

Estimation of Flame Temperature and Alkali Emission During the Combustion of Sugarcane Bagasse in Laboratory in Combustion Chamber Type Grate Using Spectroscopy Method

Carlos T Salinas^{a*}, Paulo Roberto Tazinazo Cândido^b, Chun Lou^c, Daniel
Marcelo-Aldana^d

^{a,b}Posgraduate Program of Mechanical Engineering, Santa Cecilia University, Rua Cesário Mota 08, Sala F-34, Santos (SP) CEP 11.045-040, Brazil

^aUniversity of Piura, Av. Ramón Mugica 131, Urb. San Eduardo, Piura, Perú

^cSchool of China-EU Institute of Clean and Renewable Energy, Huazhong University of Science and Technology, Wuhan 430074, Hubei, People's Republic of China

^dUniversity of Piura, Av. Ramón Mugica 131, Urb. San Eduardo, Piura, Perú

^aEmail: csalinas_99@yahoo.com

^bEmail: paulocandido@sabesp.com.br

^cEmail: clou@hust.edu.cn

^dEmail: daniel.marcelo@udep.edu.pe

Abstract

Knowing the temperature of the combustion of solid biomass residues and how alkaline gases must be supplied during combustion is an area currently under study in the international community. The correlation between temperature and concentration of alkaline gases in the combustion phases is an open research for some types of biomass, among which sugarcane bagasse. This information optimizes the operation of thermoelectric boilers that use solid biomass waste as fuel, improving its efficiency and maintenance costs. The aim of the study was to estimate the temperature of the flame during the combustion of sugarcane bagasse in a pilot chamber that simulates burning in a grid, as well as an estimate of the potassium concentration in the flue gases. Temperature estimates were made using the two-color spectrometry technique in the visible light range.

* Corresponding author.

The potassium concentrations in the flue gases were estimated through analysis of the emission lines present in the electromagnetic spectra collected by a spectrometer for different combustion temperatures. In the experiments, the biomass flame was of the diffusion flame type. Considered the combustion phases - devolatilization, char combustion and ash formation - temperature were varying in the range of 1000 K to 1700 K. The average emission of potassium in the flue gases was evaluated in the range of 0.126 ppm to 0.631 ppm, considering the combustion phases. For the combustion conditions, no alkaline sodium gases were detected.

Keywords: Potassium; Biomass; Combustion; Sugarcane; Spectroscopy.

1. Introduction

The use of renewable energy sources has gained importance in recent years, contributing to meet the growing demands for energy (on average 3.0% per year, globally) and to reduce the environmental impacts generated by the use of fossil fuels. The production of energy in Brazil is mainly by hydroelectric plants, with 7.93% of its energy matrix constituted by other renewable sources, including biomasses from agriculture and cities [1]. The production of electric energy through the combustion of biomass in boilers, including sugarcane bagasse and straw, has been encouraged through new legislation in Brazil [2]. Profits from sales of energy generated by burning sugarcane residues contribute to the financial stability of mills in periods of fluctuation in sugar and alcohol prices [2]. Burning biomass reduces costs for final disposal of waste produced by agriculture and cities [1,2], in addition to reducing the emission of methane and CO_2 due to the decomposition of biomass in landfills and increasing the useful life of landfills [3]. In Europe and Asia, different types of biomass are used for heat generation, being known the harmful effects of alkali metals, especially potassium, for the operation and maintenance of facilities, as it produces corrosion and the appearance of scale and slag at lower temperatures [4]. The sugarcane bagasse, the focus of this paper, is rich in potassium, released in the form of gas during combustion in the boilers, generating corrosion at high temperatures and producing deposits in the heat exchangers that reducing their efficiency. Knowing the concentrations of alkali metal gases released during the combustion of solid biomass residues is an area under study that concerns the international community. The study of the correlation between temperature and concentration of alkaline gases during the combustion phases (devolatilization, char combustion and ash formation) is an open research for some types of biomass, among which are sugarcane residues generated in sugar and alcohol production. This information allows to optimize the operation of thermoelectric boilers that use solid waste as fuel, improving their efficiency and reducing maintenance costs [5,6]. Scientific community has been studied the use of chemical additives that are insufflated to the flue gases from solid biomass residues to convert volatile inorganic elements, such as potassium and chlorine, into compounds less aggressive to installations. Thus, the determination of the concentration of alkaline gases in the combustion of solid biomass residues is decisive for the dimensioning of the volumes of additives used to mitigate the problems caused by them to the boilers [5,6]. Pre-treatment of biomass for removal of alkali metals (leaching) and burning combined with coal are also used to minimize the corrosive effects of alkali metals [7]. Among the alkali metals, potassium is the most present in biomass such as sugarcane bagasse, as it is an important element for the development of the plant and increased sugar content, generating greater productivity in the production of refined sugar and alcohol. Helps to reduce pests and fungi and is essential for plant transport mechanisms. Potassium is intensively supplied to the plant by natural and chemical

fertilizers, including vinasse, KCl and K_2O [6,8,9]. Soluble salts like KCl are found in bagasse and other parts of sugarcane [10]. Sugarcane bagasse on a dry basis has 12.5% carbon (fixed); 69.9% of volatile materials and 17.6% of other materials [11]. Quantitative analyzes on the release of potassium and other metals in biomass combustion have been carried out using different methods based on the use of laser spectroscopy or spectroscopic X-ray analyzes of the ashes. The Flame Emission Spectroscopy (FES) method is added to them, which allows estimating temperatures and concentrations of chemical elements released in combustion from measurements of the electromagnetic spectrum of the flame made by a spectrometer. Using the spectrometer, measurements are made of the intensities of electromagnetic radiation produced by the flame for the wavelengths in the range of visible and near infrared light and in particular for the characteristic wavelengths of chemical elements and compounds, where the presence of emission or absorption lines characterize their presence and concentrations. Potassium has emission lines at wavelengths 766.490nm and 769.896nm. The temperature is estimated based on Planck's law for black bodies applied to the two-color method. The potassium concentration is estimated by comparing the intensities of the emission lines obtained at the temperature of the experiment with intensities obtained in the calibration process using known concentrations of potassium salts and at controlled temperatures [4]. For studies in industrial furnaces, flame emission spectroscopy (FES) is a simple and less expensive method, as it does not depend on devices such as lasers. The development of control loops for boilers using FES as a temperature gauge has become feasible. The potassium and chlorine released in the combustion of sugarcane residues, originating in a large part of KCl , generate corrosion in the pipes and heat exchangers, as they react with their protective layers based on iron oxide chromium [11]. Studies on the emission of alkali metals in the combustion of municipal solid waste in industrial incinerators, where not only potassium, but also sodium is present, were carried out using flame emission spectroscopy (FES). The study indicated that temperature and radiation intensity measurements from the alkali metal emission lines using FES can be used in logic to control the air blower and the solid waste feeder [12, 13]. The objective of this work was to estimate the temperature and potassium concentration in the combustion of sugarcane bagasse using the flame emission spectroscopy (FES) method. The experiments were carried out in a grid-type pilot combustion chamber set up in the thermal processes and combustion diagnosis laboratory at Santa Cecilia University.

