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GASES EMISSIONS AND EXCESS AIR MEASUREMENTS FOR PERFORMANCE ANALYSIS OF A WOOD STOVE

Felipe Alfaia do Carmo, facmil@gmail.com
Sérgio Aruana Elarrat Canto, aruana@ufpa.br
Universidade Federal do Pará, Campus Universitário José da Silveira Netto, Rua Augusto Corrêa, 01, 66075-110, Guamá, Belém – PA, Brasil.

Manoel Fernandes Martins Nogueira, mfmn@ufpa.br
Universidade Federal do Pará, Campus Universitário José da Silveira Netto, Rua Augusto Corrêa, 01, 66075-110, Guamá, Belém – PA, Brasil.

Carlos Edilson de Almeida Maneschy, cemaneschy@ufpa.br
Universidade Federal do Pará, Campus Universitário José da Silveira Netto, Rua Augusto Corrêa, 01, 66075-110, Guamá, Belém – PA, Brasil.

Tiago da Silva Santos, tssantos1803@gmail.com
Universidade Federal do Pará, Campus Universitário José da Silveira Netto, Rua Augusto Corrêa, 01, 66075-110, Guamá, Belém – PA, Brasil.

Hussein Felix Gazel, husseingazel@yahoo.com.br
Universidade Federal do Pará, Campus Universitário José da Silveira Netto, Rua Augusto Corrêa, 01, 66075-110, Guamá, Belém – PA, Brasil.

Abstract. *Millions of people in Africa, Central and South America and Asia rely on rudimentar and ineficient wood stove that causes respiratory diseases and demand for large quantity of biomass from native forest. The international agents as World Bank, Unesco and International Energy Agency has pointed out the relevancy of wood stove. Research on this subject has been done by Shell Foundation and Aprovecho Research Center that indicates Rocket Stove technolgy as the most promising and able to provide efficiency together with low cost. This work presents performance results obtained from one wood rocket stove manufactured by a Brazilian company named Ecofogão. The stove performance was measured caractherizing the amount of energy supplied to the stove in the biomass and caracterizing the eluding gases. The incoming energy was quantified through the high heating value for the Jatobá (using a bomb calorimeter) plus the Ultimate Analysis (content of carbon, hydrogen, nitrogen and oxigen, Proximate Analysis (content of moisture, fixed carbon, volatiles and ash) and the mass flow rate of biomass feed to the stoven. The leaving energy in the exaustion gases was quantified measuring its temperature and composition imediately at the exit of the stoven what is the inlet of chaminey. The results show the presence of* CO_2, O_2 *and CO in the concentration ranges of (0.9% to 6.30%), (14.30% to 19.90%) and (0.17% to 2.50%) respectively. The excess air is in the range (3.33 to 23.33) based on carbon dioxide measurements in the eluted gases. These results provided information to promote also further improvements on the stoven design.*

Keywords*: wood stove; biomass; combustion gas; excess air*

1. INTRODUCTION

Research has shown that the hazards of kitchens continue to affect many millions of people, largely in the form of smoke from improper cooking devices used in poorly ventilated areas. The victims are mainly women and small children, as they spend many hours in these unhealthy environments. Wood and other biomass still dominate as domestic cooking fuels, especially in the kitchens of poor regions and it is likely to remain the case for a long time. (Pandey, 1997).

Due to this problem in recent years a growing number of studies on wood stoves have been done seeking the measurement of their efficiency, better way to use it and especially on methods to reduce emissions of greenhouse gases. Still and MacCarty (2008) in their work did a survey of seven standards existing on testing wood stoves, and made a historical study of their development. Among the various tests described in such paper, was a standard proposal by Shell Founding, the Water Boiling Test (WBT), which was used in this study to evaluate the wood stove. The test consists of three phases.

In the first phase, the cold-start high-power test, it begins with the stove at room temperature and uses a pre-weighted bundle of wood or other fuel to boil a measured quantity of water in a standard pot. At the end, the boiled water is replaced with a fresh pot of cold water to perform the second phase of the test.

The second phase, the hot-start high-power test, follows immediately after the first test while stove is still hot. Again, the tester uses a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot.

The third phase follows immediately from the second. Here the test determines the amount of fuel required to boil a measured amount of water at 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world.

