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ENCIT-2018-XXXX (XXXX IS THE MANUSCRIPT NUMBER, TIMES NEW ROMAN, CENTERED, BOLD, SIZE 14) THE ACOUSTIC ENHANCEMENT ANALYSES IN THE COMBUSTION PARAMETERS OF THE EUCALYPTUS FIREWOOD

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Abstract.

This work aims to analyze the influence of acoustic enhancement in the combustion process of eucalyptus firewood. The influence of acoustic was evaluated by the addition of sound waves in the primary air supply pipe of the boiler. The comparative study considers both combustion processes: with and without acoustic enhancement. In this way, the study of the addition of waves to reduce pollutants such as CO, NOx and soot appears. A comparative analysis of the temperature profiles and gas composition levels at specific points of the combustion chamber and the chimney, considering combustion with and without acoustic enhancement, was carried out. From the analysis of the results it was observed that the acoustic enhancement has a direct influence on the biomass combustion, increasing the heat transfer rate of the fuel to the working fluid and reducing the amount of pollutants , as NOx and intermediate products of incomplete reaction. Through the results it was observed that the maximum temperature of the combustion products increased 13.72% with the acoustic enhancement. In addition, the heating rate with acoustic enhancement presented a 4 times higher rate compared to the same process in the absence of the acoustic process.

Keywords: *Sound pressure level, Pulsating combustion, Biomass combustion, Acoustic field*

1. INTRODUCTION

The combustion can be defined as a chemical exothermic reaction, between to substances called fuel and an oxidizing agent like the air. These reactions occur at high speed and temperature, with intense liberation of light and heat. The biomass used in an oxi-reduction reaction can be obtained from different renewable resources, like plants, wood, agricultural residues, excrement and even waste. The biomass is every organic material from vegetable or animal source, used in energy production. In relation to the direct biomass combustion, the wood and the charcoal has a predominant space inside the Brazilian energy matrix.

The utilization of biomass is justified mainly because it is a renewable resource, and when its use is controlled and planned it produces low environmental impacts, besides being available even in distant places. Additionally, the carbonic gas emissions product of its direct combustion are practically equal to the amount of carbonic gas absorbed by the plant during its life , consequently there is no net increase in the greenhouse effect in the atmosphere related to its burning.

Researches in the acoustic enhancement area showed that acoustic pulsation tend to increase the momentum transfer, mass and heat. Furthermore, the maximum power equipment grows, because, the increase of the heat rate released per kilogram fuel. Consequently, there is an expressive maximization in the combustion efficiency and reduction in the CO, NOx and soot particles emissions.

According work (Zinn, 1992; Alfie *et al*., 2014) using acoustic enhancement it is possible to reduce the design and constructive changes in the furnaces. However, a problem usually encountered it the noise production, but that can be mitigated with acoustic insulation installation.

Raun *et al*. (1993), in their research about pulsating combustion, shown that the resonance occurs between oscillations at the source or between some external forced element like a speaker system. In addition, Raun *et al*. (1993) classified the work into groups according to the method employed to force acoustic oscillation, whether for heat transmission, conduction or combustion. Within the latter, the variable that stimulates the enhancement may be a natural pulsating supply (elastic wave), a variable turbulence or even variations in the surface or velocity of the flame.

Although the most of the work (Patiño, 2009) was done in flames generated by gaseous fuels in turbines, the pulsating combustion can also be used for solid fuels. The main advantages observed are the increase of the process efficiency and the reduction of contaminant concentration.

Another important research (Zinn *et al*., 1982) this area is a comparative study of non-pulverized coal combustion with and without resonance. With this study, the authors observed an improvement in the air-fuel mixing and an increase in the combustion intensity, mainly for an air excess near stoichiometric. Beyond these advantages, it is worth highlighting the contaminant emissions reduction of carbon monoxide CO (partial combustion) and unburned particles.

Carvalho *et al*. (1987) verified near 20% increase in the combustion efficiency for the pulsating combustion and a reduction around 58% of particles emissions. In this paper it is possible to identify other benefits from pulsating combustion with high heat transfer rate as the elevated combustion intensity, contaminant emission reduction and the possibility to work with lower air excess, near the stoichiometric, reducing the lost heat by combustion products in the chimney exit gases.

