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SIMULTANEOUS BIOMASS FLAME TEMPERATURE AND SPECTRAL EMISSIVITY ESTIMATION BY INVERSE METHOD

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Abstract. This work presents a numerical and experimental study in a laboratorial rig to measure local flame temperature during the biomass combustion. Most of practical situations of biomass combustion is a transient and non-stable phenomenon. A spectral analysis method in the visible spectrum range was used for measurement of local temperatures in a sugarcane bagasse flame. The two-color method considering spectral flame emissivity variation joint with an inverse numerical procedure is used to simultaneous estimation of flame temperature and spectral emissivity. Also, a sequential iterative numerical procedure is tested. It includes the application of two-color method considering grey emissivity between two near spectral intensity data in a first step. In a second step and iterative procedure considering spectral emissivity variation along whole spectral range is applied. To apply the numerical methods was used several spectral intervals in the visible range. In inverse estimation, the Levenberg-Marquardt method is used and a polynomial and a cosine models for estimation of coefficients were tested. Six test of biomass combustion were made focusing the sensor to the reaction zone, and spectral data collected. The flame temperature estimated for the six spectral data were closed to 1530 to 1540 K. Also, the spectral emissivity is closed in all six-combustion test. Instantaneous bagasse flame temperature in the range of 1400 K to 1500 K in the reactive combustion zone were found. An image processing method was used to measure the temperature in the same reactive combustion zone and the comparison show reasonable agreement. The results in this work also are in reasonable agreement with results in literature.

1 INTRODUCTION

Combustion temperature and environmental pollutant emissions are some of the most important parameters to know when attempting to diagnose a combustion system. The quality of the process is directly related to the temperature of the combustion flame. Therefore, it is necessary to use an accurate method to measure this temperature. Over the years, different methods have been developed to measure the temperature of a flame within a combustion chamber. A large part of these methods is based on the two-color method for calculating temperature, which uses as input the spectral intensity found at two different wavelengths. In its most basic approach, this method considers that the spectral emissivity remains constant throughout the two wavelengths chosen to calculate the temperature. However, this condition is not always met. An experimental system that uses an empirical model of spectral calculation and that can measure the wall temperature and the temperature of the flame inside an oven, using information from the radiation collected in the visible spectrum is present in [1]. A spectral analysis that allows determining if the grey body condition is fulfilled for certain types of flame is proposed in [2]. For the solidified gasoline and coal flame the grey body condition was fulfilled, however, for the red phosphorus flame the emissivity could not be considered independent of the wavelength.

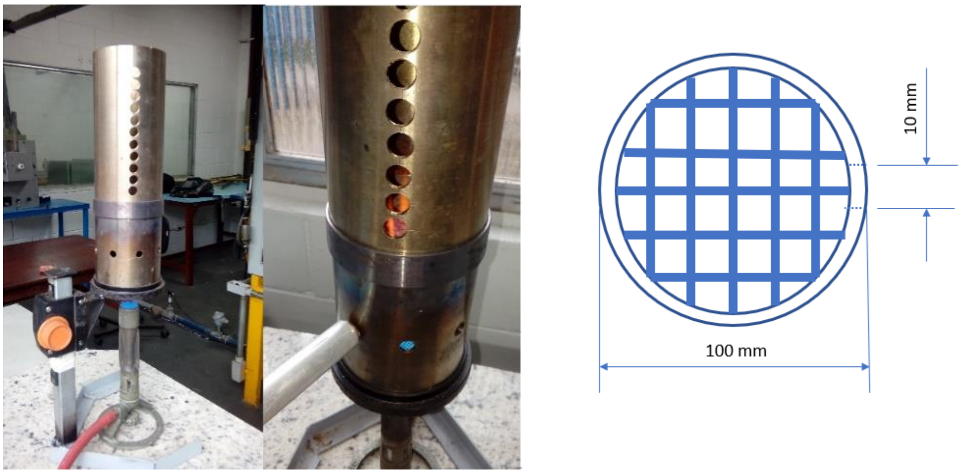
Various works have been developed in which models for emissivity as a function of wavelength are proposed. Thus, the calculation problem is converted into an iterative method that seeks to estimate the parameters of the model, together with the temperature in such a way that the error is the minimum possible. Measurements of the temperature and emissivity (dependent on the wavelength) of a laminar diffusion flame using hyperspectral images is carried out in [3]. And in [4] is present the measurement of the temperature distribution and emissivity of a candle flame using hyperspectral images. In both works a polynomial model was used to represent emissivity as a function of wavelength. In [5] is present a study of an improved two-color method, which integrates a model of the emissivity ratio using a sinusoidal model and its application in air-fuel flames of industrial furnaces. Inverse methods [6] is used in different applications in thermal sciences and can be applied in simultaneous estimation of flame temperature and emissivity.

