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EXPERIMENTAL INVESTIGATION ON MASS LOSS, IGNITION TIME AND FLAME BEHAVIOUR OF BIOMASS IN HTAC FURNACES

Ramona DINU[1], Adrian BADEA[2], Tiberiu APOSTOL[3], Cosmin MĂRCULESCU[4], Eduard MINCIUC[5], Radu KUNCSER[6]

Prezentul articol tratează câteva dintre problematicile cheie cu privire la procesul de combustie a biomasei (pelete de lemn) în instalații de tip HTAC (High Temperature Air Combustion). Comportamentul procesului de combustie a fost analizat în urma efectuării unei studiu experimental, în timpul căruia au fost variați anumiți parametri ai procesului. Pierderea de masă, timpul de aprindere şi comportamentul flăcării au fost investigate în cazul a două temperaturi ale aerului de combustie (800 şi 1000 °C). Influența asupra procesului a fractiei de oxigen în aerul de combustie a fost de asemenea analizată.

This paper outlines some of the key issues currently being debated regarding the combustion of biomass material (wood pellets) within the high temperature air combustion technologies (HTAC). An experimental study was performed in order to evaluate the combustion behavior when some process parameters were varied. The mass loss, the ignition time and the flame behavior were investigated for two temperature of the combustion air (800 and 1000 °C). The percentage of oxygen inside the combustion air and its influence on the process was also investigated

Keywords: biomass, combustion, high temperature air combustion, mass loss, ignition time, flame

1. Introduction

The combustion of solid fuels like biomass has a history stretching over many years. In the present environmental context, biomass represents an alternative to the fossil fuels as far it is a renewable energy source preserving the environment. It is providing about 10% of the world total primary energy supply

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[1] PhD. Eng., Department of Power Plants and Industry Power Engineering, Power Engineering Faculty, University POLITECHNICA of Bucharest, Romania, ramona.dinu@gmail.com
[2] Prof., Power Engineering Faculty, University POLITECHNICA of Bucharest, Romania
[3] Prof., Power Engineering Faculty, University POLITECHNICA of Bucharest, Romania
[4] Lecturer, Department of Power Plants and Industry Power Engineering, Power Engineering Faculty, University POLITECHNICA of Bucharest, Romania
[5] Lecturer, Department of Power Plants and Industry Power Engineering, Power Engineering Faculty, University POLITECHNICA of Bucharest, Romania
[6] PhD. Student, Department Energetique et Environement, Ecole des Mines de Nantes, Romania

[1]. There are various pathways to convert biomass into energy due to its versatile character. One of these conversion methods is combustion. If the growing-burning cycle is carefully controlled, the biomass combustion of does not produce more CO_2 than it absorbs during its growth [2]. Even if biomass combustion presents an advantageous CO_2 balance, the combustion techniques are still polluting and require constant improvements comparative to other conversion systems. One of the most promising technologies for biomass combustion is High Temperature Air Combustion (HTAC). The major advantages of this technology are already known. The HTAC furnaces provides for the following: significant energy savings (reduced fuel consumption), low environmental impact, NO_x emissions reduction, efficient and stable combustion, enhanced heat transfer and reduced combustion noise [3- 10].

In this work, the combustion of biomass (wood pellets) in a HTAC facility is studied. The mass loss, the ignition time and the flame behaviour are investigated for various combustion conditions (different temperatures of combustion air and different oxygen/nitrogen ratio within the combustion air).

2. Experimental frame

2.1. Sample material

In the experiment, woody biomass pellets were selected as the sample material in order to investigate the mass reduction and the ignition time during combustion process. The material is very homogenous and has the following ultimate analysis: 70.91%wt C, 3.73%wt H, 5.78%wt O, 1.40%wt N, 0.32%wt S and 0.01%wt Cl. The fuel has about 19.41%wt of volatile matter, 62.79%wt of fixed carbon, 11.10%wt of ash (550 °C), and 6.7%wt of moisture content at 105°C. The utilised pellets had lengths between 13mm to 15mm and the diameters between 8mm up to 9mm. The average pellet weight was about 5g. The feedstock material had a higher heating value of about 28.95MJ/kg and a lower heating value of about 27.99MJ/kg.

