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SINTERING OF CLAY PELLETS, CHARCOAL AND FLY ASH IN A COMBUSTION CELL IN FIXED BED: ANALYSIS OF PROPAGATION OF A COMBUSTION REACTION FRONT THROUGH A POROUS MATERIAL

Alvino Oliveira Melo
Emanuel Negrão Macêdo
Instituto Federal de Educação Tecnológica do Maranhão - IFMA
Universidade Federal do Pará - UFPA
alvino@ifma.edu.br
enegrao@ufpa.br

Márcio Ferreira Martins
Universidade federal do Espírito Santo - UFES
marciofm@ct.ufes.br

Danielly Quaresma
Universidade Federal do Pará - UFPA
danysq@gmail.com

José Antônio da Silva Sousa
Universidade Federal do Pará - UFPA
jass@ufpa.br

Alacid Neves
Universidade Federal do Pará - UFPA
alacidneves@ufpa.br

Abstract. *A great preoccupation of humanity turns around the preservation of the environment, seeking constantly through studies and searches alternatives to find a balance of coexistence between man and nature. Normally, industries in general, produce waste at its majority toxic which damage the environment, humans being and other diversities of life inserted in it. Inserting itself in this context, this paper makes a study of evolution of the temperature of combustion of a mixture, in predefined proportions of fly ash from boiler industries, clay and charcoal. The experiments were performed in a combustion reactor in order to assess the temperatures and if the values of these temperatures would be sufficient to initiate the process of sintering of the pellets. For the experiments performance, parameters such as inlet velocity of the fluid (air), diameters of the pellets (mixture of charcoal, ash and clay) and size of charcoal crushed in a disk mill were varied and the effect of variations of these parameters were analyzed for each experiment. The historical temperatures were recorded by a data acquisition instrument and subsequently plotted for analysis. Temperatures varying in the range of 800°C-1200°C were obtained and these values are sufficient to initiate the process of sintering of the pellets.*

Keywords: *Combustion reactor, charcoal, ash, clay, porous media.*

1. INTRODUCTION

Porous medium it is a material that consists of a solid matrix with interconnected voids. Suppose that the solid matrix is either rigid, the usual situation, or it undergoes small deformation. The interconnectedness of the voids or pores allows the flow of one or more fluids through the material. As examples of natural porous media can cite beach sand, sandstone, limestone, wood, and the human lung. (Bejan, 2006).

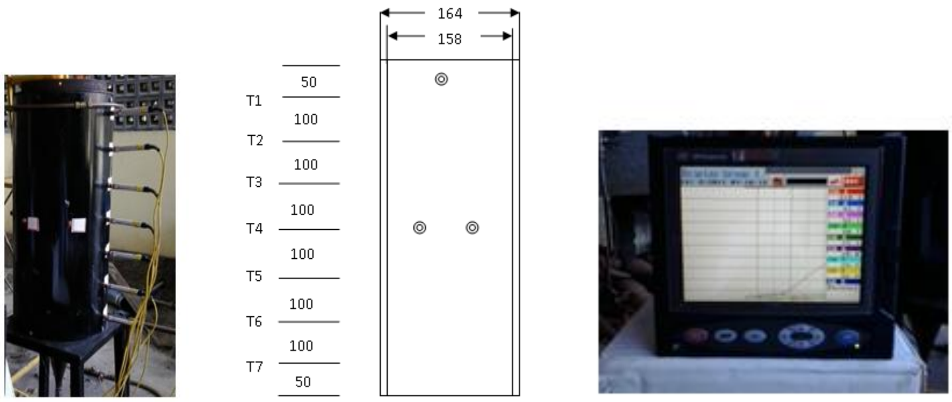
Several experimental and theoretical studies of the combustion of coal or wood particles in a fixed bed have been conducted in order to understand the phenomena that occur during the combustion process in porous media such as heat and mass transfer. However, the parameters that govern the combustion of solids in the bed, such as the effects of particle size, heat and mass transfer in porous media, and the interference between the solids reactions and gas phase, are not fully understood (Kaviany, 1991). To understand these processes of complex interpretations, a combustion reactor was developed and filled with a porous solid material, pellets, predominantly spherical in geometric shape, consisting of a mixture previously defined with a percentage of clay, from the banks of the Guamá River, fly ash from the steel industries of Pará-Brazil and charcoal.