Aprovecho Research Center (2007) tested the GTZ-Andes stoves using the standard Shell-UCB 2003 Water Boiling Test. During this research, four different wood stoves were tested. CO concentration in the flue gas was not measured due to testing in windy environments. It was, however, estimated based on previous measurements of observable smoke leakage. They estimated that the CO concentration gas emissions were in the range 15-20 ppm in all wood stoves.

MacCaty (2008) tested a stove developed by Larry Winiarski and Nancy Hughes with a name of Ecocina Stove. The Ecocina Stove consists of a tiled combustion chamber surrounded by a wide sheet metal body. The Ecocina was tested using a 2003 UCB Water Boiling Test (WBT). The test results of the Ecocina stove are compared to the performance of the conventional biomass stove. The Ecocina produced only 1/3 of both, carbon monoxide (CO) and particulate matter (PM), emissions compared with the conventional stoves. The CO concentration was below the benchmark of 20 g and the particles were 724 mg, while the benchmark is 1500 mg

Anozie et al. (2004) evaluated cooking energy cost, efficiency, impact on air pollution and policy in Nigeria. In this work were used as fuel wood for cooking was used beans and yams in water. When the water was boiled, particulate emission during open air burning of fuel wood was 4.33×10^6 µg but when the yam was cooked, this became 6.92×10^6 µg while the beans cooking released 8.56×10^6 µg. The range found of daily air pollutants were: particulate matter $2.71 \times 10^6 - 1.44 \times 10^8$µg; sulphur dioxide $1.13 \times 10^5 - 1.89 \times 10^7$µg; oxides of nitrogen $9.55 \times 10^6 - 2.04 \times 10^9$µg; carbon monoxide $2.39 \times 10^6 - 1.05 \times 10^9$µg and total organic carbons $2.67 \times 10^5 - 9.55 \times 10^8$µg.

According Pinheiro and Valle (1995) the precise control of excess air influences both the optimization of thermal efficiency and in reducing the level of pollutant emission of thermal systems. He said the control of excess air is the solution more cost effective for reducing the emission of pollutants, and should be evaluated first.

Nogueira and Lora (2003) said that there is an optimum value for the coefficient of excess air. And this value for the burning of biomass in suspension and grid are 1.2 and 1.3 respectively. They said that if the coefficient of excess air in the system is greater than the optimum value there is an increase of heat losses in flue gas. While in cases where excess air is smaller than the optimum value appear in the gas products from incomplete combustion, which represents a waste of energy.

The Ecofogão (Figure 1) is a wood-burning stove produced commercially by Ecofogão Company. The model "metallic multiple use" has a block of refractory ceramic material, which is the combustion chamber of biomass in a rocket-stove type, where biomass is burned to generating hot gases to heat the casting iron plate on the ceramic block. The combustion gases are leaded under the plate throughout a helical fin until the chimney. Such constructive concept provides different temperatures on the plate where the food coking occurs and leads the combustion gases to a chimney avoiding kitchen contamination.

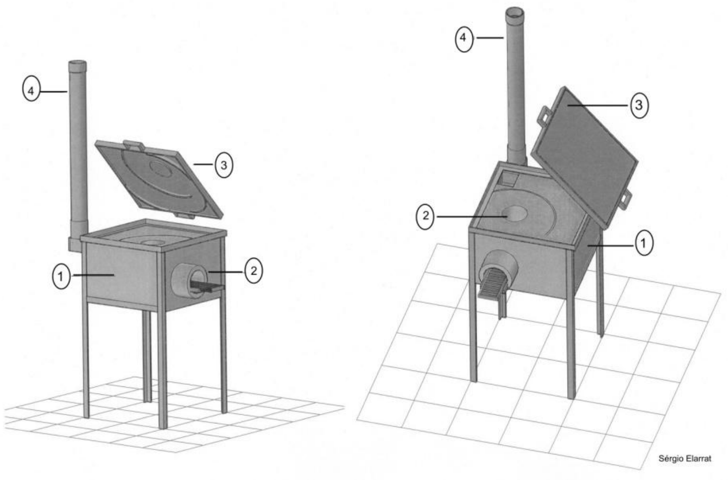


Figure 1 – (1) Shows the Ecofogão's refractory ceramic base; (2) Combustion chamber-type rocket stove; (3) Metal plate with fin on the underside for directing the combustion gases and (4) Chimney.

This paper presents the results of carried out experiments in this stove. The results show the energetic characterization of the fuel, the hot gases temperature distribution under the iron plate, the gases emissions concentration and air excess evaluation.