2.2. Experimental apparatus

The experimental campaign was carried out in a cylinder-type batch furnace of about 1000mm length with a horizontal combustion chamber having an inner diameter of about 100mm. This facility was developed at the Royal Institute of Technology (KTH), Stockholm, Sweden. Fig.1 illustrates the schematic representation of the facility.

The first step of the experimental procedure is heating up the combustion chamber. Hence, a flow of methane (1) and air (2) are feed up into the burner (5).

During combustion process of the methane, which takes place into the first part of the combustion chamber (6), the ceramic honeycomb (7) is heated up until the required temperature is reached. Then, the flue gases resulted are passed through the second part of the combustion chamber (8) and are evacuated through the facility outlet (16). When the desired temperature of the honeycomb was attained, the burner was shut down. The next process step starts with the admission of the oxygen (3) and nitrogen (4) flows into the combustion chamber. This gaseous mixture (oxygen and nitrogen) is heated up by passing through the already hot honeycomb and its purpose is to oxidize the biomass sample. At the same time, the biomass sample is inserted into the cooling chamber (9) through the special flange (11) where it is constantly cooled by a nitrogen flow (10) in order not to react with the oxygen existing in the combustion chamber.

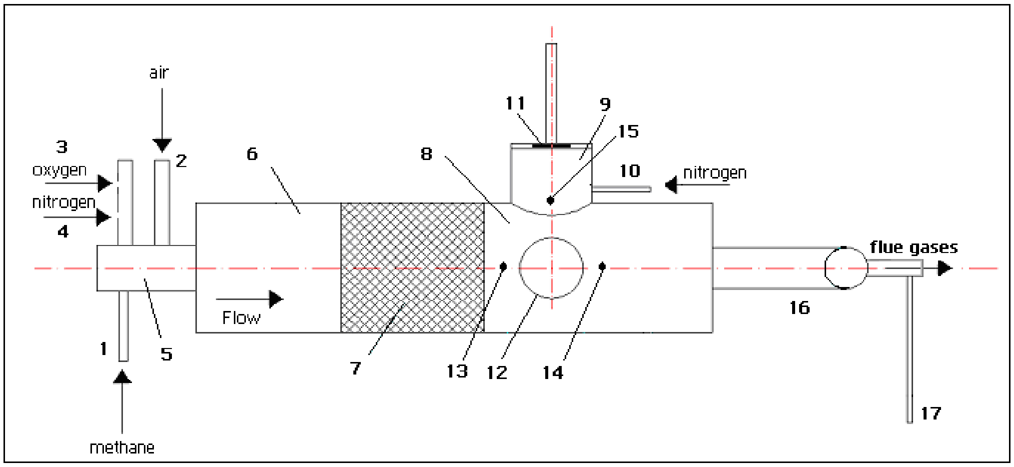


Fig. 1. HTAC facility scheme [4]

Legend:

1- methane inlet;
2- oxidation air inlet;
3- oxygen inlet;
4- nitrogen inlet;
5- burner;
6- 1rst part of the combustion chamber;
7- ceramic honeycomb;
8- 2nd part of the combustion chamber;
9- cooling chamber;
10- cooling nitrogen inlet;
11- pellet inlet flange;
12- glass window;
13- thermocouple (T_1);
14- thermocouple (T_2);
15- thermocouple (T_3);
16- facility outlet;
17- flue gas analysis probe.

The flows of oxygen and nitrogen were measured by three BRONKHORST flow meters. After a short time, when the conditions inside the combustion chamber are stable, the biomass sample is inserted into the reaction zone and kept for a specified duration. A glass window (12) was mounted on one side of the furnace in order to observe the combustion process. A digital camera was recording the experiments. During the experiments, the temperature of oxidizer, the temperature of the flue gases and the temperature of the pellet centre were measured by means of three thermocouples (13, 14, and 15) S-type. A sample from the evacuated flue gases is analyzed in order to predict the concentration of CO, CO2 and NO_x.

Before and after the experiment, the samples were weighted with an electronic balance. The time was counted with an electronic timer. The data acquisition system is a KEITHLEY Multimeter type 2700 and the software is EXCELINX. The flue gas analysers were calibrated using a gas calibrator to make sure the gas system was working in perfect condition.