2. Materials and Methods

2.1. Methods

The work was developed in two stages. In step 1, the pattern of combustion temperatures for sugarcane bagasse was preliminarily estimated, in order to guide the procedures in step 2 in which potassium concentrations were obtained. The temperatures were estimated using the radiation intensities of the electromagnetic spectra collected during combustion and the two-color method over the entire spectrum in the visible and near infrared light range made available by the laboratory spectrometer, selecting pairs of 30 nm distant wavelengths [11, 14]. The "Chauvenet Criterion" was used to discard atypical temperature estimates, avoiding distortion of the mean and standard deviation [15]. The potassium concentrations were obtained by correlating the radiation intensities of the emission lines characteristic of the potassium present in the electromagnetic spectra collected in the experiments, with the intensities obtained in a calibration process performed using different concentrations of potassium and known temperatures [4,5].

2.2. Sugarcane bagasse samples

The samples of sugarcane bagasse used in this work were provided by a sugar and alcohol plant located in the city of Pirassununga, state of São Paulo, Brazil. The samples come from mechanized harvesting and have approximately 53% humidity according to the plant's daily operational reports. The samples are ground bagasse with irregularly sized pieces.

2.3. Experimental Combustion Chamber

The experiments to collect the electromagnetic spectra of the sugarcane bagasse combustion were carried out in the experimental combustion chamber shown in figure 1. Figure 2 shows a schematic drawing of the chamber: on the left, side view of the stainless-steel tubes with the holes for inserting the spectrometer probe and indicating the position of the grid and, on the right, top view of the grid.



Figure 1: Experimental combustion chamber

The combustion chamber was constructed using 100 mm diameter stainless steel tubes with a flame produced by a Meker burner and Liquefied Petroleum Gas (LPG). The bottom tube has a length of 120 mm and a grid at the top to retain biomass. Longitudinal holes in the upper tube with a diameter of 10mm and distance between centers of 15 mm allow the insertion of the probe containing the spectrometer lens to collect spectral data. Additional tube with the same characteristics as the upper tube can be attached to it by expanding the height of the chamber.

In the experiments carried out, between 3 g and 5 g of sugarcane bagasse biomass, without any type of packaging, were inserted through the top of the preheated combustion chamber until the point where the grid had a weak red color, which, in heat treatment, corresponds to an approximate temperature of 800 K [16]. After inserting the biomass in the combustion chamber, the flame from the Meker burner was extinguished in order not to influence the results of the experiments and not consume the oxygen in the air necessary for the

combustion of the biomass. After approximately 15 s, a period in which the remaining moisture was vaporized, the biomass started to burn and the thermal irradiation spectra were collected by the spectrometer.

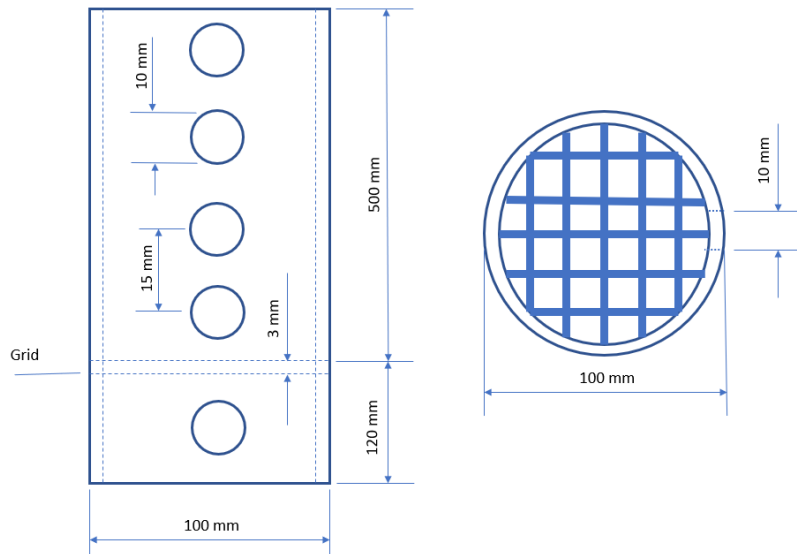


Figure 2: Schematic drawing of the experimental Combustion chamber

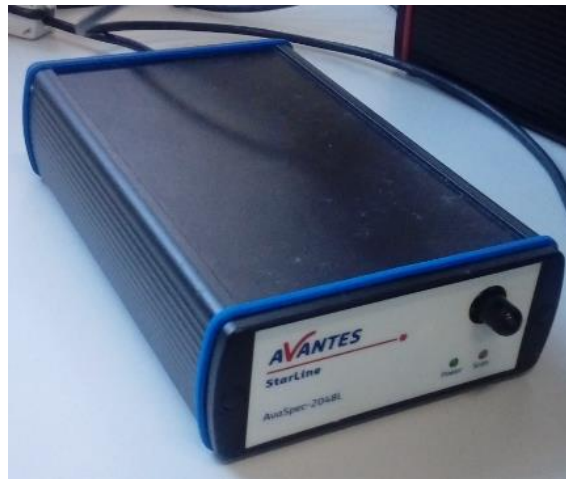


Figure 3: Spectrometer

2.4. Instrumentation

Figure 3 shows the spectrometer used to collect the electromagnetic spectra produced by the combustion of sugarcane bagasse. The spectrometer has a probe with a collimating lens that aligns the light beams from the flame for conduction by optical fiber to the body of the spectrometer, where the luminous intensity (photon count), represented internally by electrical quantities resulting from photovoltaic conversion, needs to be converted for power units. The spectrometer breaks down the light into wavelengths in the order of nanometers, making available for each wavelength the photon count and their respective values in energy units, producing electromagnetic spectra in the range of light visible to the human eye, from near infrared and a portion of the

ultraviolet band.

2.5. Temperature estimation using the electromagnetic spectrum

Every body with a temperature above absolute zero emits thermal radiation. Thermal radiation energy is transmitted by electromagnetic waves at different wavelengths (or frequencies) and, therefore, does not depend on physical contact between bodies to occur. The rate of energy emitted by radiation by a body (E - emissive power) is related to its temperature by the equation (1) [17].

$$E = \varepsilon\sigma T^4 \quad (1)$$

Where ε is the emissivity of the body that depends on its physical characteristics; σ is the Stefan-Boltzmann constant and T the body temperature in K [17]. It is therefore possible to estimate the temperature of a body by measuring the radiation emitted by it, even from a distance, as long as we know the emissivity of the body and can treat the radiation reflected by it from other sources. Spectrometers are used to measure the emissive power, collecting the electromagnetic waves coming from the body. They provide the emissive power per wavelength of the electromagnetic spectrum, called the spectral emissive power. Electromagnetic waves are of various lengths (or frequencies), the electromagnetic spectrum encompasses all of these wavelengths. For example, the range of visible light corresponds to the wavelength range from 400 to 760 nm. Planck's law for black bodies, idealized bodies that, for any temperature, emit maximum of radiation at each wavelength of the spectrum in a diffuse way (regardless of direction) and that absorb all incident radiation, can be adapted with inclusion of emissivity (ε) to relate the spectral emissive power to the temperature of real bodies as (2) [17].

$$E(\lambda, T) = \varepsilon \frac{2\pi hc^2}{\lambda^5 (e^{\frac{C_2}{\lambda T}} - 1)} \quad (W/m^2nm) \quad (2)$$

Where λ is the wavelength for which the spectral emissive power is being determined (E), T is the body temperature, h Planck's constant, c is the speed of light and C_2 is hc/k where k is the Boltzmann constant [16].