According to Rocha *et al*. (2008) the acoustic field changes the flame structure considerably. As the oscillation increase the amplitude wave as showed at Fig. (1). The flame with acoustic intensification becomes blue, showing drastic changes in a flame predominantly diffusive. This flame has a flame pre-mix characteristics. Besides the visual analyses, the alterations in the flame structure by the acoustic field presence can be observed by radial and axial oxygen, carbon dioxide, carbon monoxide, NO_x compounds concentrations distributions and temperature profile (not shown in this figure).

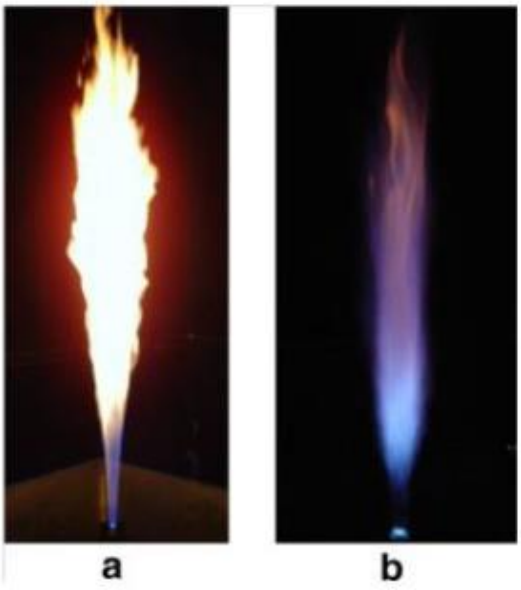

Figure 1: a) Flame without the acoustic field presence; b) Presence of the acoustic intensification (ROCHA *et al*., 2008).

In a study conducted by Yu *et al.* (1991) on the Intensification of Combustion of a Pre-mixed Flame by Acoustic Forces with Emphases in the Role of Structural Vortices of Large Scale is seen how the formation of vortices influences the combustion of propane. In the development of this research it was noticed that the acoustic forces produces a significant increase in the combustion rate by the generation of large-scale periodic vortices. These vortical structures accelerate the drag and improve the mixing between the reactants and the recirculating hot gases as shown in Figure 2. The research carried out by the author also reveals that the combustion performance is closely related to the dynamics of the flow, the perfomance of the chamber can be optimized by controlling the dynamics of vortices in the reaction zone. Thus, by combining passive and active control techniques in the upstream and downstream injection of vortices in the flame zone it is possible to significantly increase the combustion efficiency while slightly lowering the pressure fluctuation levels. To measure the rate of heat release the author uses chemiluminescence spectroscopy by measuring C2 radicals appearing in the reaction zones.