The fuel used in the combustion reaction was charcoal, crushed in a disc mill in order to control the grain size. In this work were studied parameters such as the rate of supply of air, the influence of the size of the fuel particles (charcoal) and pellets (clay, charcoal and fly ash) during the combustion reaction.

During the reaction, the smoldering combustion was predominantly, where the smoldering is a fundamental combustion problem involving heterogeneous chemical reactions and the transport of heat, mass and momentum in the gas and solid phases. The fundamental difference between smoldering and flaming combustion is that, in the former, the oxidation reaction and the heat release occur on the solid surface of the fuel or porous matrix and, in the latter, these occur in the gas phase surrounding the fuel. (G. Rein, 2009). Data acquisition was taken by "Paper-Less Recorder PHL" properly attached to the thermocouples axially distributed throughout the combustion reactor. Nine experiments were performed. The experiments 1, 2, 3, 4 and 5 were discarded due the problems presented during the evolution of the combustion reaction throughout the bed. In this paper, the front reaction combustion analysis it is realized for experiment 8, once that alls experiments studied presents a similar characteristic in combustion regime. The velocity combustion analysis take in consideration the experiments 6, 7, 8, and 9. Temperature profile analysis in reactor also it is considered the experiment 8.

2. DESCRIPTION OF THE EXPERIMENT

The experiment consists of a fixed bed reactor shown in Fig. 1a, it is based in a work developed in the Université de Tolouse by Martins (2008) . The fixed bed reactor is a cylinder made of carbon steel with a thickness of 1/8" with 158 mm internal diameter, 700 mm height and 164 mm of external diameter shown in Figure 1b. For getting one-dimensional propagation of the combustion front, walls of the reactor are insulated by an insulation layer of rock wool fiber with 30mm thickness. By means of this insulation radial losses are minimized and propagation on the reactor axis can be considered one-dimensional. Seven type K thermocouples are distributed throughout the reactor, keeping appropriate distances shown in Fig.1a. Figure 1b shows the reactor in situ. The data taken by "Paper-Less Recorder PHL" shown in Fig. 1c, were plotted and analyzed.



(a) (b) (c)

Figure 1 - (a) Combustion reactor in situ; (b) Reactor schematic draw; (c) Paper-Less Recorder

3. EXPERIMENTAL SET UP

The experimental set up shown in Fig. 2, it is composed by: 1-combustion cell; 2-cone; 3-acrylic tube; 4 and 5- control valves; 6-exhaust;7-air collector; 8-air exhaust; 9-thermocouples; 10-manometer; 11-burner; 12-cover; 13-centrifugal fan; 14-crown. Air it is initially introduced into the combustion reactor by means of a exhaust (6) connected to the reactor outlet for a 1/2 inch copper tubing. A perforated grate ensures a distribution of air flow, beyond to avoid efficiently the reactor obstruction with ashes suctioned by the exhaust. The air flow rates are controlled by manual valves (4) and (5), the velocity of air flows are measured for each experiment through a anemometer with the reactor previously filled with the pellets, before start the combustion,**.** A centrifugal fan (13) was used to cool the gas temperature at the reactor exit. Seven thermocouples are placed inside the reactor such that their extremity are located on the center line of the combustion reactor axis as show Fig. 1a and Fig. 1b. A thermocouple placed on the outside surface of the reactor was used to measure the temperature of the reactor at that location, and in accordance with the temperature recorded by the data logger, it was observed that the temperature at the outer surface is approximately 10% of the internal temperature , showing this way that the heat flow along the bed can be considered one-dimensional.