For wavelengths between 400nm to 1000nm and temperatures between 800K to 2200K, conditions in which the experiments in this work were carried out, the term $e^{\frac{C_2}{\lambda T}}$ in (2) is much higher than 1, making it possible to simplify (2) to (3), which corresponds to the equation of Wien's radiation law [18].

$$E(\lambda, T) = \varepsilon \frac{2\pi hc^2}{\lambda^5 (e^{\frac{C_2}{\lambda T}})} \quad (W/m^2nm) \quad (3)$$

The temperature equation for the two-color method is obtained by selecting two wavelengths, λ_i and λ_j , of a spectrum collected by the spectrometer with the body at temperature T . Dividing $E(\lambda_i, T)/E(\lambda_j, T)$ on both sides of (3) and isolating the T we get the temperature equation of the two-color method (4). As the spectrometer provides the emissive power for different wavelengths (spectral), it is possible to estimate the temperature several times by varying the wavelength pairs [18].

$$T = \frac{c_2 \left(\frac{1}{\lambda_j} - \frac{1}{\lambda_i} \right)}{\left(\ln \left(\frac{E(\lambda_i, T)}{E(\lambda_j, T)} \right) + \ln \left(\frac{\varepsilon_j}{\varepsilon_i} \right) + 5 \ln \left(\frac{\lambda_i}{\lambda_j} \right) \right)} \quad (4)$$

where

T is the estimated temperature.

c_2 is $\frac{hc}{k}$ (h Plank's constant; k is the Boltzmann constant; c the speed of light), corresponding to $1,43878 \times 10^{-2} \text{ m K}$.

λ_i and λ_j are the wavelengths.

$E(\lambda_i, T)$ and $E(\lambda_j, T)$ the spectral emissive powers at the wavelengths λ_i and λ_j in $(W \cdot m^{-2} \cdot nm^{-1})$.

ε_i and ε_j are emissivities at wavelengths λ_i and λ_j .

Soot particles in the flame have a gray body property, a body in which the rate of change in emissivity as a function of variation in wavelengths approaches zero. For nearby λ_i e λ_j (less than 128nm), one can simplify (4) assuming that $\frac{\varepsilon_i}{\varepsilon_j} \cong 1$, which allows us to estimate temperatures using (5) [17]. In step 1 of the work, we used the 30nm distance between wavelengths and (5).

$$T_{i,j} = \frac{c_2 \left(\frac{1}{\lambda_j} - \frac{1}{\lambda_i} \right)}{\left(\ln \left(\frac{I_i}{I_j} \right) + 5 \ln \left(\frac{\lambda_i}{\lambda_j} \right) \right)} \quad (5)$$

2.6. Estimation of concentration of chemical elements by spectroscopy method

When atoms receive photons from a source, their electrons can change their energy level, if the energy of the photon corresponds to the quantized energy of the element. Each chemical element has specific amounts of energy that generate a change in level, smaller or larger amounts do not generate such a transition. Since the energy of a photon corresponds to the Planck constant (h) multiplied by its frequency, according to the work of Planck [18], each element has characteristic frequencies for which photons are absorbed by atoms. Upon absorbing the photon, the atom transitions from the fundamental state to the excited state. The atom's tendency is always to return to the fundamental state and, when this return transition occurs, the absorbed energy is released at the same characteristic frequency of the element, not necessarily in the same direction, generating emission or absorption lines in the electromagnetic spectrum. The presence of emission or absorption lines in the electromagnetic spectrum at frequency (or at wavelengths) characteristics of the chemical elements show their presence in the gases passed through the photons. In addition to the presence of the element in the gas, it is possible to estimate its concentration through the radiation intensity of the emission or absorption lines, being necessary to know the relationship between the excited free atoms and those that remain in the fundamental state, established by the Boltzmann distribution (6) [19].

$$\frac{N^*}{N^0} = C e^{-\frac{E}{kT}} \quad (6)$$

Where N^* is the amount of excited atoms; N^0 is the amount of atoms in the ground state; C is a system constant; E is the excitation energy of the atom; k is the Boltzmann constant e T the temperature.

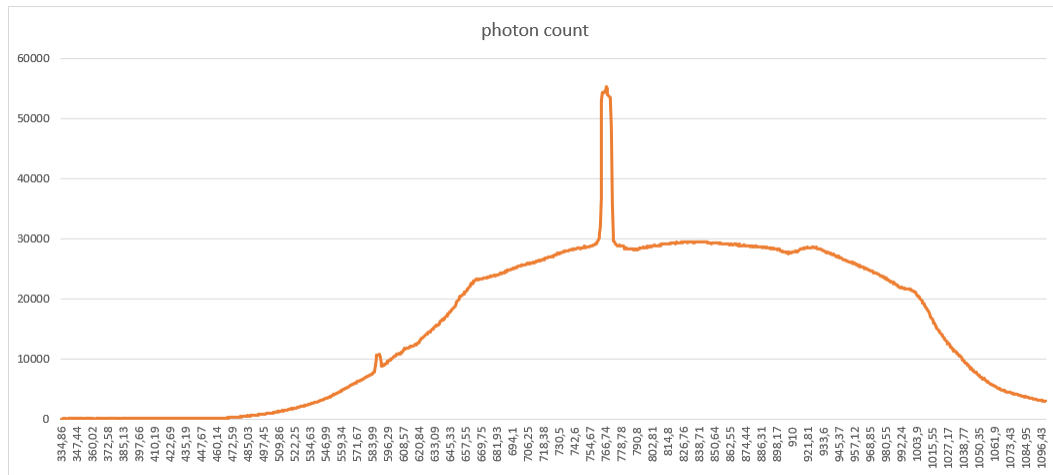


Figure 4: Electromagnetic spectrum of sugarcane bagasse in photon count

Figure 4 shows a spectrum in photon counting unit collected in this work during the combustion of sugarcane bagasse. The peak irradiation intensity corresponding to the emission lines at the characteristic wavelengths of potassium at 766.490nm and 769.896nm, according to the spectrum database of the American institute NIST (National Institute of Standards and Technology).

2.7. Conversion of photon count to energy unit

To estimate the temperature using the two-color method, it is necessary to have the electromagnetic spectrum in units of energy. For conversion of photon count to energy unit it is necessary to calibrate the spectrometer as described in [19], a process carried out in an oven where blackbody characteristics are present, allowing to correlate the electrical quantities of the spectrometer with the thermal intensities radiated by the blackbody established by Planck's law. For the spectrometer used, such calibration was performed on *Huazhong University of Science and Technology* - HUST, China, the results being made available through software provided with the spectrometer. Temperatures in the range of 1,000K to 2,500K are used with variations from 1K up or down [4,5].

Figure 5 shows the spectrum in figure 4 converted to an energy unit.