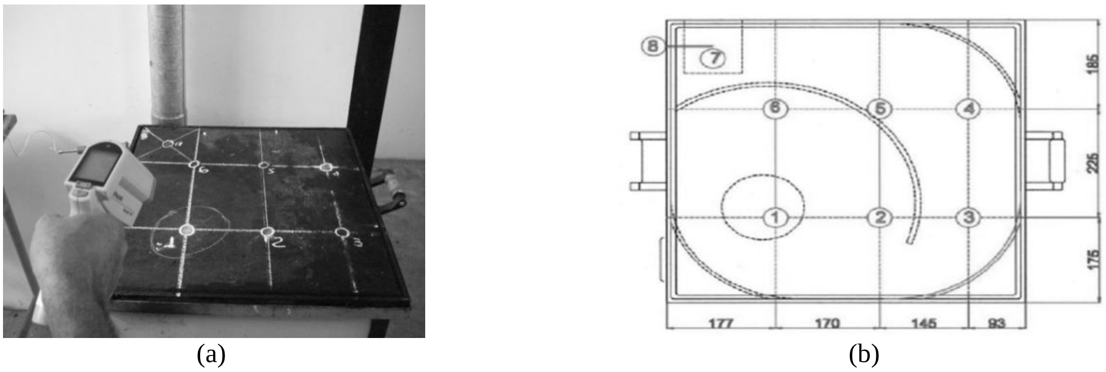
2. MATERIALS AND METHODOS

In order to evaluate the performance of any thermal energy system the energetic characteristic of the fuel must be known in advance. In this case, the fuel was the wood Jatobá and its energetic characteristics was determined through the quantification of the following parameters: humidity, volatile, fixed carbon and ash contents (through Proximate Analysis), carbon (% C), hydrogen (% H), oxygen (% O), nitrogen (% N) and sulfur (% S) contents (through Ultimate Analysis), bulk density (through balance), high heating value-HHV (through Bomb Calorimeter), low heating value-LHV (calculation from HHV and ultimate analysis). Table 1 shows the standards and equipment used for the energy characterization of Jatobá wood.

Table 1: Standards and equipment used for the energy characterization

Test	Standards Test	Standard for storage and preparation of biomass	Equipment	
			Description	Specification
Ash	ASTM D1102-84	D346, D2013	Furnace	Carbolite AAF-1100
Volatile	ASTM E872-82	D346, D2013, E871	Furnace	Carbolite AAF-1100
Humidity	ASTM E871-82	D346, D2013	Furnace	Odontobrás EL – 1.4
HHV	ASTM E711-87	D346, E1, E180, E775, E790, E829	Bomb Calorimeter	Ika Werke C2000
Elemental analysis	Manual of Equipment	Manual of Equipment	Elemental analysis	Perkin Elmer Series II CHNS/O 2400
Carbon content	Summary of ASTM as the sum of the levels of ash, volatile and humidity less 100%	D346, D2013, E871	-	-
Bulk density	Obtained by quantifying the amount of fuel mass that fits in 1 cubic meter	-	A case with a cubic meter volume and a digital balance	Toledo digital balance with maximum load of 15 kg and division of 5 g.

Hot gas temperature distributions under the iron plate were carried out during phase 3 of WBT with assistance of a computer simulation three-dimensional finite element method. On the iron plate was chosen eight points (Figure 2) where the surface temperatures were measured using pyrometer laser. Point eight is located at the entrance of the chimney, to determine the output temperature of the flue gases.



(a)

(b)

Figure 2 – (a) Shows the location of the point where the plate surface temperature were measured with the pyrometer laser and (b) Shows the points set up and the distance between them.

Once known the temperature on the plate surface, the plate matter and the gas flow properties under the plate, the gas temperature was evaluated through heat transfer calculation. The flow characterization was done through the measurement of temperature and velocity of the exhaust gases at the chimney using a turbine digital anemometer (Figure 3). The following assumptions were adopted for numerical calculation:

- The gas composition was 100% nitrogen;
- It was applied the real dimensions of the Ecofogão;
- The plate’s material is 100% cast-iron;
- The combustion chamber and refractory were ceramic.

Figure 3 - Digital turbine anemometer acquiring velocity data and gas temperature.