3. Results and Discussions

The experiments were carried out for two different temperatures of the oxidizing agent (800ºC and 1000ºC) and under different concentrations of the oxygen in the oxidizer, which ranged between 5% and 100%. The combustion time was varied between 30 seconds until 5 minutes for each case. 50 experiments were carried out.

3.1 Mass loss

Figures 2 and 3 illustrate the mass reduction behavior of the feedstock material, for different oxygen concentrations in oxidizing agent at different temperatures (800°C and 1000°C). As it can be observed from the curves trends, the oxygen concentration and oxidant temperature play an important role in the combustion process. For a better understanding, Kuo [11] divided the mass loss phenomenon into three stages: the period prior to ignition (from 100% to about 90% mass loss) corresponding to the drying phase, the flaming combustion stage (between 90% to about 20%) corresponding to the volatiles combustion phase and the char combustion stage (between 20% and 0% mass loss). In the first stage, moisture and some gases from the decomposed biomass are lost. In the second stage, the volatiles substances are released and burnt. Char is consumed during the third mass loss stage. The remaining material is ash.

Making a comparison between the two graphs it can be observed that for higher temperatures (1000°C), the mass reduction is more rapid for the drying and volatile oxidation phases, compared to the lower temperature (800°C) due to the higher heat transfer rate. It is clear that the mass reduction it is almost no influenced by oxygen concentration for the 5% and 10% cases but it is dependent on it when oxygen concentration increases over 21%. For lower temperature (800°C), the devolatilization and volatiles oxidation process becomes more rapid when concentration of oxygen increases (see Fig.3). As expected, the drying and devolatilization time is faster for high oxygen concentrations (over 70%). Also, the char combustion process is similar for both temperatures of oxidant. For oxygen concentrations of 70% and 100% and combustion time ranged between 3 to 5 minutes, the whole sample was consumed. The remaining material was only ash. For medium and low oxygen concentrations (under 70%), the sample was incomplete combusted and the remaining material was char and ash.