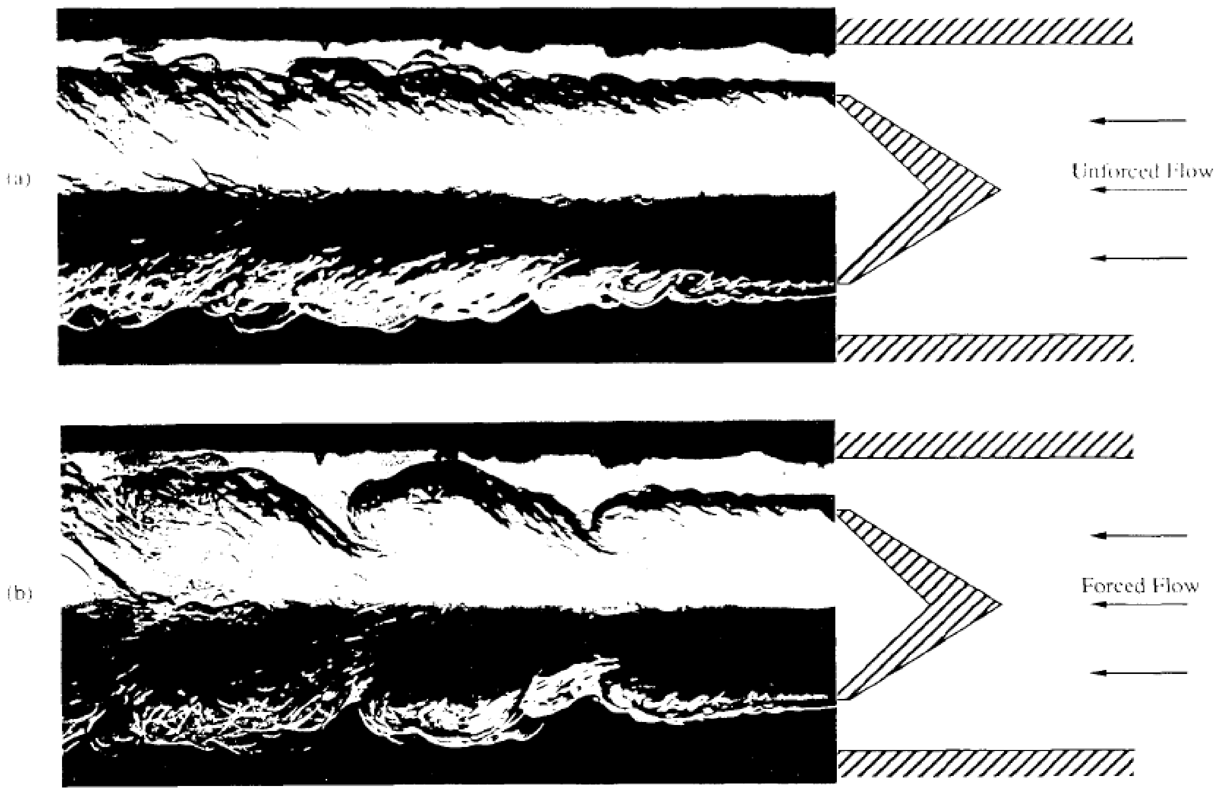

Figure 2: Visitation of sparks in the reaction bed. a) Absence of acoustic forces; b) Presence of acoustic forces (frequency of 1210 Hz) (YU *et al.*, 1991).

The main parameters that influence the increase in energy release are amplitude and frequency of the acoustic waves, equivalence ratio and average flow velocity. For the frequency regime studied by the author, the intensity of combustion increases linearly with the disturbance level. Since the strong vortices increase the amount of entrained reactants the intensification of combustion is proportional to the strength of the vortices, while the combustion process is limited by the rate of mixing of the fuel and the oxidizer. However, as the equivalence rate (fuel-rich mixture) increases, the chemical reaction time decreases and thus, the reaction zone is enlarged, it approaches the flame fronts and thus the increase of the mixture associated with the reagents entrained by the vortices can be significant. For low quivalency ratios (close to the flame blanking limit) the acoustic forces have extremely small effects on the combustion rate because the chemical reaction time is not enough to consume the increase of reagents dragged by the vortices. Based on the data analysis performed by the author, it can be seen that the optimization of combustion occurs when the acoustic frequency coincides with the preferential mode of the hydrodynamic field in the region near the "near wake region" (Yu *et al.*, 1991).

According to Yu *et al.* (1991a) in his work on Modeling the Intensification of Combustion of Coal Slurry Fuels Using High Intensity Acoustic Fields, studies the increase of Nusselt and Sherwood numbers in the presence of high intensity acoustic fields compared to those in the absence of sound. Thus, increasing the combustion intensity and consequently reducing fuel consumption time brings a number of advantages to the process, such as increasing the installed capacity of small combustion chambers and also reducing grinding costs since larger size particles can be the same chamber without reducing installed power. Most of the work developed in the field of acoustic intensification focuses on the study of the global effects of the oscillation of the flow of reagents on the heat and mass transfer rates, however the work developed by Yavuzkurt *et al.* (1991a) theoretically studies the fundamental aspects of this problem in order to understand the governing mechanisms, although it is extremely complex because it involves the interaction of the acoustic field with the fluid, nonlinear effects such as the formation of shockwaves, standing waves and the absorption of acoustic energy by the gas and solid particles . Thus the particles are exposed to a sound pressure level ranging from 160 to 170 dB at the approximate frequency of 2000 Hz. As a conclusion the author notes an increase in Nusselt and Sherwood numbers of 31, 48 and 62.5% in the levels of sound pressure of 160, 165 and 170 dB, respectively.