This work presents a numerical and experimental study in a laboratorial rig to measure local flame temperature during the biomass combustion using a spectrometric method, the two-color method and the Levenberg-Marquardt inverse method to estimate simultaneously the local flame temperature and emissivity.

2 MATERIALS AND EXPERIMENTAL SET-UP

2.1 Experimental rig

An experimental test ring is mounted in the laboratory to obtain the spectrum of the bagasse flame during a bagasse combustion process to calculate the flame temperature. A combustion chamber was used together with a spectrometric system. Combustion chamber is a small vertical tubular combustion chamber type as is show in figure 1(a), to simulate grate bagasse combustion type. The furnace has many viewing ports in the tube wall to install the sensor of the spectrometric system in different level positions. A small chimney is installed in the upper wall of the furnace as an exit for combustion gases allowing the circulation of fresh air into the furnace supporting the combustion process. The combustion process is carried out in a batch procedure using small samples of sugarcane bagasse between 2 g to 5 g.



(a) (b)

Figure 1. Experimental combustion chamber

Figure 1(b) shows a schematic drawing of the chamber. The combustion chamber was constructed using 100 mm diameter stainless steel tubes with a flame produced by a Meker gas 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 10 mm 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.

2.2 Bagasse characteristics

The bagasse samples for the combustion test in the laboratory were collected at a power plant in Pirassununga City, Sao Paulo State. The bagasse samples were collected in the same condition as they are used to burn at the boiler with 50% of moisture. During the transporting of the samples some variation of moisture occurred. Before the experimental tests in the laboratory, measurement of the sample moisture was carried to the chemical department laboratory at Santa Cecilia University only after following the procedure stated in [7]. Three bagasse samples of approximately 1 g are used for measuring the moisture content and the result is show in table 1. Routine reports in the power plant includes information of the proximate analysis of bagasse burned in the boiler furnace. The ultimate analysis in dry and ash free basis of bagasse in the power plant is presented in Table 2.

Table 1. Average Moisture of Bagasse Samples in Laboratorial Tests

Test	Moist Sample (g)	Dry Sample (g)	Moisture (%)	Average Moisture (%)
1	1.0386	0.7269	30.0115	27.9748
2	0.9914	0.7059	26.9013	
3	0.9929	0.7247	27.0117	

Table 2. Ultimate Analysis of Some Samples in routine report in the power plant.

C %	H %	0 %	N %	Sulfur %	Chlorine %	High heating Value MJ/Kg
48.17	6.55	44.9	3.64	Less to 0.10	0.0449	16.12

2.3 Spectrometric system and Imaging system

The spectrometer system consists of a spectrometer, a measuring probe and a portable computer. An AvaSpec-USB2048 Fiber-Optic Spectrometers with 2048 pixels is used to process the incoming light data. The measurement wavelength range of the spectrometer was 200 nm to 1100 nm. The spectral resolution of this spectrometer is 0.8 nm. The measuring probe consists of a collimating lens and a fiber-optic cable. The COL-UV/vis collimating lens, screws onto the end of the fiber optic entrance connector and converts the divergent beam of radiation into a parallel beam. The spectrometer is connected to a portable computer through a USB cable via and AvaSoft-8 USB2 interface. For experiments reported in this paper, the exposure (integration) time is about several hundred milliseconds, which means the measurement of radiative intensifies at different wavelengths by the spectrometer is performed almost simultaneously. The spectrometric system was used to collect spectral intensities of sugarcane bagasse flame through the viewing port of the boiler furnace every one second. Figure 2 shows a scheme of the spectrometric system.

The imaging system consists of a color CCD camera, an objective lens with a viewing angle field of 90° in the horizontal direction fixed at the top end of the CCD camera and a laptop with a frame grabber. The flame radiation conveyed by the lens entered the color CCD camera. The shutter speed of the color camera is adjustable from 1/120 to 1/10000 s. The video signal from the CCD camera is transferred into the laptop through a video cable. A USB frame-grabber transfers the CCD camera's analogue signal into a two-dimensional digital color image with 24-bit true color. Combined with a DELL Latitude D630 laptop, the system provides a frame rate of 24 frames / s with a 24-bit true color. Every color flame image is saved as a 24-bit RGB Windows Bitmap (BMP) file. When the CCD camera is installed in the boiler furnace to capture flame images on-line, it should be cooled by air or water. However, while the portable system works, flame capturing time in every viewing port is very short. Furthermore, the objective lens and CCD camera were packaged by a steel shell. As a result, there is no cooling air for the measurement in the power plant.