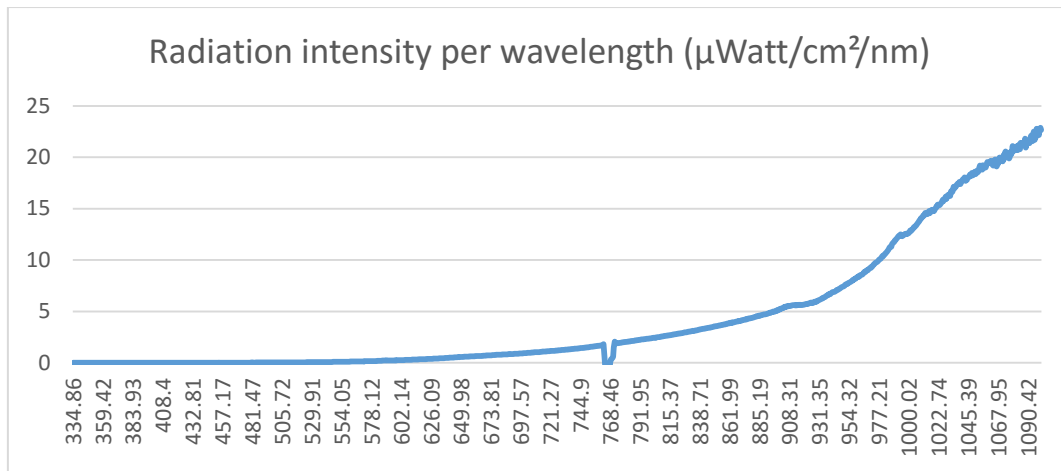


Figure 5: Electromagnetic spectrum of sugarcane bagasse in energy unit

2.8. Calibration for estimation of potassium concentration

To estimate the potassium concentrations in the combustion gases, another calibration is required as described in [4,5]. Through a nebulizer, known concentrations of potassium-based saline solution (for example, potassium chloride - KCl) are sprayed, under controlled and known operating conditions, in a flame of known and controlled temperature. Using the spectrometer, measurements of irradiation intensities are made in energy units of the emission lines characteristic of potassium. The result of this calibration is the function f that best approximates the expression $I = f(C, T)$, considering all measurements performed in the calibration, where C is the concentration of potassium gas in the flame, calculated based on the concentration of the solution and the operating conditions (flow rates, pressure and ambient temperature), T is the estimated temperature of the flame and I is the irradiation intensity measured by the spectrometer. After this calibration, when obtaining a flame spectrum from any experiment, the temperature is estimated using the two-color method, in the spectrum the intensity of irradiation is obtained for the characteristic wavelength of potassium (or other element chemical that you want to study) and, using the function obtained in the calibration, one get the potassium concentration. Such calibration was performed by [5], the results being made available through software developed in accordance with the patent [5]. The function f calibration method used by [5] to estimate the potassium concentration described in the previous paragraph is the polynomial function presented in (7).

$$I = \sum_0^m \sum_0^n a_{mn} C^m T^n \quad (7)$$

I , C and T are the same quantities described previously. The coefficients a_{mn} are obtained using the least squares method applied to the data obtained in the calibration. The peaks of irradiation intensity at the characteristic wavelengths of potassium, measured by the spectrometer, are necessary to determine the calibration coefficients a_{mn} . In the calibration process, saline solutions with different potassium contents are used, keeping the temperature constant by maintaining the mass flow rates of fuel and oxidizer. The temperature is estimated using the two-color method from the electromagnetic spectra captured by the spectrometer. Full

calibration procedure can be seen in [5]. The relationship between the potassium concentration in the solution in ppm (C_s) and the vaporized concentration in the flame (C_{vc}) is presented by the equation (8) [5].

$$C_{vc} = \frac{f_m C_s v_s}{M} \frac{R \cdot T_r}{P(v_{O_2} + v_{N_2} + v_{C_2H_4})} \quad (8)$$

where:

C_{vc} is the concentration of potassium vaporized in the flame (ppm);

f_m is the molar fraction of potassium in the solute (%);

C_s is the concentration of the solute (ppm);

v_s is the mass flow rate of the solution ($\frac{g}{s}$);

M is the molar mass of potassium ($\frac{g}{mol}$);

R is the ideal gas constant ($\frac{atm \cdot L}{mol \cdot K}$);

T_r is room temperature (K);

P is the pressure (atm);

$v_{O_2}, v_{N_2}, v_{C_2H_4}$ are the volumetric flow rates of oxygen, nitrogen and ethylene gases ($\frac{L}{s}$).

3. Results

3.1. Preliminary temperature estimation

The results of step 1 of the work are presented in figures 6, 7 and table 1. They refer to the preliminary estimation of the flame temperature in the operational conditions of the tests, used in step 2 to establish the temperature ranges for which the concentrations of potassium were distributed. Experiments from step 2 of this work with estimated temperatures inconsistent in relation to the values obtained in step 1 were removed from the analysis, considering that they were due to noise and operational failures. Figure 6 shows the three electromagnetic spectra related to the combustion of sugarcane bagasse used in step 1, collected and selected visually when the flame had the highest intensity. On the horizontal axis, there are wavelengths in nanometers (nm). In the vertical axis, there are the irradiation intensities in $\frac{\mu W}{cm^2 \cdot nm}$. The greater the slopes of the curves, the higher the corresponding temperature, considering that, under Planck's law, shorter wavelengths are more energetic; which indicates that the temperature of experiment 3 is lower and that of experiment 1 is higher.

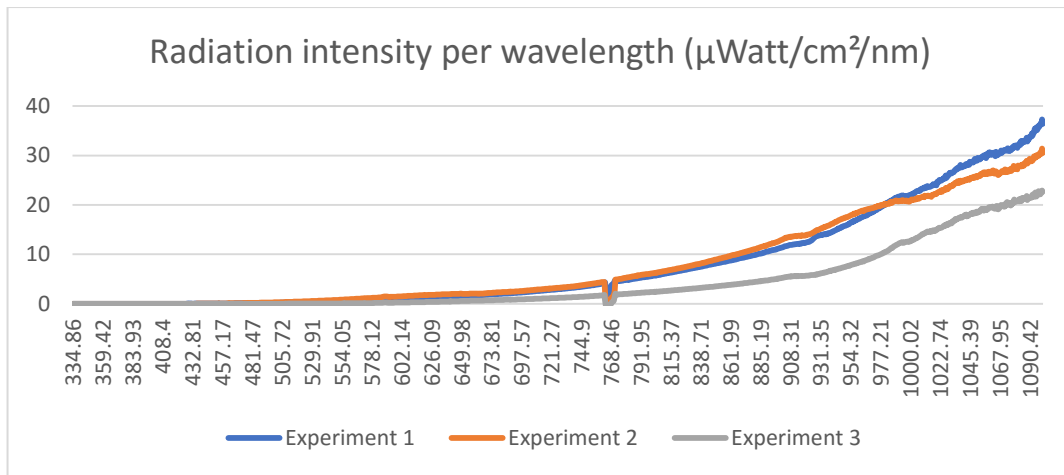


Figure 6: Spectra of thermal radiation in the combustion of sugarcane bagasse

Figure 7 shows the temperatures calculated for the three spectra in figure 7 using the two-color method for wavelength pairs λ and $\lambda + \Delta\lambda$, with $\Delta\lambda$ equal to 30nm. The choice of $\Delta\lambda = 30nm$ due to the greater stability of the estimated temperatures compared to lower values of $\Delta\lambda$. The temperatures were estimated for the entire range of wavelengths provided by the spectrometer. Estimates of temperatures very different from the average (outliers) were removed statistically using the “Chauvenet Criterion”.

