations in relation to the final temperature and the residual mass, which does not compensate the energy spent with the kiln for drying. Showing that costs with a biomass pretreatment will not bring a significant benefit to the biomass combustion process. By showing that only drying with the biomass exposure to the atmosphere is sufficient to remove the moisture required to carry out its combustion satisfactorily.

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