The flue gas composition was carried out using a gas analyzer named Tempest 100. During phase 3 of WBT equipment was placed every 15 minutes on top of the chimney to collect data. Such data also allowed the determination of the air excess coefficient. All tests were performed three times and data presented are the results of the arithmetic average of these tests.

3. MATHEMATICAL EQUATIONS

The LHV is calculated subtracting the condensing heat of the steam that exists in the products gas from the heat of combustion (absolute value) at the same reactants temperature and pressure. Nogueira et al. (2008) suggest the following equation to evaluate the LHV as function of the HHV plus Proximate and Ultimate Analysis.

$$LHV = HHV \times (1 - \omega_{wb}) - [9 \times H \times (1 - \omega_{wb}) \times h_{lv}] - \omega_{wb} \times h_{lv} \tag{1}$$

Where ω_{wb} is the moisture containing in the biomass (wet basis) obtaining from proximate analysis, H is the biomass hydrogen mass fraction obtained from the ultimate analysis and h_{lv} is the difference between the enthalpy of saturated liquid and enthalpy saturated vapor of water at atmospheric pressure.

According Nogueira and Lora (2003) to evaluate the excess air (α) can use relations based on the concentrations of CO_2 (Eq. 2) or O_2 (Eq. 3) in products of combustion if the gases are at equilibrium. They recommend that in practice, the excess air (α) determined by this method, is kept at the lowest possible level, until the presence of soot or CO indicates that there is existence of incomplete combustion.

$$\alpha_{CO2} = 21/CO_2\% \tag{2}$$

$$\alpha_{O2} = 1/[1 - (0.048 \times O_2\%)] \tag{3}$$

Another way to calculate the excess air is the mass ratio between real and stoichiometric amount of air in a combustion process, as in Eq. 4.

$$\alpha = \frac{m_{real\ air}}{m_{stoichiometric\ air}} \tag{4}$$

Which in, $m_{\text{air stoichiometry}}$ is the stoichiometric air mass; $m_{\text{air real}}$ is the real air mass. The calculation of $m_{\text{theoretical air}}$ comes from the stoichiometry reaction and can be calculated according to Eq. 5.

$$m_{stoichiometry\ air} = \left(\frac{n_{air} \times MW_{air}}{n_{fuel} \times MW_{fuel}}\right) m_{fuel} \tag{5}$$

Which in, MW_{air} and MW_{fuel} are the air and fuel molecular weight and n_{air} and n_{fuel} are the mol number of air and fuel in the stoichiometric reaction. $m_{air\ real}$ is the air mass effectively used to consume the biomass, m_{fuel} during the experiment. It is evaluated multiplying the air mass flow rate that went into the combustion by the time needed to consume the biomass, as in eq. 6.

$$m_{air\ real} = \dot{m} \times t \tag{6}$$

Which in, $\dot{m}$ is the mass air flows rate in kg/s and t the time interval of data collection, that in this case was five minutes. Considering the air a perfect gas the mass air flow rate can be described as a function of air pressure, temperature, air velocity at the entrance in the combustion chamber, and the cross sectional area of the entrance to the combustion chamber, as eq. 7.

$$\dot{m} = \frac{P_{air} \times v_{chamberentrace} \times A_{cross\ section}}{T \times R} = \frac{P_{air} \times v_{chamberentrace} \times d^2 \times \pi}{T \times R \times 4} \tag{7}$$

All this data was collected in entrance of combustion chamber, where the $P_{air}$is the air pressure and was considered the same of ambient pressure 101,325 kPa; T is the air temperature in Kelvin and was considered the same of ambient temperature and was collected in time intervals of 300 seconds with a thermometer; $v_{chamberentrace}$ is the air velocity of 4 m/s; $A_{cross\ section}$ is the cross section area with a diameter of 0.14 m; R is a universal gas constant with the value of 0.287 kPa.m³/kg.K.

To assess whether the air-fuel mixture is rich or poor is necessary to calculate the equivalence ratio defined as the ratio air-fuel ratio of the reagents by air-fuel ratio at stoichiometric conditions, as Eq. 8.

$$\Phi = \frac{m_{air\ real} / m_{fuel\ air}}{m_{air\ stoichiometry} / m_{fuel\ stoichiometry}} \tag{8}$$

The $m_{fuel\ air}$ (real fuel mass) and $m_{fuel\ stoichiometry}$ (stoichiometric fuel mass) in this experiment are equal and defines as 0.5 kg what makes equivalence ratio equal to the air excess coefficient.