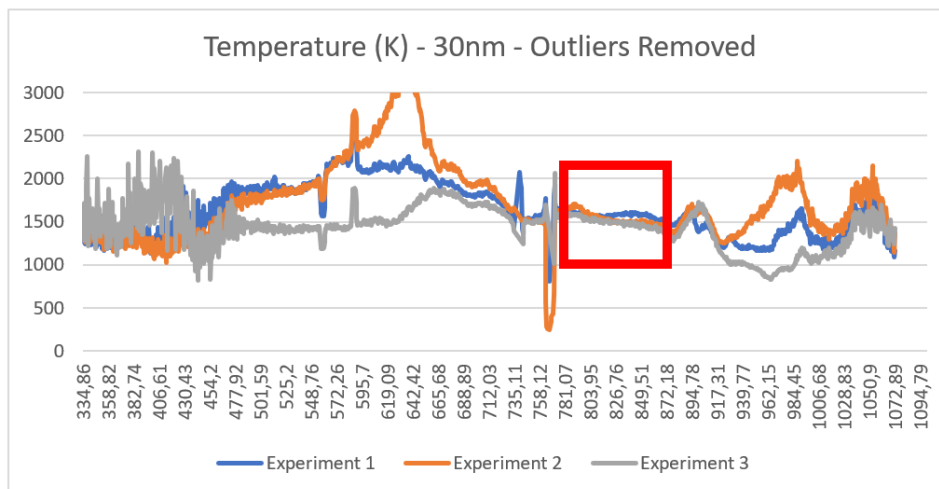


Figure 7: Estimated temperature using $\Delta\lambda$ of 30nm

Figure 7 shows the wavelengths on the horizontal axis and temperature values in K on the vertical axis for the three sugarcane bagasse combustion experiments in step 1. For each experiment, the mean and standard deviation for temperatures in the range between 775 nm and 860 nm were calculated. This range is indicated by the red rectangle in figure 7. It starts right after the characteristic wavelengths of the potassium emission lines, preventing the intensities of radiation in these wavelengths from distorting the temperature estimate. It is noted that in this range there is stability in the calculated temperatures and proximity between the temperatures of the three experiments. Table 1 shows the average temperatures and standard deviations corresponding to the three experiments in figure 7, considering the wavelength range between 775 nm and 860 nm.

Table 1: Mean and standard deviation of estimated temperatures in the range 775 nm to 860 nm

	Experiment 1	Experiment 2	Experiment 3
Average temperature in K (M)	1.581,6	1.557,7	1.509,6
Standard Deviation in K (SD)	25,6	70,0	48,4
Deviation % (SD / M x 100)	1,6%	4,5%	3,2%

3.2. Estimation of potassium concentration

Table 2 shows the potassium concentration during the combustion of sugarcane bagasse, corresponding to step 2 of this study. The first column refers to the temperature ranges defined in line with the results of step 1 of this study, using the maximum temperature of 1,700 K, defined based on the results presented in Table 1, and the minimum temperature of 1,000 K, considering the results obtained by [4] in studies with camphor wood and rice husk. The second to the eighth columns present statistical values referring to the results obtained in the one hundred and fifteen experiments considered in this study, distributed over the temperature ranges in the quantities indicated in the last column.

Table 2: Potassium content in sugarcane bagasse combustion

Temperature (K)	Average (ppm)	StdDev (ppm)	Minimum (ppm)	Maximum (ppm)	Median (ppm)	Lower Quartile (ppm)	Upper Quartile (ppm)	Experiments (un)
1000-1050	0,434	0,472	0,020	1,540	0,295	0,205	0,420	8
1050-1100	0,681	0,669	0,020	1,800	0,485	0,088	1,240	12
1100-1150	0,475	0,536	0,030	1,820	0,290	0,090	0,630	17
1150-1200	0,511	0,603	0,020	1,610	0,270	0,070	0,520	9
1200-1250	0,382	0,520	0,020	1,830	0,110	0,060	0,515	12
1250-1300	0,250	0,444	0,010	1,300	0,060	0,045	0,158	8
1300-1350	0,150	0,184	0,010	0,380	0,020	0,020	0,320	5
1350-1400	0,515	0,658	0,050	0,980	0,285	0,283	0,748	2
1400-1450	0,450	0,622	0,010	1,800	0,230	0,070	0,465	11
1450-1500	0,273	0,397	0,010	1,090	0,100	0,030	0,180	9
1500-1550	0,449	0,458	0,030	1,160	0,253	0,113	0,758	8
1550-1600	0,117	0,122	0,020	0,360	0,100	0,025	0,145	7
1600-1650	0,263	0,356	0,010	0,670	0,110	0,060	0,390	3
1650-1700	0,465	0,376	0,170	1,000	0,336	0,223	0,588	4
General	0,410	0,502	0,010	1,830				115

For the elaboration of table 2 related to the concentration of potassium released in the combustion of sugarcane bagasse, of the total of 181 (one hundred and eighty-one) experiments carried out, 66 (sixty-six) outliers were removed, resulting in 115 (one hundred and fifteen) presented in the table. Two criteria were used for removal:

- a) 10% of experiments with lower potassium concentration values and 10% of experiments with higher values were removed;
- b) Complementarily, experiments were removed considering the quartiles and the spreading of potassium concentration values in relation to the median of the set, using the following procedure:
 - i. Calculate the first quartile (Q1), corresponding to the median of the 50% lowest values;
 - ii. Calculate the third quartile (Q3), corresponding to the median of the 50% highest values;

- iii. Calculate: $E = Q3 - Q1$, which is a measure of the spread of values in relation to the median of the whole set;
- iv. Remove experiments with potassium concentration below $Q1 - 1.5 \times E$;
- v. Remove experiments with potassium concentration greater than $Q3 + 1.5 \times E$.

Figure 8 graphically reproduces the mean and median of potassium concentrations as a function of the temperature ranges tabulated in table 2.