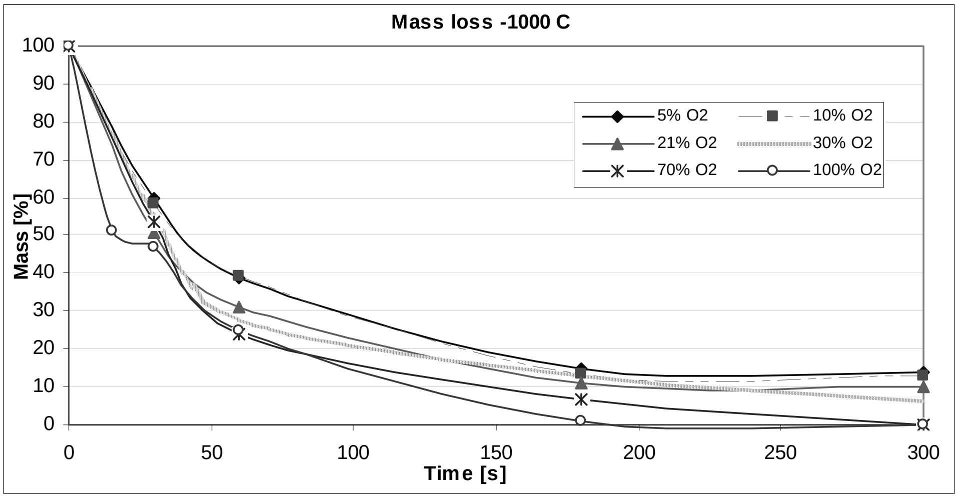


Fig. 2. Mass loss curves for different O_2 concentrations at 1000 °C

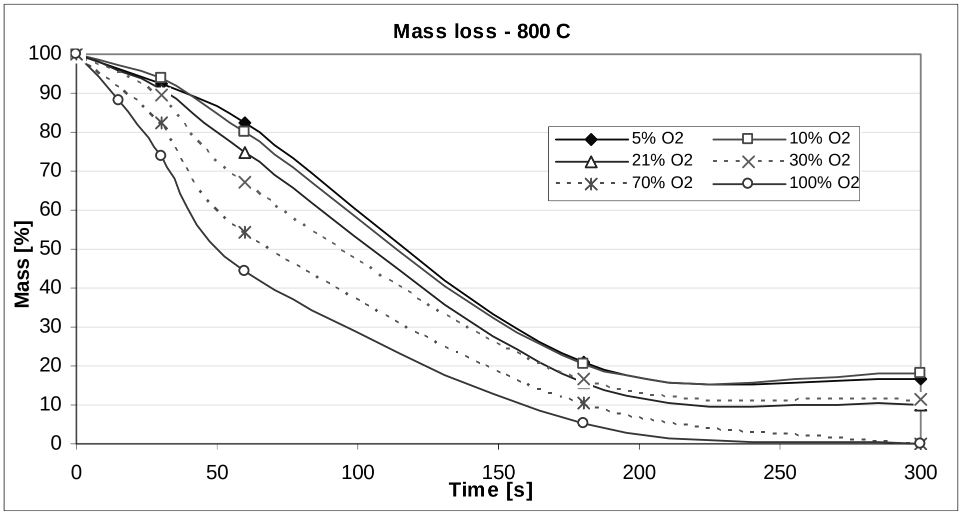


Fig.3: Mass loss curves for different O_2 concentrations at 800 °C

3.2. Ignition time and flame behaviour

Ignition of wood is the start of visual and sustained combustion (smoldering, glow, or flame) fueled by wood pyrolysis [12].

Figures 4 and 5 show the pellet's ignition time at different temperatures and oxygen concentration for five minutes time of the experiment respectively three minutes time. The ignition time was considered the time passed until the very first visible flame was observed with the naked eye during the experiment, into the combustion chamber. The ignition time was determined based on the recorded experiments. As the two figures demonstrates, the ignition time is highly dependent on the combustion parameters: the oxidant temperature and oxygen concentration. The ignition is faster when both the oxidant temperature and oxygen concentration are higher.

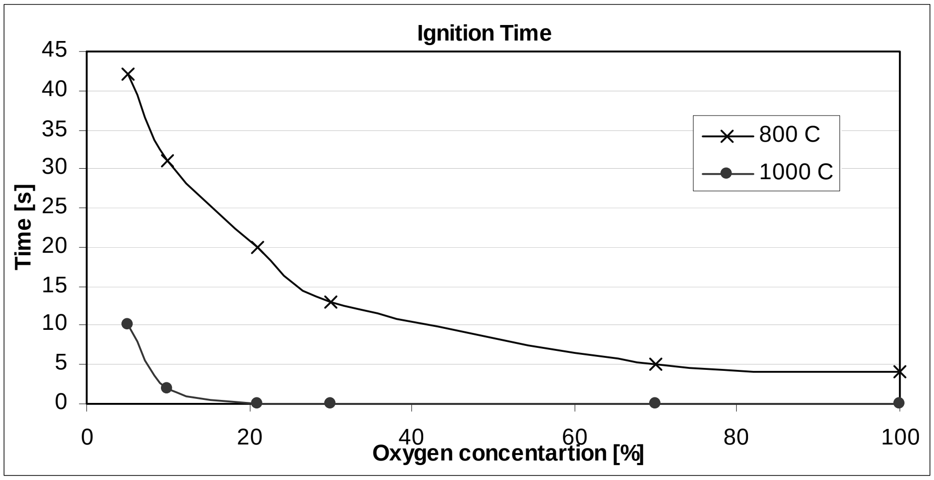


Fig. 4. Ignition time for different concentrations of O_2 and oxidant temperature (5 min)