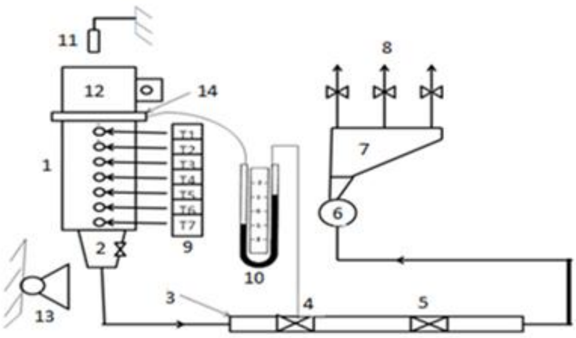


Figure 2 **-** Combustion process set up

4. EXPERIMENTAL PROCEDURE

4.1 Pellets production procedures

The production of the pellets are described in the five steps following: i) Drying the coal and clay in a electric kiln at a temperature of 105°C; ii) Crushing the coal in a disc mill; iii) Grind coal and clay for 30 minutes in a ball mill; iv) Homogenization of the coal, clay and fly ash in the ball mill during one hour; v) Production of aggregates in a cement mixer; vi) The aggregates (pellets) produced were removed from the mixer and heated in a electric kiln at 105°C for a period of 24 hours. The pellets were manufactured with 40% clay, 30% fly ash and 30% charcoal powder.

After performing several experiments it was concluded that for each 1 kg of aggregates would be ideal to use approximately 400ml of water, obtaining in this way an aggregate (pellets) that after drying in an electric kiln becomes resistant enough to be used in reactor combustion during the experiment.

4.2 Combustion reaction procedure

The fixed bed reactor was filled with 80% of coal milled with size suitably selected with sieves and 20% pellets until a height of 700 mm (completely filled). The fuel (coal milled) was slightly compressed and the procedure was adopted for the different tests. The ignition of the solid fuel (coal milled) begins with an external flame of a burner, using butane gas as a fuel, uniformly distributed across the surface of the fuel as shown in Fig. 3, to make the process homogeneous. After completing the process of ignition, start the self sustenance of the flame propagation. The time for ignition of the fuel and the self sustenance flame was about 6 minutes when the thermocouple 1, placed at a distance of 50mm from the top of the reactor, accused a temperature of approximately 700°C, then cut the fuel (butane gas) to the burner and the combustion reaction progressed self sustained. The burner was placed at a distance of about 13mm from the top of the reactor.

The process variables are the velocity of the oxidant forced flow, the diameter of the pellets and the coal particle size. Temperatures are recorded as a function of time by the seven thermocouples distributed axially along the reactor and properly connected to the data logger (paperless recorder). The propagation of the reaction front is determined by the time taken for the reaction cross two consecutive thermocouples. The arrival of the reaction front in a thermocouple is determined by a sudden increase in temperature. Only thermocouples placed in the center line of the fuel bed is used to calculate the speed of propagation of the flame front (X. Zhou, 1995).

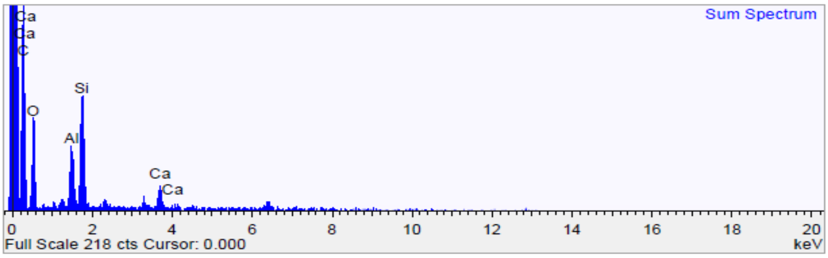
Figure 3- Combustion Ignition of the solid fuel in the combustion cell

5. ELEMENTAL CHEMICAL ANALYSIS OF THE PELLETS RESULTS

5.1 Analysis of pellets before combustion in the reactor

Table 1 shows the elemental chemical analysis of the pellets before combustion. The table shows the predominance of carbon before combustion of the pellets into the reactor.

Table 1 - Chemical composition of the pellets before the combustion.