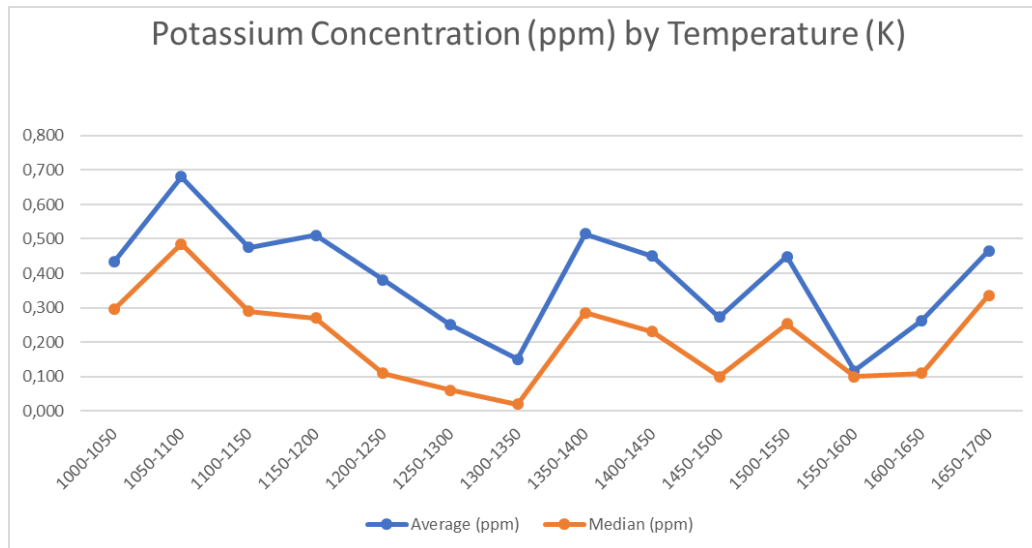


Figure 8: Potassium Concentration (ppm) by Temperature (K)

4. Discussion

Few information about potassium concentration released during sugarcane bagasse combustion is found in the literature. A study about combustion of camphorwood and rice husk can be found in [4]. Figures 9 and 10 graphically show temperature and potassium concentration released in combustion of camphorwood and rice husk as a function of time, showing variations in temperature and potassium concentration in three combustion phases: devolatilization, char combustion and ash formation. In the camphorwood combustion graphs shown in figure 9, the biomass ignition occurs at 35s after exposure to the burner, after which there is a temperature peak in the order of 1,800K referring to the devolatilization phase, with variation in the concentration of gaseous potassium between 0.2ppm and 1.96ppm. The devolatilization phase lasts approximately 19s, and after its closure, the temperature drops to approximately 1,100K. This is followed by the char combustion phase that lasts approximately 213s and with a variation in the potassium concentration between 0.2ppm and 3.05ppm, with an increase in temperature reaching 1,440K. At 266s, the ash formation phase begins, in which the temperature is stable and the potassium concentration declines slowly, with significant potassium emission in this phase [4].

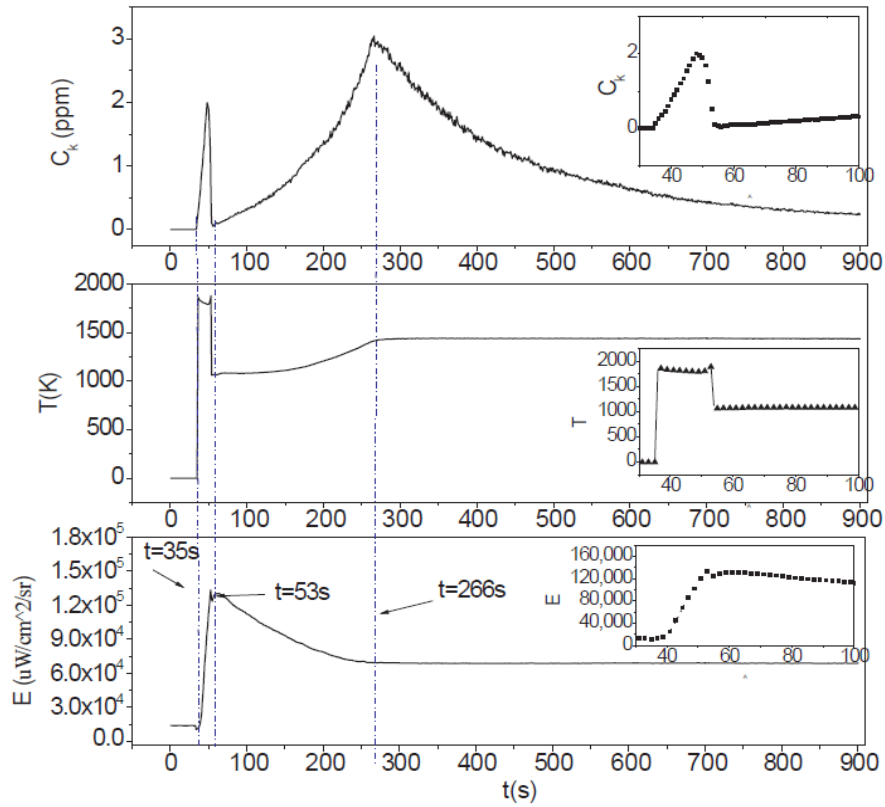


Figure 9: Camphorwood combustion [4]

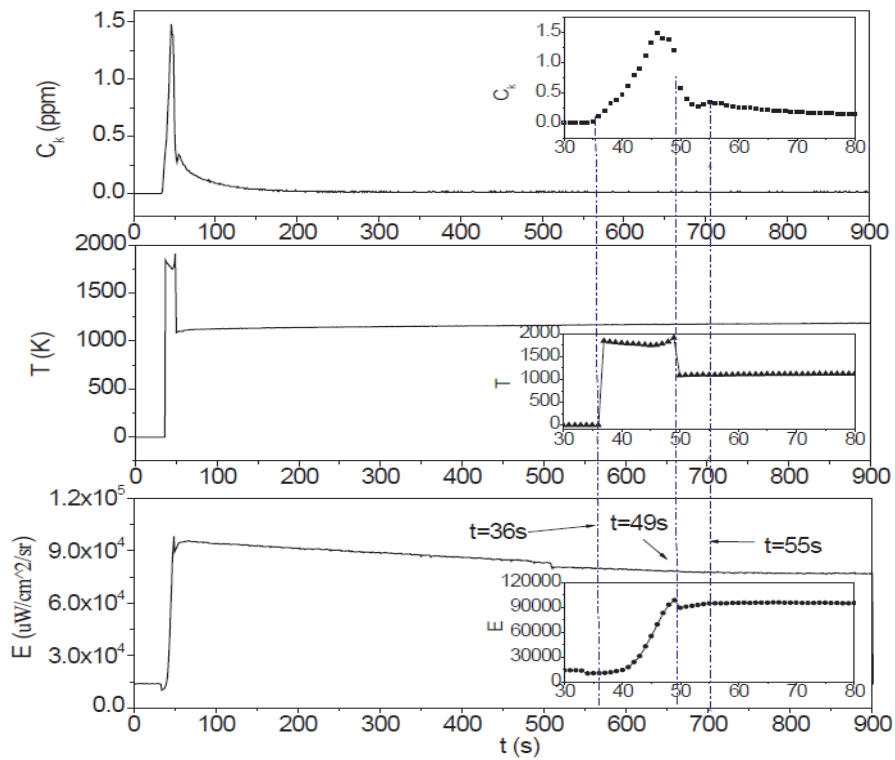


Figure 10: Combustion of rice husk [4]

In the graphs of combustion of rice husk presented in figure 10, the devolatilization phase is similar to that of camphorwood, reaching a temperature of 1,700K with a variation of 0.2ppm to 1.48ppm in the concentration of potassium in the flue gases. The char combustion phase, however, is short, 5s, due to the low fuel content and large amount of ash. In the ash formation phase, after 55s, when the temperature remains close to 1,100K, the concentration of gaseous potassium drops rapidly to zero, due to the high presence of SiO_2 (96.36% in ashes) which reacts with potassium forming potassium silicates and reducing its concentration at this stage. In camphorwood, the presence of SiO_2 is smaller (10.38% in ashes) and most react with CaO (53.77% in ash), which explains the higher concentration of gaseous potassium released in this biomass compared to rice husk [4].