After compiling the data for air excess and equivalence ratio, a comparison between species mass fraction obtained through the Tempest from the exhaustion gases and the concentration obtained with the software COMGAS (ROCHA, 2009) was done. This software is a software tool produced by the research group EBMA UFPA, which is made a simulation of combustion and gasification processes in chemical equilibrium.

4. RESULTS

4.1. Energetic characterization

The results of the energy characterization are presented in Table 3. This table allows the empirical chemical formula for the testing fuel, Jatobá as eq. 9.

$$C_{4,374}H_{5,476}O_{2,464}N_{0,124}S_{0,024} \tag{9}$$

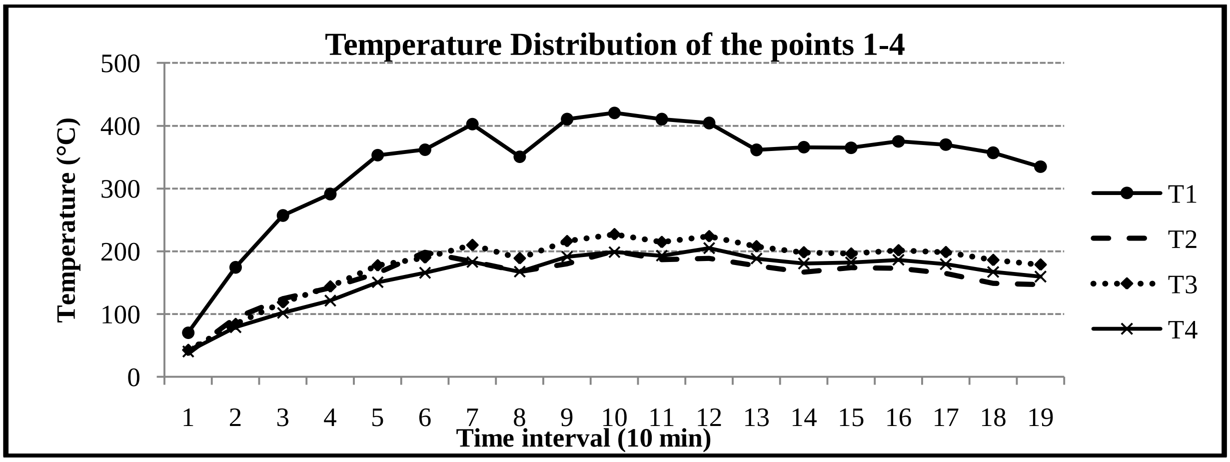
Table 3. Results of the energy characterization of Jatobá wood.

Characteristic energy	Results
HHV (kJ/kg)	20,350.83
LHV (kJ/kg)	19,125.59
%Humidity	9.4
%Volatile	79.06
%Ash	0.37
% Carbon content	20.57
%C	52.54
%H	5.52
%O	39.43
%N	1.74
%S	0.78
Bulk density (kg/m³)	200

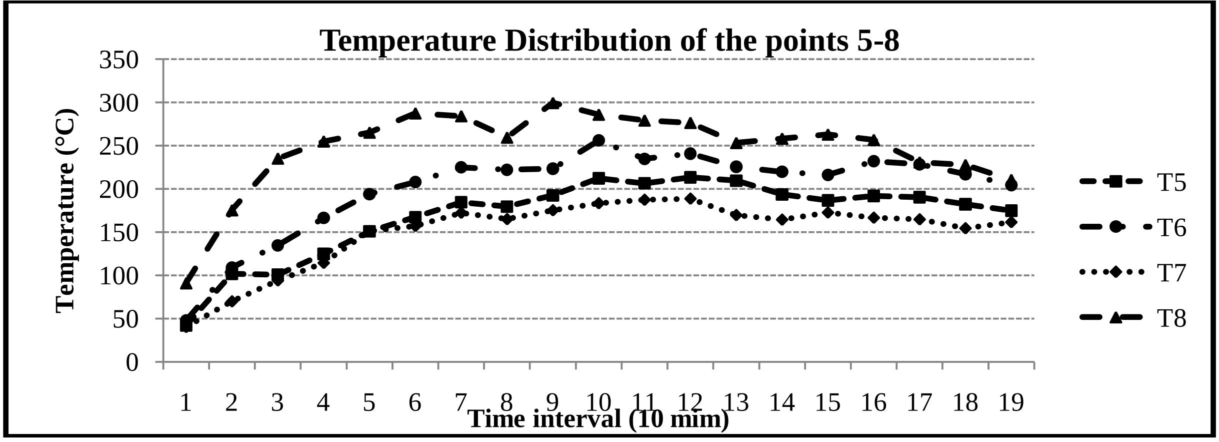
Using the stoichiometric reaction and eq. 4 have the stoichiometric air fuel mass ratio for combustion of Jatobá wood is $6.31\ \mathrm{kg_{air}/kg_{fuel}}$.