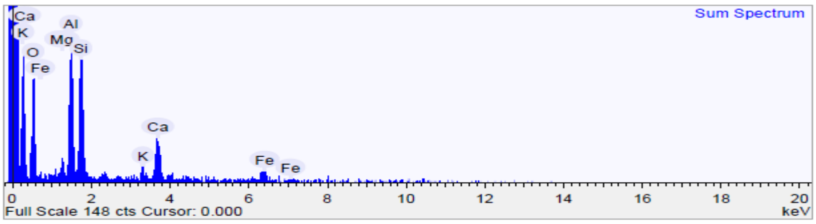


Elements	Atomic Weight (%)
Carbon	58,819
Oxygen	30,422
aluminum	2,561
Silícon	5,087
Calcium	2,111

5.2 Analysis of pellets after combustion in the reactor

Table 2 shows the elemental chemical analysis of the pellets after combustion. Table shows that after the combustion process, the carbon in the pellets went fully consumed, remainder proportion of oxygen, aluminum, silicon, calcium and iron.

Table 2 - Chemical composition of the pellets after combustion.



Elements	Atomic Weight (%)
Oxygen	47,853
Magnesium	2,345
Alumínum	13,860
Silícon	17,935
Potassium	2,446
Calcium	8,943
Iron	6,618

6. THERMO GRAVIMETRIC ANALYSIS RESULTS

Thermo gravimetric analysis of the samples was performed taking in consideration the mass loss of the sample during the combustion reaction. Figure 4 shows that dry of the sample is performed until a temperature approximately 50°C. Between temperatures (50-350ºC) observes a very small quantity of mass consumed, indicating that in this temperature range the pellets react slowly in the combustion reaction, showing that in this range the pellets absorb heat in the reaction which is a characteristic phenomenon of an endothermic reaction.

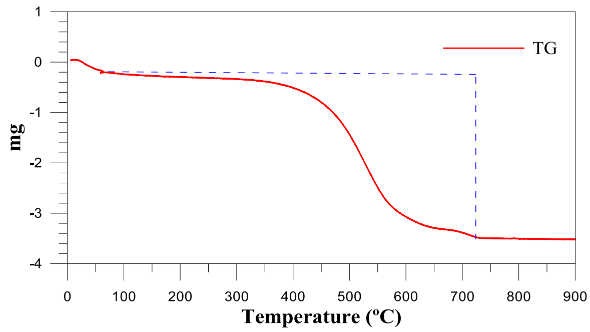


Figure 4 - Thermal analysis of the pellets in an atmosphere of synthetic air.

The major mass loss occurs in the temperature range of about (350-750ºC), because in this range the pellets have absorbed sufficient heat to start a more intense combustion and in consequence mass consumption is accelerated. Between range (750-900ºC) the quantity of matter remains constant, indicating the end of the reaction. Figure 4 shows that at the end of the combustion process, approximately 85% of matter were consumed during the combustion. After end of the combustion, it is expected the combustion reactor be cold, then is removed all material that after combustion has undergone a sintering process, as illustrated in Fig.5.

Figure 5. Aspect of pellets after sintering process during the combustion reaction.

7. RESULTS OF EXPERIMENTS PERFORMED IN COMBUSTION REACTOR

7.1 Combustion front analysis

The result of the experiment shown in Fig. 6, was conducted with air flow velocity of 0.55 m / sec, the pellet diameters varying between 10 mm - 13 mm, the charcoal ranging between 1.70 mm - 4.0 mm. The passage of the front of ignition is determined by historical temperatures. At a temperature of approximately 50°C, it is completely removed 3.5% of moisture of the pellets. The fuel temperature remains substantially constant at the point where temperature reaches a maximum value, approximately 1200°C, perhaps due a uniform distribution diameter pellets in this experiment. There was a consumption of approximately 76% of the total mass of fuel that has reacted within the bed. It is observed that near of the maximum temperature region an instability of the temperature. This instability can be attributed to the effect of accommodating of the fuel pellets as the charcoal is consumed. From the maximum temperature point where there was a accommodation of the fuel, the structure of the bed becomes more stable and the temperature evolution becomes smoother. After completion of the reaction the temperature decreases rapidly, showing that there is little heat generation after the forward reaction has been completed. The maximum temperature remains practically constant throughout the bed and decreases significantly only when the forward reaction consumes the whole fuel.