In Table 3 the proximate analysis of sugarcane bagasse is presented to make a comparison with camphorwood and rice husk biomasses. It shows the percentage comparison of volatiles, ash and fixed carbon between the sugarcane bagasse and camphorwood and rice husk biomasses.

Table 3: Proximate analysis of biomass (% by mass)

Biomass	Volatility (%)	Ash (%)	Fixed Carbon (%)
Sugarcane bagasse	79,29	4,55	16,14
Camphorwood	87,93	0,89	11,18
Rice husk	69,12	16,2	14,69

Sources: Sugarcane bagasse [20]. Camphorwood and rice husk [4]

Table 4 shows the percentage comparison, based on mass, of SiO_2 , CaO and K_2O between sugarcane bagasse and camphorwood and rice husk biomasses in ashes. Sugarcane bagasse show higher K_2O than the other biomasses in this case.

Table 4: Presence of oxides in ashes (% by mass)

Biomass	SiO_2 (%)	CaO (%)	K_2O (%)
Sugarcane bagasse	60,96	5,97	9,02
Camphorwood	10,38	53,77	7,99
Rice husk	96,36	0,88	1,8

Sources: Sugarcane bagasse [20]. Camphorwood and rice husk [4]

It was not possible to generate in this work a temporal analysis of temperature and potassium concentration, as performed by [4] for camphorwood and rice husk. However, comparatively, the temporal behavior of the burning of sugarcane bagasse in the phases of devolatilization, char combustion and ash formation can be estimated through the following considerations:

- a) The devolatilization phase of the sugarcane bagasse should last between 14s (duration for the rice husk)

and 19 s (duration for the camphor wood), considering that the percentage of volatiles in the sugarcane bagasse is intermediate in relation to the two other biomasses. We estimate the duration of this phase for the sugarcane bagasse in 17s, considering the phase time proportional to the percentage of volatiles in the biomasses. The maximum temperature reached in this phase depends in the combustion process, in the experiments in this work were in the range of 1600 K to 1700 K. They was similar to that of the other biomasses, in the range of 1,700K (rice husk) to 1,800K (camphorwood). In table 2 of potassium concentrations by temperature range produced in this study, there is a peak of 1ppm in the temperature range from 1,650K to 1,700K, indicating corresponding to the devolatilization phase. Due to the reduced number of experiments in this temperature range, higher expected values for potassium concentration may not have been observed in this work, since there is a greater presence of K_2O in the sugarcane bagasse ashes than in the rice husk ash and there is a greater amount of volatiles in the bagasse [4]. With these characteristics the bagasse closest to camphorwood, we estimate that the maximum concentration of gaseous potassium in the bagasse devolatilization phase is between 1.48ppm (rice husk) and 1.96ppm (camphorwood).

b) The lower percentage of ash from sugarcane bagasse in relation to rice husk allows us to estimate that its char combustion phase is of longer duration [4]. Using the same cause and effect relationship, it is estimated that the char combustion phase of the sugarcane bagasse has a duration close to, but shorter than, that of camphorwood. We estimate that the duration of the char phase for sugarcane bagasse is 163 seconds, considering proportional the variation of time as a function of the variation in the percentage of biomass ash. Using as a reference the temporal behavior of the combustion of camphorwood in which in the char combustion phase the temperatures vary between 1,100K and 1,440K, we can see in table 2 that the temperature variation for sugarcane bagasse this phase starts at a temperature in the range of 1,000K to 1,050K and ends at a temperature in the range of 1,500K to 1,550K, taking into account the means, medians and upper quartile. The temperature ranges in which the number of experiments is equal to or less than three, due to the low representativeness, were disregarded in this analysis. To estimate the value for the maximum potassium concentration point in this combustion phase, considering the curve pattern in which the potassium concentration increases along with the temperature until reaching the maximum, we consider the highest concentration values of the lower and upper quartiles between 1,000K and 1,550K of table2. Therefore, we estimate that the potassium concentration at the highest point of the curve in the char combustion phase is in the range between 0.205ppm and 1.240ppm.

c) Potassium reacts with SiO_2 to form insoluble silicates, reducing the concentration of potassium gas in the ash formation phase [4]. In view of the percentage differences of SiO_2 , based on mass, in ash from the biomasses and considering them proportional to the length of time in which the potassium concentration is greater than zero in the ash formation phase, we estimate that for sugarcane bagasse there is emission of gaseous potassium for 306s, starting at the maximum concentration reached in the previous phase and declining to zero after the estimated time. The greater presence of CaO in the sugarcane bagasse in relation to rice husk, which would contribute to increase the estimated 306 s, due to CaO reacting with SiO_2 instead of potassium [4], was not considered in the estimates due to the difficulty in correlating the rate of this reaction, therefore maintaining the time of 306 s.

The results obtained in the experiments conducted in this study on the combustion of sugarcane bagasse and

analyzed comparatively with results obtained with other biomasses available in the literature, allow to estimate that the temperature in the phases of devolatilization, char combustion and ash formation vary in the range from 1,000 K to 1,700 K and that the concentration of gaseous potassium released behaves and is comprised between the lower and upper curves shown in figure 11, where in the horizontal axis there is time in seconds and in the vertical the concentration in ppm.

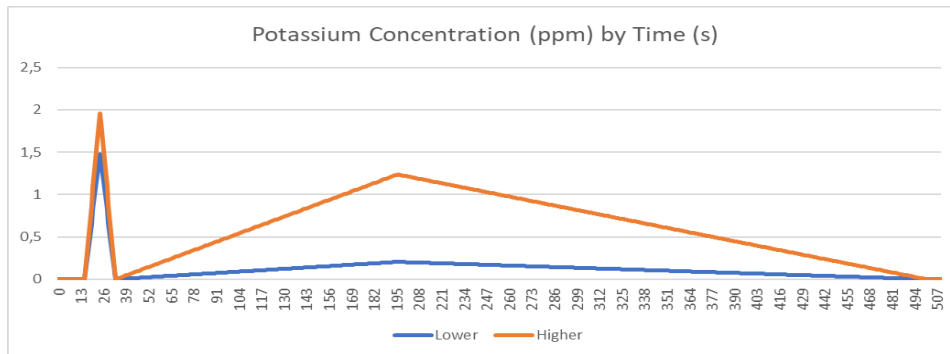


Figure 11: Potassium concentration profile - sugarcane bagasse

In figure 11, the three phases of combustion are distinguished: devolatilization lasting 17s and with peak concentration between 1.48ppm and 1.96ppm; char combustion that starts at 33s and lasts 163s, reaching the second peak at the end of this phase with a concentration between 0.205ppm and 1.240ppm and ending the ash forming phase in which the potassium concentration decays to zero in 306s. The rates of growth and decay of the potassium concentration were considered linear because it was not possible to determine the correct pattern. The margin between the lower and upper limit curves shown in figure 11 and, consequently, the average concentration of gaseous potassium released in the combustion of sugarcane bagasse can be reduced by minimizing the fluctuations in the measurements of the electromagnetic spectra generated due to the type of turbulent flame produced by the combustion process used.