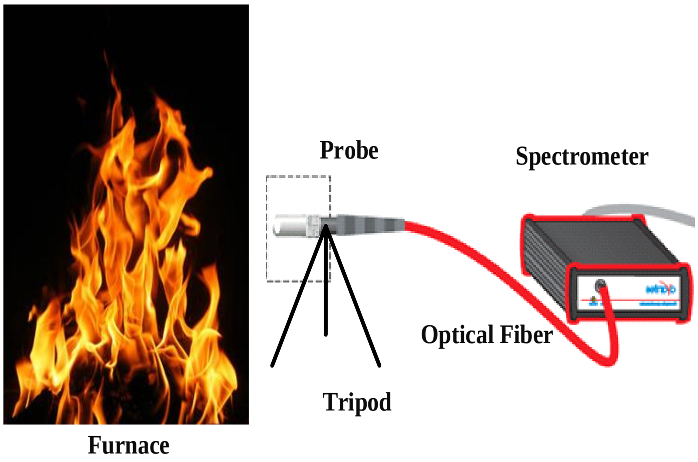


Figure 2. Scheme of the spectrometric system

The combustion chamber has two tubes. The bottom tube has a length of 120mm and a grate at the top to simulate combustion of biomass in grate. Longitudinal holes in the upper tube with a diameter of 10mm and distance between centers of 15mm allow the insertion of the spectrometer lens to collect spectral data and select position to focus the reaction zone.

Six tests of bagasse combustion were made in the tubular combustion chamber simulating grate combustion. Bagasse samples of 3 g were used in every test. The bagasse combustion is the diffusion type, and the combustion is instable along the time. For collected an optimal spectral the integration time will need be to modify along the time. The integration time is adjusted by the spectrometer software and it is collected five spectral data in every test. After that, it is select a spectral data with a better emission capture following the criteria of spectral data with emissions near of 60000 counts.

3 THEORICAL BASIS AND NUMERICAL METHOD

3.1 Theoretical basis

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) [8].

$$E = \varepsilon \sigma T^4 \tag{1}$$

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 [8]. 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) [8].

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

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 [8].

3.2 Formulation two-color method

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 [9].

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

The temperature equation for the two-color method is obtained by selecting two wavelengths, $\lambda_i \; and \; \lambda_j$, 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 [9].

$$T = \frac{C_2\left({}^{1}/_{\lambda_j} - {}^{1}/_{\lambda_i}\right)}{\left(Ln\left({}^{E(\lambda_i,T)}/_{E(\lambda_j,T)}\right) + Ln\left({}^{\varepsilon_j}/_{\varepsilon_i}\right) + 5Ln\left({}^{\lambda_i}/_{\lambda_j}\right)\right)} \tag{4}$$

where T is the estimated temperature; C_2 is ${}^{hc}/_{k}$ (h Plank's constant; k is the Boltzmann constant; c the speed of light), corresponding to $1{,}43878 \, x \, 10^{-2} \; m \, K . \lambda_i \; and \; \lambda_j$ are the wavelengths. $E(\lambda_i, T) \; and \; E(\lambda_j, T)$ the spectral emissive powers at the wavelengths $\lambda_i \; and \; \lambda_j \; in \; (W.m^{-2}.nm^{-1})$. $\varepsilon_i \; and \; \varepsilon_j$ are emissivities at wavelengths $\lambda_i \; and \; \lambda_j$.

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 $\lambda_i \; e \; \lambda_j$ (less then 128nm), one can simplify (4) assuming that ${}^{\varepsilon_i}/_{\varepsilon_j} \cong 1$, which allows us to estimate temperatures using (5) [10]. In step 1 of the work, we used the 30nm distance between wavelengths and (5).

$$T_{i,j} = \frac{c_2\left({}^{1}/_{\lambda_j} - {}^{1}/_{\lambda_i}\right)}{\left(Ln\left({}^{I_i}/_{I_j}\right) + 5Ln\left({}^{\lambda_i}/_{\lambda_j}\right)\right)} \tag{5}$$