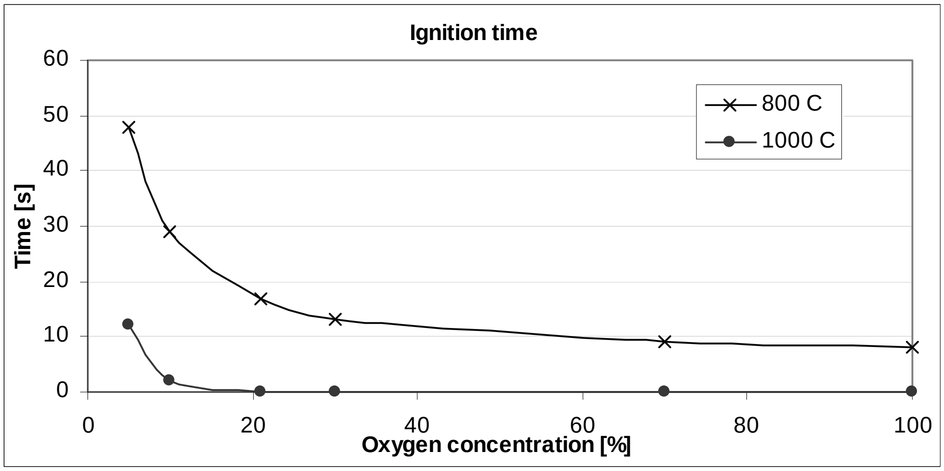
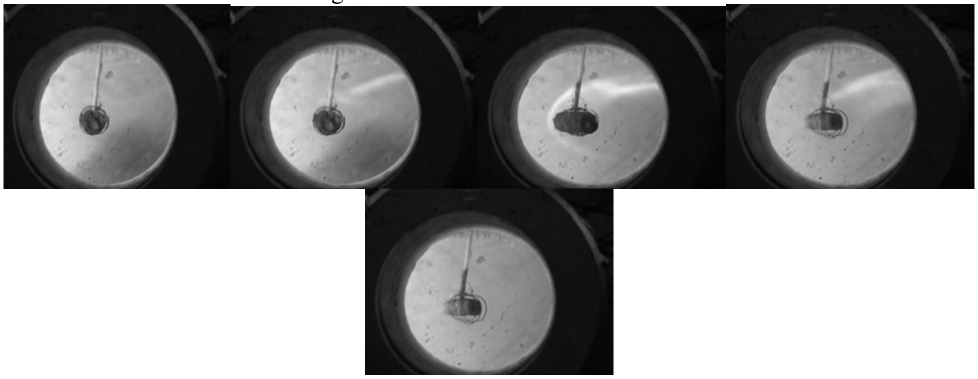


Fig. 5. Ignition time for different concentrations of O_2 and oxidant temperature (3 min*)*

The next paragraph describes the combustion behavior for different amounts of oxygen inside combustion air.

- ***Oxidant at 1000ºC and 5% oxygen concentration***

The ignition occurred after 10 –15 seconds from the start (see Fig.6). A weak yellow flame was observed at the far end of the window at one of the pellet extremity. The flame increased progressively in length and it became little whiter. At about 85 - 114 seconds, the sample seemed to be entirely covered by the flame. The flame was brighter in the upper part of the sample and hardly visible at the bottom. After another 15 - 20 seconds, the flame disappeared leaving the sample with a black color (char and ash).


5s 10s - ignition 100s 110s

125s – char

Fig. 6. Wood pellet combustion for the case 1000 ºC and 5% O_2

- ***Oxidant at 1000ºC and 10% oxygen concentration***

The ignition occurred after about 2 seconds from the beginning. A small yellow flame appeared at one of the pellet's extremity. The flame increased rapidly, it became whiter and brighter in time, and covered the entire sample. After about 100 seconds, the flame started to decrease and after another 30 - 50 seconds, it disappeared. The remaining material was char and ash and it was oxidized without glowing.

- ***Oxidant at 1000ºC and 21% oxygen concentration***

In this case, the ignition of the sample was instantaneous and it started with a little bright yellow flame at one of the sample's extremity. The flame was developing quickly, thus the whole sample was covered (after 6 seconds from the ignition). During the flaming phase, small glowing particles were falling down from the biomass sample. At about 115-130 second from the ignition, the flame disappeared. The remaining char was still oxidized with red – yellow glowing color.

- ***Oxidant at 1000ºC and 30% oxygen concentration***

The ignition occurred instantaneously with a small bright yellow flame located at one of the sample's margins. In less than 6 seconds, the pellet was entirely covered by the bright flame. The phenomenon was similar with to the 21 % oxygen case. After about 85 seconds from the start, the flame disappeared leaving the "incandescent" char.