4.2. Temperature distribution on the hot plate

According with Figure 2, the temperature distribution collected by the pyrometer laser is shown in figures 4.



(a)



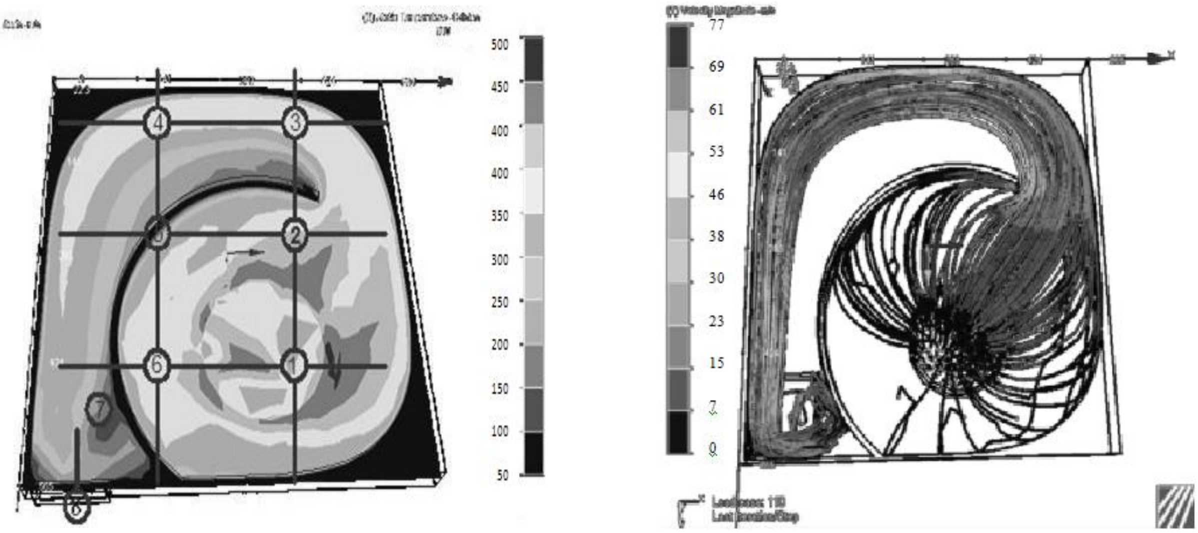
(b)

Figure 4 – (a) Diagram that shows the temperature of the points 1-4 on the plate
(b) Diagram that show the temperature of the points 5-8.

This diagram shows which in the point 1 that is located on the exit of the rocket-stove chamber, has the highest temperature readings, with a peak of 420 °C. The results of point 8 show that the temperatures of hot gas at the entrance of the chimney are in the range 250-300 °C. The diagrams show that the stove does not have a uniform temperature, because the fins present under the plate. This causes differences in temperatures around 200 °C in nearby regions.

4.3. Hot gases temperature distribution under the iron plate

Figure 5 shows the calculation results for the gases velocity under the plate with the trajectory of points described in the mesh. It may be noted the effect of centrifuge that concentrates the gas on the outer wall of the fin, leaves stagnation areas under the plate and bottlenecks for gas flow. The speed of the hot gas is around 7 m/s. Also shown in Figure 5 is the simulation of the gas temperature in the plate where it is demonstrated how the distribution of temperature is uneven. For example in the output of the burner is close to 450 °C whereas in fin external surface is close to 200 °C.