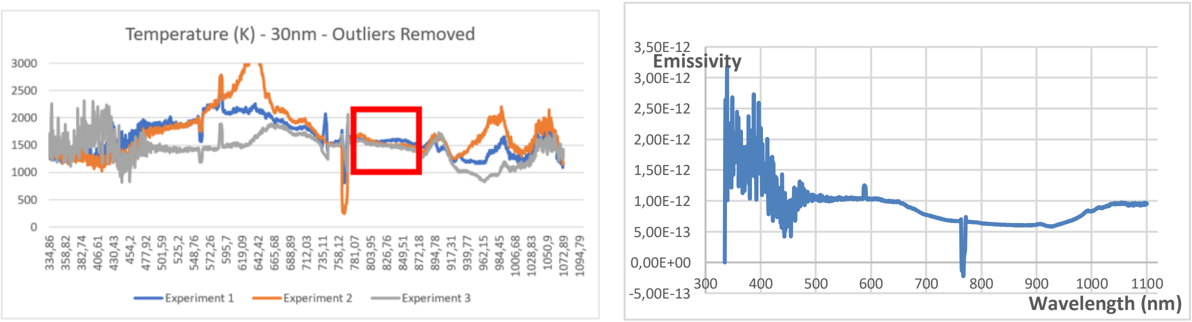
3.3 Numerical procedure

Temperatures are calculated using the two-color method for wavelength pairs λ and λ+Δλ, with Δλ equal to 30 nm. The temperatures were estimated for the entire range of wavelengths provided by the spectrometer, outliers were removed statistically using the Chauvenet Criterion. The Levenberg-Marquardt Inverse Method [6] was used to calculate simultaneously the spectral emissivity variation and the flame temperature. In the inverse method were used the procedure of parameters estimation and polynomial and sinusoidal models.

4 RESULTS AND DISCUSSION

Six spectral data of flame emission were collected in six bagasse combustion experiments.

Figure 3(a) shows the temperatures calculated using the equation (5) for three collected spectra 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 $\Delta\lambda$. Temperatures were estimated for the entire range of wavelengths provided by the spectrometer, then, the flame emissivity is calculated. The result for experiment 1 is show in figure 3(b). It can be observed that in range of wavelengths demarked by red square, the emissivity is approximately stable. This range is used to calculate the temperature. In sequence the flame temperature is recalculated using the equation (4) considering the flame emissivity. After few iterations, the result converges. The flame temperature estimation is show in Figure 4.



(a) (b)

Figure 3. Estimated flame temperature and emissivity using $\Delta\lambda$ of 30nm

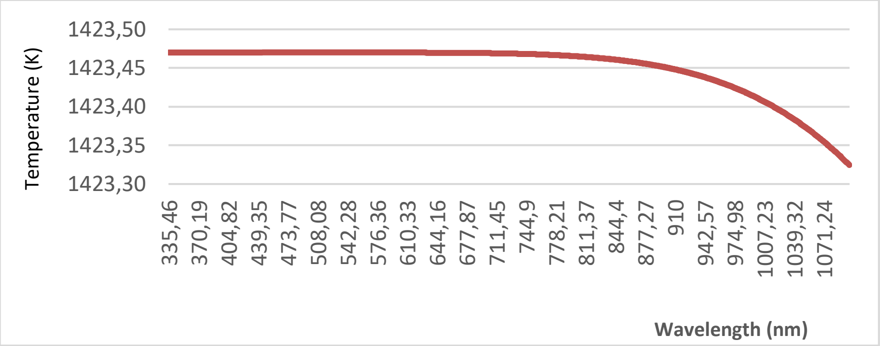


Figure 4 Temperature estimation by sequential method

The Levenberg-Marquardt Inverse Method was used to calculate simultaneously the spectral emissivity variation and the flame temperature. In the inverse method were used the procedure of parameters estimation and polynomial and sinusoidal models for emissivity variation. In figure 5 is shown the comparison of the numerical convergency for three models used in the inverse method. Polynomial model converged about after 320 iterations and sinusoidal model converge faster.

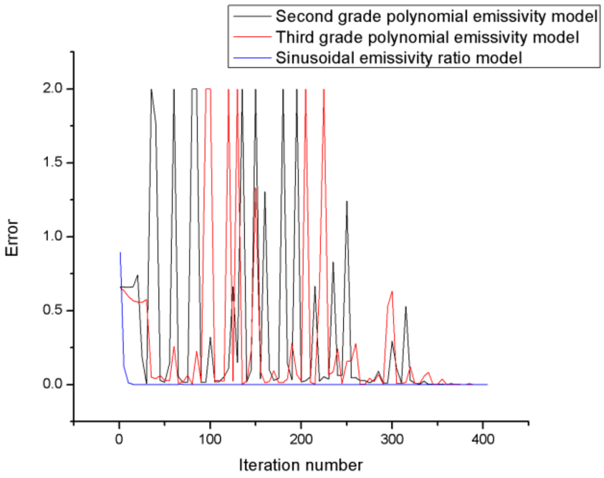


Figure 5. Convergence comparison of second and third order polynomial emissivity estimation and sinusoidal emissivity ratio estimation from for experiment 6.