In the work developed by Borisov *et al.* (1971) entitled Effects of Acoustic Vibrations on a Gas Flame in a Confined Space, we investigate the effects of the acoustic field on a turbulent flame formed in a combustion chamber by the analysis of the concentration of gases, temperature, acoustic field and characteristics of the turbulence in the chamber. In order to measure the intensity of the turbulence in the flame, a method proposed by Ebrahimi (1967) was used based on the measurement of the noise level with an acoustic transducer powered by a 2-stage transistor amplifier. It was thus realized that the main reason for increasing the turbulence intensity in the presence of acoustic vibrations was the increased hydrodynamic instability of the fuel mixture flowing into the chamber. In addition, the sound effect could create additional swirls in the main stream and consequently increase the intensity of the turbulence. Another possible reason for increasing the value of turbulence intensity in the presence of acoustic vibrations would be the dispersion of sound velocity in the flame, leading to the appearance of additional turbulence fluctuations resulting from a tangential discontinuity of the temperature gradient, shock wave. In this way the intensification of the mixing process is due to the increase of gas and air instability in the combustion chamber.

In a very similar work developed by Yavuzkurt *et al.* (1991b) in the Modeling of the Intensification of the Combustion of the Coal using High Intensity Acoustic Fields it is studied how the high intensity acoustic field induces an oscillating speed on the pulverized coal particles, resulting in an increase in the rate of heat and mass transfer. Thus, using a computer program (PCGC-2), several aspects of the pulverized coal combustion can be predicted, including increasing the rate of heat transfer and mass expressed in the Nusselt and Sherwood coefficients, in due order. Thus, the author notes an increase of the Nusselt and Sherwood coefficients of approximately 45, 60 and 82.5% for the sound pressure levels of 160, 165 and 170 dB respectively at a frequency of approximately 2000 Hz. In addition, it can be seen from the work produced that the main performance of the acoustic field is in the phase of burning the carbon, so it is expected that the acoustic field applications will result in chambers in more than 20% smaller than the conventional ones for the same capacity.

2. METHODOLOGY

The experimental tests for this work were performed in NEST / IEM / UNIFEI laboratories in a fixed bed water and fire tube hybrid boiler (Fig. 3). The biomass (eucalyptus wood) physical and chemical characterization, including the elementary and immediate composition, was presented in the work of Oliveira (2014).

This work is divided in three stages:

Step 1: Boiler tests under predetermined standard conditions and permanent regime without acoustic enhancement (control tests);

Step 2: Acoustic enhancement tests on the primary air supply in steady state and standard conditions similar to step 1.

The experimental installation consists of an acoustic system, air compressor, water cooled probe, combustion chamber and their connections as shown in Figure 3. The acoustic system consists of a loudspeaker with an amplified speaker of 400 W and a frequency generator, whose response varies from 21 to 200 Hz.

In the initial stages, temperature profile data were acquired in the combustion chamber, the chimney and the steam outlet. The combustion gas composition was acquired in the combustion chamber and in chimney.

In this way, from 3 temperature probes installed in key points of the boiler, a temperature profile is elaborated which is monitored temporarily from periodic data points. Thus, the process of combustion of the biomass that goes through the drying, heating and devolatization process of the biomass that makes up the first stage called the heating zone is also followed. Followed by the stable firing zone where the greatest heat release occurs and in a lasting form that is from the firing of the fixed carbon. Finally, the burn out zone, which considers the combustion of residual carbon or coke.

The tests were built considering a frequency inside the frequency range answers to the speaker of the Acoustic System. Besides, another consideration was taken into account like the length duct connection. The length duct connection for constructive interference as defined in the open tube theory has to be multiple of the wavelength. The wavelength is related with the air sound velocity and the frequency produced by the frequency generator.

The speaker (acoustic system) was attached to the boiler, besides; a water cooled probe to capture combustion gas samples on bed level of the combustion chamber was developed to guarantee the acquisition of the necessary data for the research, as shown in Fig. 3:

Figure 3. Complete boiler assembly.

Therefore, using a 50Hz frequency with the air sound velocity at 20 [^{o}C] it is possible calculate the wavelength. This work frequency was selected as a medium set point for the frequency generator.

For simplicity reason in the structure duct calculation the duct length was taken equal to a half wavelength, for a harmonics number equal to 1, λ =2 L, half wavelength is equal to length duct to a open tube theory and for harmonic number *n* equal to 1.