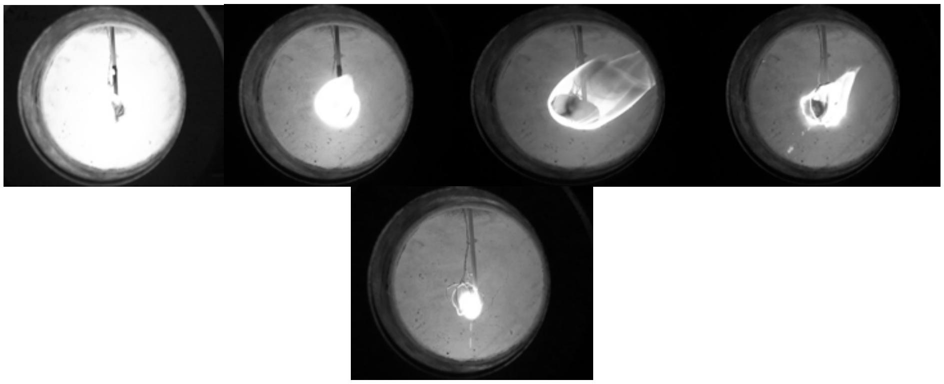
- ***Oxidant at 1000ºC and 70% oxygen concentration***

After the sample was introduced, the flame appeared instantaneously and in about 2-3 seconds, it covered the entire pellet. The flame was brighter and whiter that in other cases and was more compact around the sample. This fact was due to higher concentration of oxygen. Little glowing pieces fell down from the sample into the combustion chamber. During the flaming phase, it was visible how sample glows. At about 65 second from the start, the flame totally disappeared, leaving the glowing char with a white – orange color. For a five-minute experiment, the sample was entirely consumed. The remaining material was only ash.

- ***Oxidant at 1000ºC and 100% oxygen concentration***

When pure oxygen was used, the ignition of the sample was instantaneous an explosive (see Fig.7). The white flame was very violent extremely bright and enclosed the entire sample in less than 2 seconds. After another 2 - 4 seconds, the flame became higher. A black soot was observed while volatiles were burning. The flame started to decay at about 30 seconds and disappeared after about 50 seconds from ignition. During both phases of volatiles and char oxidation, little glowing particles fell down from the sample. For the five minutes experiment, the sample was entirely consumed. Ash was the remaining material.

0s - ignition 2s 7s 70s

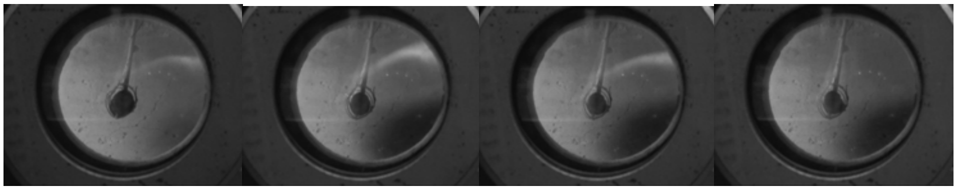


170s - char

Fig. 7: Wood pellet combustion for the case 1000 ºC and 100% O_2

- ***Oxidant at 800ºC and 5% oxygen concentration***

The ignition occurred after 42 – 50 seconds from the start (see Fig.8). A very weak flame was hardly observed in the far end of the window at one of the pellet extremity. The flame increased progressively in length and it became more visible and little yellow in the upper part of the sample. It was very difficult to distinguish if the flame covered the entire sample. After another 160-165 seconds, the flame disappeared, leaving the sample of black color (char and ash). For the case of 30 seconds time, no flame was observed during the experiment.



42s- ignition 100s 145s 160s

Fig. 8: Wood pellet combustion for the case 800 ºC and 5% O_2

- ***Oxidant at 800ºC and 10% oxygen concentration***

For 800ºC and 10% oxygen concentration, after the sample was introduced, at about 10 –11 seconds, the sample started to become black at the margins. The ignition occurred after 30 - 32 seconds from the start with a very weak flame, which was barely visible in the upper part of the sample. The flame increased progressively in time, becoming longer and yellow. It is difficult to say when the sample was covered by the flame. After 130-140 seconds from the start, the flame disappeared. The remaining material was char and ash and it was oxidized without glowing. For the case of 30 seconds time, no flame was observed during the experiment.