In figure 6 is shown the comparison of the flame emissivity estimation by the two color method and by the Levenberg-Marquardt inverse method for three set of experimental data. It can be seen good agreement in the range of emissivity values and in the variation profile of the spectral emissivity.

Flame temperature estimation by the three methods is shown in Table 3. Estimations of the flame temperature by the two color method is made by selecting a proper spectral range where spectral emissivity is approximately constant. Temperature calculation by sequential method gives a close temperature estimation along all spectral range and is close to standard two color method values. Simultaneous estimation of flame temperature and emissivity by the Levenberg-Marquardt method is in agreement with estimations by the two color method. For the spectral data in this work the third order polynomial model give estimations closer with two color method estimations. Sinusoidal model in this case gives bad estimations.

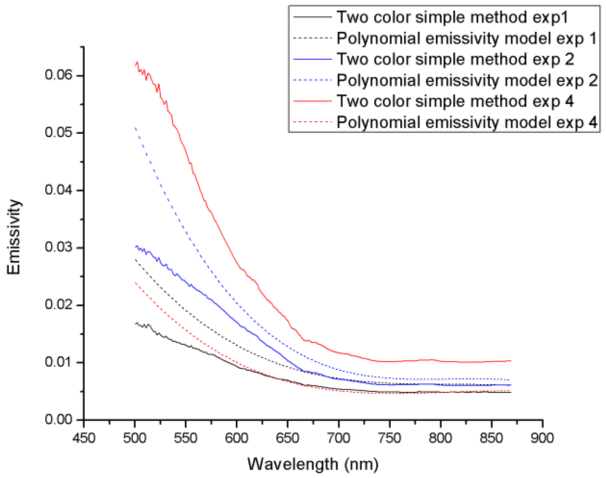


Figure 6. Emissivity comparison of emissivity estimated by two color method and emissivity estimated by a third order polynomial emissivity model for experiments number 1, 2 and 4.

Table 3. Temperature estimation comparison by two color method, and sequential two color method and Levenberg Marquardt method.

Experiment number	Two color method	Sequential two color method	Percentage variation	Levenberg – Marquardt Method	Percentage variation
1	1562.50	1562.49661	0.021696%	1529.2	2.131%
2	1544.00	1543.99665	0.021697%	1522.2	1.412%
3	1507.47	1507.46673	0.021692%	1420.6	5.765%
4	1581.30	1581.29657	0.021691%	1692.1	7.007%
5	1558.79	1558.78662	0.021683%	1420.8	8.853%
6	1430.50	1430.4969	0.021671%	1430.4	0.007%

To comparison, a portable imaging system was used to measure the flame temperature during a combustion test. The imaging system measure the average flame temperature in the focused zone, while the spectrometric method can measure the flame temperature in a local point. In Figure 8 is show the flame temperature measured in experiment 1 using the thermal imaging method. This result agrees with estimations of flame temperature calculated based in spectral data collected by the spectrometric system.

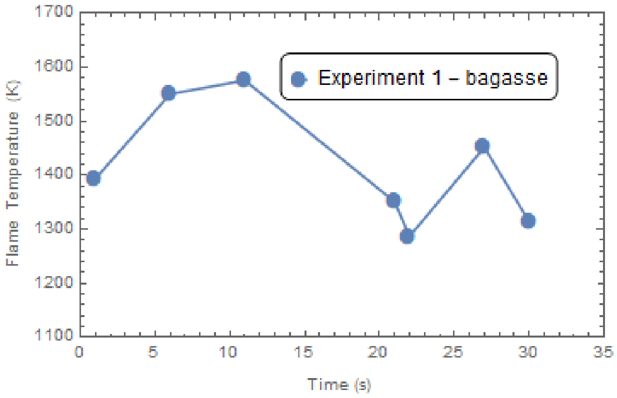


Figure 8. Temperature measurement by thermal portable system, during combustion in experiment 1.

5 CONCLUSIONS

A sequential two-color method including the emissivity spectral variation was applied and compared with results from standard two-color method. Estimations of temperature in both methods agree.

The Levenberg-Marquardt Inverse Method to simultaneous estimation of flame temperature and emissivity in sugarcane bagasse combustion using polynomial models to spectral emissivity variation was applied successfully. The results from the use of a sinusoidal model did not give a good estimate.

Flame temperature estimations were in the range of 1400 to 1585 K.

Values of flame temperature estimations from two-color method and from Levenberg-Marquardt Inverse Methods are in reasonable agreement with discrepancies in the range of 0.007 % to 8.85%.

Comparison of measurements using spectrometric method and imaging method also agrees.

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