5. Conclusions

Flame temperature of reaction zone during sugarcane bagasse combustion for three different experiments in a pilot tubular combustion chamber was estimated. In all experiments the combustion occurs with diffusion flame type. By using the two-color method, the results of that measurements are in the range of 1500 K to 1600 K. These results agree with results in the literature. Experiments with continuous spectra data capture were performed to estimate potassium released during combustion. The weighted average concentration considering the variations in the potassium concentrations during the combustion phases of the sugarcane bagasse, is estimated in a value between 0.126 ppm and 0.631 ppm. Sugarcane bagasse sample used in this work release less potassium gases during the combustion in comparison with potassium emissions from camphorwood and rice husk.

6. Recommendations

New works that modify the process of combustion and packaging of sugarcane bagasse in pellets, aiming to

produce laminar flames, in which the flue gas flows are arranged in parallel lines following the contours of the biomass, possibly minimizing the oscillations in the electromagnetic spectra, reducing the margins of the results obtained in this study. They may also contribute to the improvement of the shape of the potassium concentration curve as a function of the time outlined in this work, allowing a continuous survey of the points of the curve and the combustion phase transitions, similarly those available in the literature for other biomasses, such as camphorwood and rice husk used comparatively in discussing the results of this study.

Acknowledgments

The first and the fourth author acknowledge the financial support of the Project Concytec (Perú) - World Bank "Improvement and Expansion of Services of the National System of Science, Technology and Technological Innovation" 8682-PE, through its executing unit Fondecyt. (contract 010-2019-FONDECYT). The second author thanks the "Companhia de Saneamento Básico do Estado de São Paulo" (Sabesp) for the financial support. This work also was supported by FAPESP of Brazil (Process 2016/01493-9), the Science and Technology Partnership Program, Ministry of Science and Technology of China (KY201401003) and the National Key Research and Development Program of China (2018YFB0604100).

References

- [1]. M.C.P. Ribeiro, C.P. Nadal, W.F. da Rocha, R.M.D. Fragoso, C.A. Lindino. "Institutional and Legal Framework of the Brazilian Energy Market: Biomass as a Sustainable Alternative for Brazilian Agribusiness". *Sustainability*, vol. 12, pp. 10, 2020.
- [2]. P.S.B. dos Santos, R.A.V. Ramos. "Increased Energy Cogeneration In The Sugar-Energy Sector With The Use Of Sugarcane Straw, Electrification Of Drives, And High-Drainage Rollers In The Extraction". *Engenharia Agrícola*, vol. 40, pp. 249-257, 2020.
- [3]. D. Dayton. "A Summary of NO_x Emissions Reduction from Biomass Cofiring". National Renewable Energy Laboratory. NREL/TP-510-32260, 2002.
- [4]. Z.L. He, C. Lou, J.T. Fu, M. Lim. "Experimental investigation on temporal release of potassium from biomass pellet combustion by flame emission spectroscopy". *Fuel*, vol. 253, pp. 1378-1384, 2019.
- [5]. C. Lou, Y. Tian. "Online Detection Method Of Concentration In Boiler Burning". US Patent 9 651 48, 2017.
- [6]. V. Barisic, J. Mahanen, E.C. Zabetta. "Role of Sodium vs. Potassium on Agglomeration and Corrosion in CFB Boilers". *Impacts Of Fuel Quality On Power Production*, the 26th international conference, September 19-23, 2016, Prague, Czech Republic.
- [7]. M.S. Bashir, P.A. Jensen, F. Frandsen, S. Wedel, K. Dam-Johansen, J. Wadenback, et al. "Suspension-Firing of Biomass. Part 1: Full-Scale Measurements of Ash Deposit Build-up". *Energy & Fuels*, vol. 26, pp. 2317-30, 2012.
- [8]. M.A.G. Silveira, L. Vitusso, N.H. Medina. "Potassium Distribution in Sugarcane". *Brazilian Journal Of Radiation Sciences*, 2015. In Portuguese.
- [9]. H.J. Almeida. "Potassium nutrition in sugarcane stalk harvested without burning". Doctoral thesis, Faculdade de Ciências Agrárias e Veterinárias da Universidade Estadual Paulista, Brazil, 2013. In

Portuguese.

- [10]. A.H. Ushima, G.P. Franca. “Emission of chlorinated compounds in combustion, gasification and pyrolysis of sugarcane straw”. *Revista IPT*, vol. 2, 2018. In Portuguese.
- [11]. C.T. Salinas, Y. Pu, C. Lou, D.B. dos Santos. “Experiments for combustion temperature measurements in a sugarcane bagasse large-scale boiler furnace”. *Applied Thermal Engineering*, vol. 175, pp. 12, 2020.
- [12]. X. He, C. Lou, Y. Qiao, M. Lim. “In-situ measurement of temperature and alkali metal concentration in municipal solid waste incinerators using flame emission spectroscopy”. *Waste Management*, vol. 102, pp. 486–491, 2020.
- [13]. C. Lou, Y. Pu, Y. Zhao, Y. Bai, B. Yao, D. Yu. “An in-situ method for time-resolved sodium release behaviour during coal combustion and its application in industrial coal-fired boilers”. *Proceedings of the Combustion Institute*, vol. 000, pp. 1–8, 2020.
- [14]. B. Muller, U. Renz. “Development of a fast fiber-optic two-color pyrometer for the temperature measurement of surfaces with varying emissivities”. *Review of Scientific Instruments*, vol. 72, pp. 3366-74, 2001.
- [15]. M. Soares. “Informações Técnicas: Critério de Chauvenet”, <http://www.mspc.eng.br/tecdiv/med200.shtml> [Sep 28, 2019].
- [16]. F. Kreith, R.M. Manglik, M.S. Bohn, S. Mark. *Princípios de transferência de calor*. 7.ed. São Paulo, Brasil: Cengage Learning; 2014.
- [17]. Y.A. Çengel; A.J. Ghajar, J. Afshin. *Transferência de calor e massa*. 4.ed. Porto Alegre, Brasil: AMGH; 2012.
- [18]. R.A. Rossow. “Blackbody temperature calculations from visible and near-ir spectra for gas-fired furnaces”. Doctoral thesis, Faculty of the Graduate School University of Missouri-Columbia, USA, 2005.
- [19]. Y.P. Sun, C. Lou, H.C. Zhou. “A simple judgment method of gray property of flames based on spectral analysis and the two-color method for measurements of temperatures and emissivity”. *Proceedings of the Combustion Institute*, vol. 33, pp. 735-41, 2011.
- [20]. D.C. Arantes. “Sugarcane bagasse: thermal and energetic analyse of the biomass”. M.A. thesis, Faculdade de Engenharia Mecânica da Universidade Federal de Uberlândia, Brazil, 2014. In portuguese.