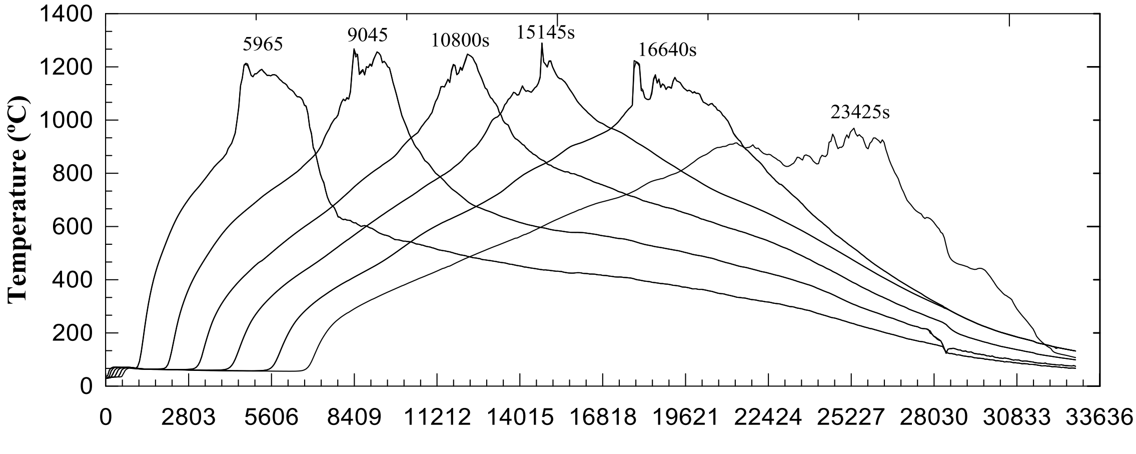


Figure 6 - Evolution of the combustion front for the experiment.

7.2 Fluid flows velocity analysis

The data present in Fig. 7, correspond to an initial air temperature of 27°C, charcoal crushed is used as fuel. The air flow velocity for experiments are shown in figure bellow. It is important notes that the velocity propagation are not constant throughout the reactor. The experiments 6 and 8 show similar velocity profiles, possibly for these experiments there was a similar uniform distribution of charcoal and pellets. It is also observed that the propagation velocity of the experiments 6, 8 and 9 increase in reactor outlet because the air is sucked from the bottom of the reactor through a exhaust. Exception is observed for the experiment 7, where the front propagation velocity reduces at the exit of the combustion reactor, possibly due obstruction of the bed by pellets that are too concentrated in the bottom of the reactor for this experiment.

Based on the above analysis, can be concluded that the uniform distribution of charcoal and the pellets inside the reactor is required for that the flow velocity of the reaction front advance smoothly without presenting many high peaks within the bed. Figure 7 shower either that the front propagation velocity decreases with increasing of air flow, this confirms the theory that the fuel system is dominated by the reaction of heat transfer to the fuel that enters and the oxidant.

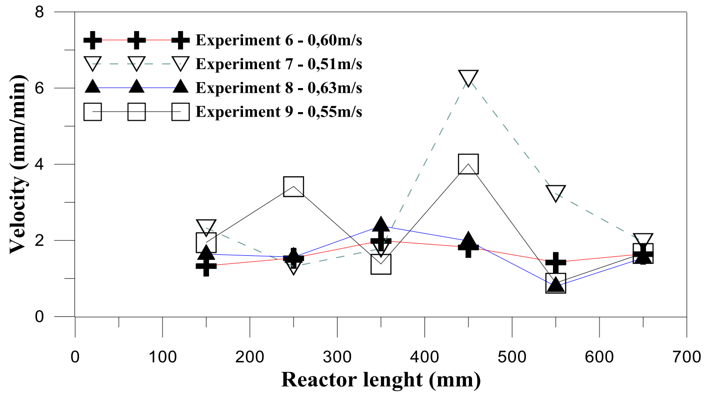


Figure 7- Propagation velocity across the combustion cell

7.3 Temperature profile analysis in reactor

To determine the axial temperature profile across the combustion reactor is first generated the graph temperatures verses time, Fig. 8. For a given thermocouple, keeping the time constant, as indicated by the arrows in bold, find the values of the temperatures to the other thermocouples. Through Excel resources, generates Tab. 3, where Z is the axial direction of the reactor measured in millimeters and temperatures are given in °C. With the results obtained, the axial temperature profile along the reactor is plotted and illustrated in Fig. 9.