- ***Oxidant at 800ºC and 21% oxygen concentration***

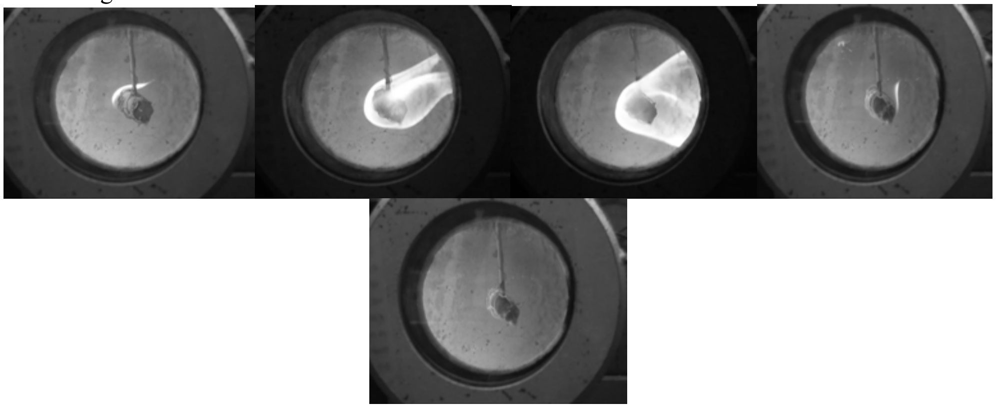
At about 15 – 20 second from the starting point, the sample became brown at the surface. After another maximum 5 seconds, the ignition occurred with a small white – yellow flame at one of the pellet's extremities (see Fig.9). The flame increased rapidly in time, becoming brighter and covering the entire sample (after 35 seconds from the ignition). A black soot was observed while volatiles were still burning. At about 120-130 second from the ignition, the flame disappeared. The remaining char was oxidized with red – yellow glowing color on the side where the sample meets the airflow.

- ***Oxidant at 800ºC and 30% oxygen concentration***

The ignition occurred at about 13 - 15 seconds from the start with a small bright yellow flame located at one of the sample's margins. The flame was bright and increased rapidly around then sample. It could be observed that the sample started to glow during the flaming phase. The flame started to decay and disappeared after 120 –130 seconds from ignition leaving "incandescent" char.

- ***Oxidant at 800ºC and 70% oxygen concentration***

For this case, after the sample was introduced, the flame appeared in less than 10 seconds at one of the pellet's margins and rapidly covered the entire sample. The flame was brighter and whiter that in other cases and was more compact around the sample. This fact was due to the higher concentration of oxygen. Little glowing pieces fell down from the sample into the combustion chamber. During the flaming phase, it was visible how the sample glows. At about 110-120 second from the start, the flame totally disappeared living the glowing char with a white – orange color. For the five minutes experiment, the sample was entirely consumed. The remaining material was only ash.



20s - ignition
35s
90s
130s
135s -char

Fig. 9: Wood pellet combustion for the case 800 ºC and 21% O_2

- ***Oxidant at 800ºC and 100% oxygen concentration***

When 100% oxygen was used, the sample ignition occurred in less than 7 seconds in an explosive mode. The white flame was very violent extremely bright, enclosed very rapidly the entire sample. The maximum size of the flame was reached after about 90 second from the start, then the flame started to decay and disappeared after another 30 - 40 seconds. During both phases of volatiles and char oxidation, little glowing particles fell down from the sample. For a five-minute experiment, the sample was entirely consumed. Ash was the remaining material.

4. Conclusions

This work has been focused on biomass combustion using HTAC technology. It has been shown that high temperature air combustion offers an attractive option for the treatment and energy utilization of solid biomass. The experiments led to the following conclusions:

- The pellet mass reduction highly depends on oxidant temperature. Mass loss rate increases with temperature. Mass loss variation strongly depends on temperature for drying and devolatilization stage. Oxidant's temperature seems to have lower influence on char oxidation phase;
- For lower oxidant temperature 800ºC, the oxygen concentration has more influence over the mass loss than for the temperature of 1000ºC;
- The ignition time is strongly influenced by the oxidant temperature and oxygen concentrations. For oxygen ratio increase with 70% the ignition delay decrease with approximately 77% from 42 seconds to 5 seconds;
- No delay time to flaming ignition was observed when the oxidant air was preheated until 1000ºC and the oxygen concentration increases over 21%. On the contrary, the time to flaming ignition increases when lower oxygen concentration (5% and 10%) and lower oxidant temperature (800ºC) are used;
- The flame color, shape and size depend on combustion parameters.

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