The acoustic pressure on the Acoustic System (AS)

The Sound Intensity Level (SIL) can be defined as the rate of energy that flows in some determinate direction, through some area, and can be calculated by Eq. (1). The flow power reference is constant and its value is express in Eq. (2):

$$SIL = 10.\log\left(\frac{I_f}{I_{ref}}\right)\left[\frac{W}{m^2}\right] \tag{1}$$

$$I_{ref} = 10^{-12}\left[\frac{W}{m^2}\right] \tag{2}$$

Where:
SIL = Sound Intensity Level [W/m^2];
I_f = Real sound power flow [W/m^2];
I_{ref} = Reference sound power flow [W/m^2];

The Sound Power Level (PWL) is the rate that sounds energy flows in determinate direction through some area. Considering that the AS has 400 [W] real sound power, it is possible to calculate the PWL according Eq. (3). The reference sound power can be verified in the Eq (4):

$$PWL = 10.\log\left(\frac{W_r}{W_{ref}}\right)[dB] = 146.99dB \quad (3)$$

$$W_{ref} = 10^{-12}[W] \quad (4)$$

Where:
PWL = Sound Power Level [dB];
W_r = Real sound power [W];
W_{ref} = Reference sound power [W];

The Sound Pressure Level is the sound wave amplitude measure and can be calculated by Eq. (5). The reference pressure [Pa] is shows in Eq. (6).

$$SPL = 20.\log\left(\frac{P_r}{P_{ref}}\right)[dB] \quad (5)$$

$$P_{ref} = 20.10^{-6}[Pa] \quad (6)$$

Where:
SPL = Sound Pressure Level [dB];
P_r = Real sound pressure [Pa];
P_{ref} = Reference sound pressure [Pa];

For singular sound sources, the PWL can be considered equal to SPL, and the real pressure of sound wave in its maximum value is calculated by Eq. (7):

$$SPL = 20.\log\left(\frac{P_r}{P_{ref}}\right)[dB] = 146.99dB \Rightarrow \mathrm{Pr} = 10^{\frac{146{,}99}{20}}.\mathrm{Pr}ef = 447.21[Pa] \quad (7)$$

Duct Calculation

The primary air supply should be done by a duct which length must be a multiple of wavelength (λ) for maximum amplitude transmission. The best representation of the displacement of the sound pressure produced in the acoustic system is synodical wave. Therefore, the wave length is the distance between two consecutive wave peaks or valleys.

The wavelength can be calculated by the air sound velocity, which is 344 [m/s] a 20 [^{o}C] and the frequency produced by the acoustic system, as defined in the Eq. (8):

$$\lambda = \frac{c}{fr}[m] \quad (8)$$

Where:
λ = Wavelength [m];
c = Air sound velocity [m/s];
fr = frequency [Hz];

The duct connection was calculated using 50 Hz frequency on the frequency generator. For this frequency the wavelength is 6.88 [m] and using a multiple number as explained by the sound theory of open tube, the duct connection should have 3.44 [m] length.

It is important to emphasize the importance of knowing these data, even if it is not for comparative and experimental in this work, because, for future studies, these data are necessary to further detail the acoustic enhancement mechanism in the mixture of air and fuel. In addition, it is important to know how much of the electrical power that arrives on the speaker is actually converted to sound pressure, the latter being responsible by the acoustical process in the combustion.

3. PRELIMINARY RESULTS

The Figure 4 shows a longitudinal of section the combustion chamber of the hybrid boiler used in the experiments with the positioning of the thermocouples T1 and T2 serving in the region of the combustion chamber and of T8 serving in the combustion bed region. These thermocouples were selected because they are located in susceptible zones. These zones can detect small temperature variations by the biomass combustion process.