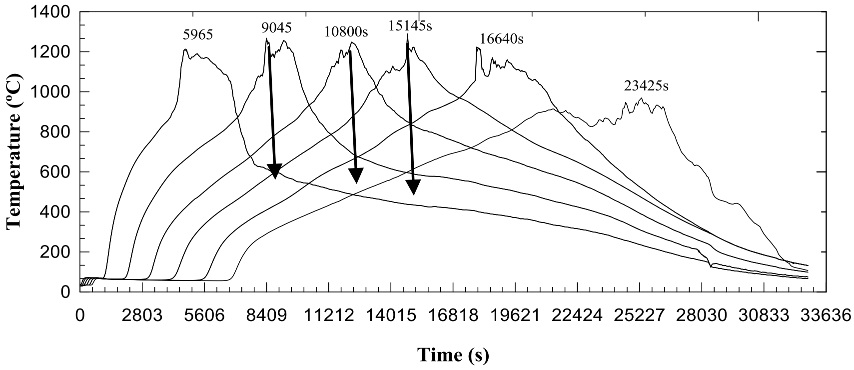


Figure 8 - Evolution of the axial temperature in the reactor

Table 3 - Data for generating the axial profile temperature across combustion reactor.

Z (mm)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)
50	495,2	412,1	330,9	308,6	282,4
150	1217,6	617,2	488	438,9	401
250	664	1283,5	698,2	597,5	543
350	425	754,8	1248,3	851,8	711
450	212,6	570,6	868	1296,2	920,3
550	58,5	293,4	659,1	831,2	1264,3
650	58,1	291,9	482,6	599,1	282,2

Figure 9 shows that the maximum temperatures of the reaction front in the place where the thermocouples are positioned, presents uniform values around 1200°C, which is a temperature sufficient to sinter the pellets. Figure 5 shows the material pellets after the end of combustion.

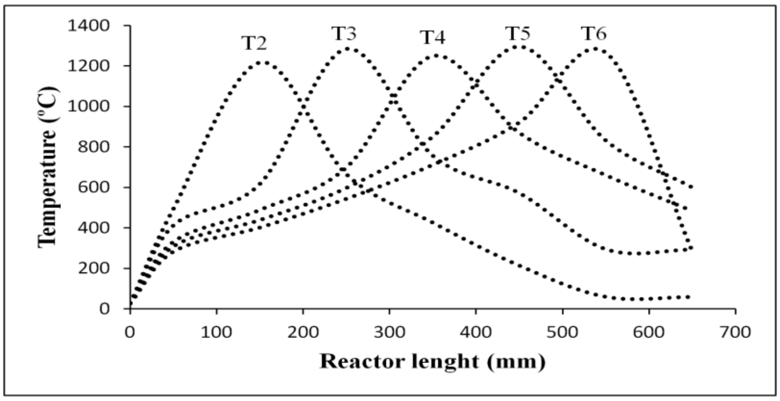


Figure 9 -Temperature profile across the reactor

8. CONCLUSION

During realization of the experiment for analysis of the combustion front, using porous solid fuel, charcoal, for sintering the pellets composed by fly ash, clay and charcoal, it can be seen that the fuel temperature remains almost constant at the point where temperature reaches a maximum value, approximately 1200 ° C, sufficient temperature for sintering the aggregates. Analysis of the fluid flow velocities it can be concluded that the uniform distribution of charcoal and the pellets inside the reactor is required for that the velocity of the reaction front progress smoothly without presenting many high peaks within the bed.

9. ACKNOWLEDGEMENTS

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Alvino Oliveira Melo
Emanuel Negrão Macêdo
Danielly Quaresma
José Antônio Da Silva Sousa
Alacid Neves