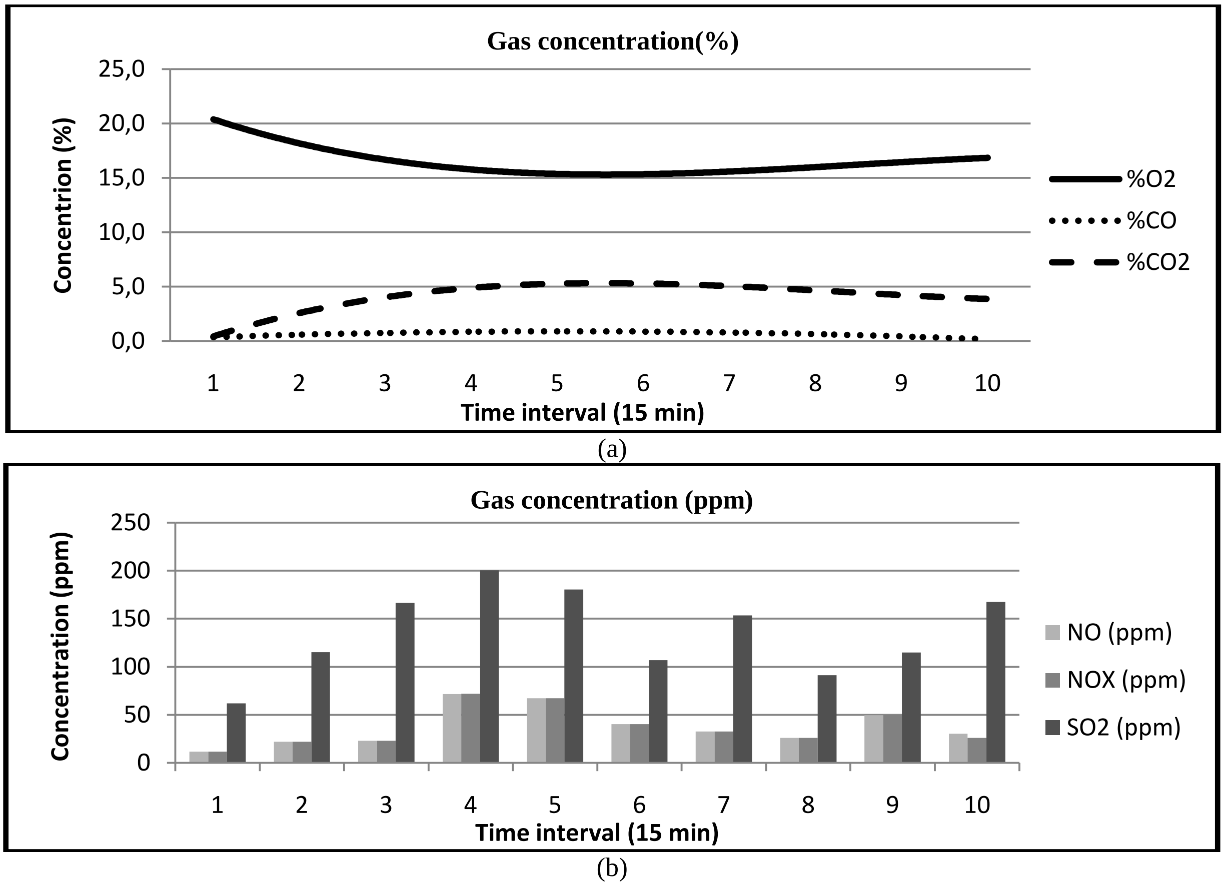


(a) (b)

Figure 5 – (a) Temperature distribution for the hot gases and (b) Results for hot gases velocity

4.4. Species concentration to flue gases

Using data obtained with Tempest 100 observed that the CO was around 0.6%, while CO_2 and O_2 were around 4 and 16% respectively, as shown in Figure 6. The same test showed that the concentration of NO and NO_X were approximately 37.5 and 37.1 ppm, besides presenting a high concentration of SO_2 that was around 135.8 ppm.



(a)

(b)

Figure 6 – (a) Diagram of concentration (%) of O_2, CO_2 and CO and
(b) Diagram of concentration (ppm) of NO, NO_X and SO_2.

4.5. Air excess quantification

The results for air excess coefficient obtaining at different times during the experiment and calculated through Eq. 2, Eq. 3 and Eq. 4 are presented in Table 4.

Table 4 – Results of air excess coefficient.