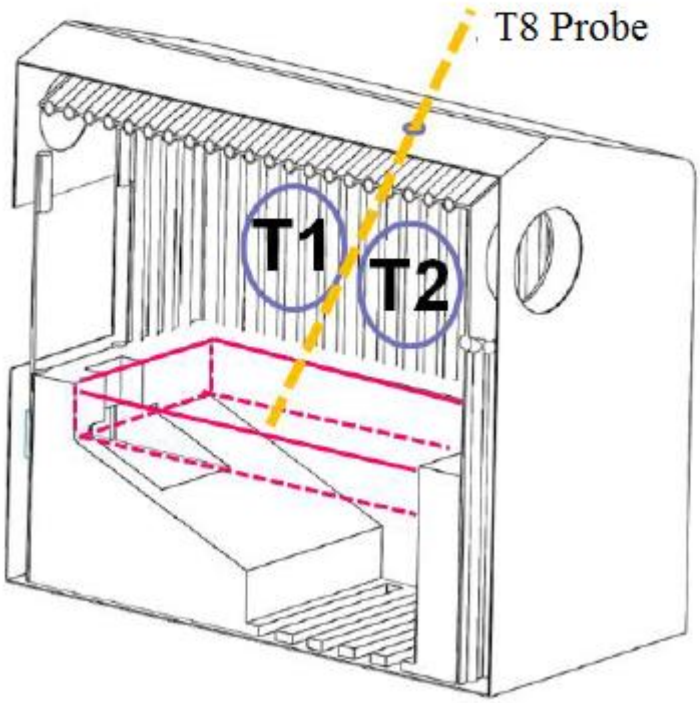

Figure 4. Thermocouples diagram T1, T2 and T8 in the combustion chamber.

With the intention to study precisely the behavior and answers to the biomass supply in relation to the combustion, it was taken a period of time. With the test is possible to perceive the combustion zones formation which have his behavior analyzed.

Figure 5 shows the responses of the T1, T2 and T8 Thermocouples from the moment the furnace was fed and the acoustic system was activated. In this way, from the Figure 4 it is possible to perceive the formation of zones of combustion whose behaviors were analyzed. The zones of combustion are divided in three: zone of heating, zone of stable burning and zone burn out. These zones or phases correspond to the consumption of the biomass throughout the combustion process.

Initially the heating zone, where occurs the drying, heating and biomass devolatilization. The second stage includes a stable combustion zone where occurs the fixed carbon biomass combustion. Finally the third zone comprises a burn out zone, where there is the end of gave energy contained in biomass. Besides, in heating zone it is possible to observe a T2 decrease while T1 and T8 increase in an inversely way. This behavior can be explained considering that when the combustion chamber is open, during the biomass feeding time, the airflow increase and consequently the volatiles are rapidly consumed, increasing T1 and T8. However, due to the cold air entrance airflow T2 tends to reduce.

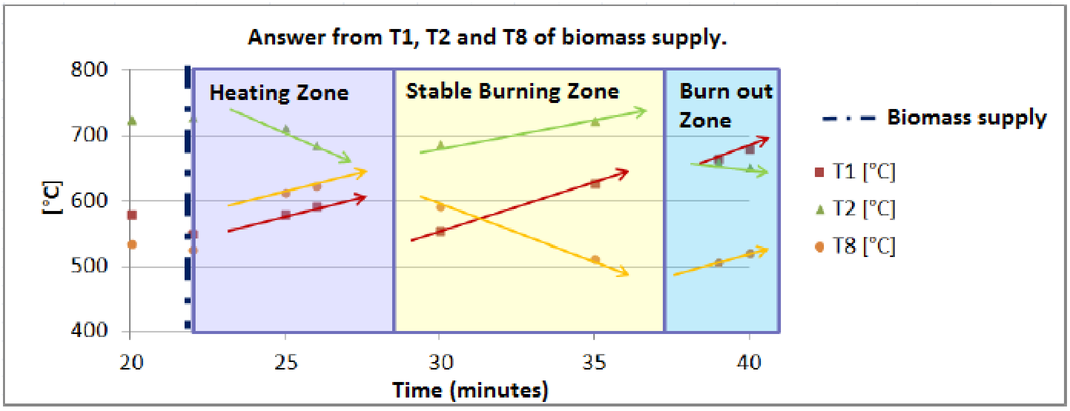

Figure 5. Combustion Zones for the biomass supply

In the stable burning zone, T1 and T2 increases due to the reactive gases flow from fixed carbon combustion. T8 however, decrease because of volatile flames extinction performed on the heating zone. Ultimately, in burn out zone T1 and T8 tend to increase due the gases combustion flow on the other hand T2 starts to decrease by the end of the energy contained in biomass.

During the acoustic intensification test it is possible to analyze the acoustic waves influence in the combustion process considering the temperature variation profile.

In this test, the main parameters considered are:

- Biomass supply mass flow: 0.0023 kg/s eucalyptus firewood;
- Acoustic System (AS) power: 400 W;
- Frequency generator: 50 Hz;

The Figure 6 shows the temperature behavior with and without the acoustic intensification:

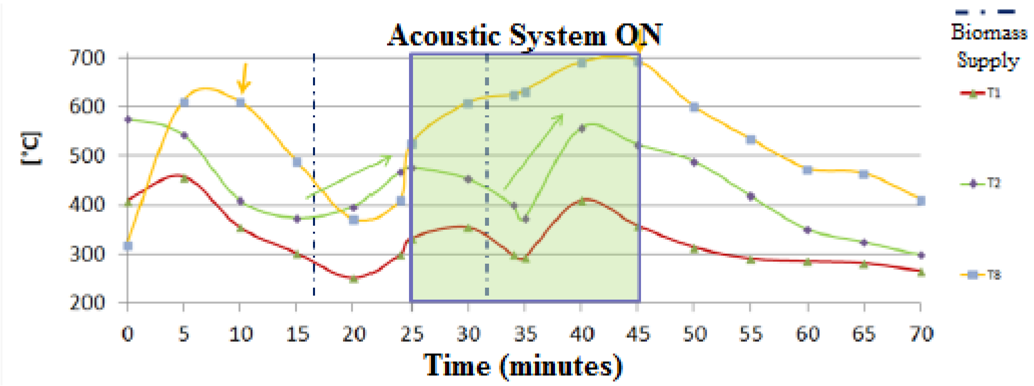

Figure 6. T1, T2 and T8 Evolution with Acoustic Intensification Test

The dotted lines represent the biomass supply moments, which occurs proximately in 17 and 33 minutes, and lasts 20 seconds. The green rectangle shows the period with the Acoustic System (AS) operating. Analyzing Figure 6 it is possible to perceive that a peak in temperature T8 occurs during the acoustic system operation. In the first T8 peak t, without acoustic intensification, the temperatures reached 612^{o}C, and during the AS operation this temperature achieved 696 ^{o}C, representing an increment of of 13.72%.

Besides the T2 temperature shows a heating rate without acoustic enhancement of 10^{o}C/min((480^{o}C-380^{o}C)/10min), while in the acoustic enhancement period this rate was proximately 36^{o}C/min ((560^{o}C-380^{o}C)/5min), almost 4 times higher, as shown by the green arrow on Figure 5.

However, many problems are associated with the pre-mix reactants like the ignition in the pre-mix chamber, instability combustion, etc. With the acoustic enhancement, it is possible to produce low temperature flames with pre-mix flame characteristics but without the problems caused by the pre-mix reactants. Besides there is a better temperature distribution and a reduction of the temperature peaks in the flame region.

The results obtained, when compared to the conventional combustion, takes low fuel consume, higher heat transfer rate, increase in the boiler and furnace efficiency.

4. CONCLUSIONS

The peak temperature value T8 on the acoustic intensification process with the Acoustic System (SA) of 400W and operating at 50Hz was increased by 13.72% in relation to its peak value without acoustic intensification. Since the temperature according to Figure 5 reaches 696°C with and without acoustic intensification, this value drops to approximately 612°C.

The rate of heating of temperature T2 during pulsed combustion with SA of 400W operating at 50 Hz was increased by almost 4 times, from 10°C/min without acoustic intensification to 36°C/min with the acoustic system in operation. These increases in temperature occur due to the increase in the heating rate, since the acoustic intensification facilitates the contact of the oxygen with the biomass and with this accelerates the combustion mechanism, giving it pre-mixed flame characteristics as explained above of work.

Therefor the acoustic enhancement has a stronger influence on the combustion process in a combustion chamber with fixed bed. This advantage is not only to improve the air-fuel mix rate, but mainly with the gas products from the biomass devolatilization. It is evident that the acoustic enhancement has stronger influence in an air-volatile mix, taking as evidence the temperature profile in Figure 6.

The difficulty to control the air excess was a problem because affect the combustion patterns from biomass and reduce the maximum temperature achieved, because, the gas product with high air excess consume energy and increase the lost heat for the chimney.

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6. RESPONSIBILITY NOTICE

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