α with a function of CO_2 concentration (Eq. 2)	α with a function of O_2 concentration (Eq. 3)	α with a function of ratio between real and stoichiometric amount of air (Eq. 4)
23,33	22,32	6,88
9,54	9,12	6,87
8,57	8,22	6,86
3,33	3,18	6,85
4,22	4,05	6,85
4,56	4,34	6,84
6,11	5,84	6,82
3,70	3,53	6,81
6,00	5,78	6,81

Table 4 shows that the air excess coefficient evaluated through O_2 and CO_2concentrations are very similar (Eq. 2 and Eq. 3) but different for the values obtained through the mass ratios (Eq. 4) showing that the combustion reaction did not achieve the equilibrium.

The table 5 shows the difference between the results of gases produced in the combustion collected with Tempest 100 and calculated with software ComGas (ROCHA, 2009) using as equivalence ratio the results obtained by Ep. 3.

Table 5 – Tempest 100 X ComGas

TEMPEPST 100				SOFTWARE ComGas			
O2%	CO%	CO2%	NO (%)	O2%	CO%	CO2%	NO (%)
19,9	0.165	0.900	0.00115	0.182	0	0.0549	0.00002315
18,55	0.350	2.200	0.00220	0.184	0	0.0521	0.00001811
18,3	0.465	2.450	0.00230	0.186	0	0.0505	0
14,3	0.786	6.300	0.00716	0.192	0	0.0501	0
15,7	0.273	4.966	0.00673	0.198	0	0.0498	0.00000942
16,03333	0.520	4.600	0.004033	0.204	0	0.0494	0.0000077
17,26667	0.340	3.433	0.003267	0.210	0	0.0490	0.00000633
14,93333	0.336	5.666	0.002600	0.216	0	0.0486	0.00000523
17,23333	0.563	3.500	0.004967	0.222	0	0.0483	0.00000434

5. CONCLUSION

The difference between measured and calculated temperature for location 8 is about 10% related to the measured value. Therefore, the calculation distribution can be used to evaluate the thermal surface tensions of the system for the plate. Based on results from calculation, having in mind that the inlet air was measured through a digital anemometer, it is easily identified a stagnation area between the exit of the combustion chamber and the flap under the plate, which resulted in a high temperature zone. Likewise, the region near the chimney entrance showed intense change in velocity resulting in a low temperature zone. These phenomena infer that such area has a trend to promote a crack fracture due to temperature gradient.

Nogueira and Lora (2003) said that the coefficient of excess air great for burning in grid is 1.3 and the test results presented in Table 4 showed that the stove operates with excess air much larger than the optimum coefficient, with this increase heat waste with the exhaust gases leaving in chimney, which indicates a loss of efficiency. However, analyzing the stove according to its primary function, which is cook food and for that purpose the temperatures do not exceed 300 °C, it can be seen in figure 4 that the temperatures reached meet this need and can still be concluded that the excess air acts beneficially as a regulator of temperature.

On the pursuit for efficiency improvement only temperature increasing is restrictions on materials that may degrade faster. The standard "Pressurized paraffin-fuelled appliances" (Standards South Africa, 2007), although devoted to other types of stoves, makes recommendations that may be appropriate to Ecofogão metallic regarding the durability of parts and materials from the stove. It recommends that where the parties are necessary contacts with the user cannot exceed 40 °C and no galvanized part can exceed 400 °C. Confirming these observations, the grid, rocket-stove burner and iron plate were exposed to high temperature and were heavily degraded, and thus were found broken in the structures of them.

The table 5 shows the upper limit for species concentration for the equivalence ratio calculated in Eq. 3, where analyzes the results obtained by the Tempest 100 realizes that the combustion is rich in air, but is not complete, that it is perceived mainly by the presence of CO.

Notice the high formation of SO_2 present in Figure 6-(b), but the chemical composition of the fuel has a low content of S. It means that such high concentration of SO_2 comes from external agents and should be investigated in future work. The concentrations of NOx and CO are below the recommended benchmark of 360 and 500 ppm, respectively (Standard 382 of CONAMA, December 26, 2006).

As a proposed design improvement the fuel-air ratio must be moved to values nearer the stoichiometric ratio with addition of more biomass in the combustion chamber making the mixture richer in fuel. This procedure would increase the temperature by increasing the reaction rate and improving the efficiency of the stove, or alternatively can be fed with small amounts at short intervals of time trying to keep the temperature high. Another solution would be to reduce the entry of air into the chamber, enriching the mixture with biomass, but this alternative may impair the feeding process of biomass. It has also the option of intervening in the chimney to change the circulation and increase the temperature at the combustion chamber. The best solution may involve joint actions and should be revealed by specific experiments for these purposes.

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