

EVALUATION OF GASES EMISSION FROM A WOOD STOVE.

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Abstract. *The Shell Foundation estimates that today over half the world's population uses biomass for cooking. In Brazil, IBGE (2008) estimates that about 6 million households have wood stoves and 3.2 million have coal stoves. According to World Health Organization (WHO), the pollution from wood and coal smokes is the eighth leading cause of death worldwide and the fourth cause in underdeveloped countries. In 2008, only Brazil had 4100 deaths, placing this country as the first in Latin America on this type of causality. Based on this high demands involving social issue, EBMA/UFPA in cooperation with the Brazilian company Ecofogão (rocket stove technology), evaluated a wood stove developed and commercialized by the last one. Stove performance was evaluated through fuel consumption, temperature on hot plate surface, eluded gases temperature and composition. The gas composition analysis showed the following concentration: 14.3% to 19.9% O₂, 0.17% to 2.5% CO, 0.9% to 6.3% CO₂, 11.5 ppm to 71.7 ppm NO, 11.5 ppm to 72 ppm NO_x and peak emissions of SO₂ with concentrations ranging from 62 ppm to 200 ppm. Once fuel ultimate analyses showed no presence of sulfur, investigation had been performed to figure out the source of such species. Detailed fueled characterization was performed and experiment done for different stove operation condition monitoring exhaust gas concentration. Metallographic analysis and chemical scanning of the metal parts of the stove was executed with an electronic microscope seeking SO₂ contaminants. The results indicated that SO₂ emissions were originated by thermal degradation of the cast iron grid. This result helps to promote further improvements on the stove design.*

Keywords: wood stove, biomass, gases emission

1. INTRODUCTION

Probably the first human applications for fire were as household heating and cooking food (Tillman, 1991). Traditional fires and cook stoves are some of the earliest technologies and often it is assumed that so much is known about them already, therefore little or no further research is needed to improve their efficiencies and dissemination. (Yuntenwi *et al.*, 2008).

In a world of about 6.8 billion people, some as 2.4 billion rely on traditional fuels (wood, charcoal, agricultural residues and dung) for cooking and heating. That number will increase up to 2.6 billion by 2030 (International Energy Agency, 2002). On this context, developing countries are consumed daily two million metric tons of wood, coal, crop waste and dung, equivalent to approximately one kilogram per day for each person (Winrock International, 2007). Although stoves have been studied on a continuing basis for over 35 years, unfortunately, today has no clear internationally accepted design standard for stoves burning biomass (Still *et al.*, 2007).

The Brazilian Ministry of Mines and Energy states that 40 percent of all energy consumed by the households in 2004 was from wood. Nine million households use wood stoves in Brazil (EPE, 2009). This demand is generated by two factors, one cultural and other socioeconomic. The cultural is due to the fact that wood stoves or their surroundings have traditionally been a place for social interaction. On the other hand there are those who use this technology because they do not have a financial capability to acquire and maintain a gas stove.

This high utilization of wood stove generates two negative environmental impacts: high consumption of firewood which leads to deforestation and air pollution, resulting on environmental or respiratory problems. In 2008, only Brazil had about 4100 deaths due respiratory problems caused by harmful emission gases from wood stoves. According Shell Foundation (2006), the exposure to indoor air pollution resulting from poor cooking technologies and practices causes the premature deaths of more than 1.6 million persons annually in the world, that is, 1 person every 20 seconds. In Brazil, early estimates put the exposed population in the range of 2.6 million households, mostly among rural settlers (Winrock International, 2007).

The number of people exposed to severe indoor air pollution derived from biomass burning is higher than the number of people affected by outdoor pollution (Saldiva and Miraglia, 2004). Indoor air pollution causes five to six times as much life shortening as the more familiar urban air pollution (Goldemberg *et al.*, 2004) and is second only to unsafe water as a cause of premature mortality (WHO, 2002).

Biomass combustion has as eluded product pollutants such as carbon monoxide, nitrogen oxides, aldehydes, polycyclic aromatic hydrocarbons, primary and secondary particles. Primary particles have a carbon core, which have several compounds adhering on its surface. Secondary particles are mainly formed by gas conversion to particles, such as nitrogen oxides to nitrates. All these species are harmful to health up to some degree and may exist at high concentration inside homes during cooking (Saldiva and Miraglia, 2004). While biomass is considered a renewable fuel, the inefficient and unhealthy use of these solid fuels in a home puts millions of the world poorest families at risk (Alam *et al.*, 2006). Particles from wood and charcoal combustion make lungs vulnerable to acute lower respiratory infections, such as pneumonia and chronic obstructive pulmonary disease and there is evidence linking indoor air pollution to asthma, tuberculosis, cataracts, low birth weight and infant mortality (UNDP, 2005).

Aiming to solve problems caused by such high demand for inefficient domestic wood stoves, several institutions such as the Shell Foundation, UN, FAO, Aprovecho Research Center, Proleña, among others, have developed methodologies to improve such facility. Joining this current effort, the Federal University of Pará has been testing a wood stove marketed by Ecofogão Company, MG. This stove is the model “metallic multiple use”. It has a block of refractory ceramic material where the biomass combustion chamber is located as a rocket-stove type. There, biomass is burned to generating hot gases, heating the casting iron plate above the ceramic block. The combustion gases are drove under the plate throughout a helical fin until achieves the chimney, see Figure 1. Such constructive concept provides different temperatures on the plate surface where the food coking occurs and conducts the combustion gases to a chimney avoiding kitchen contamination.

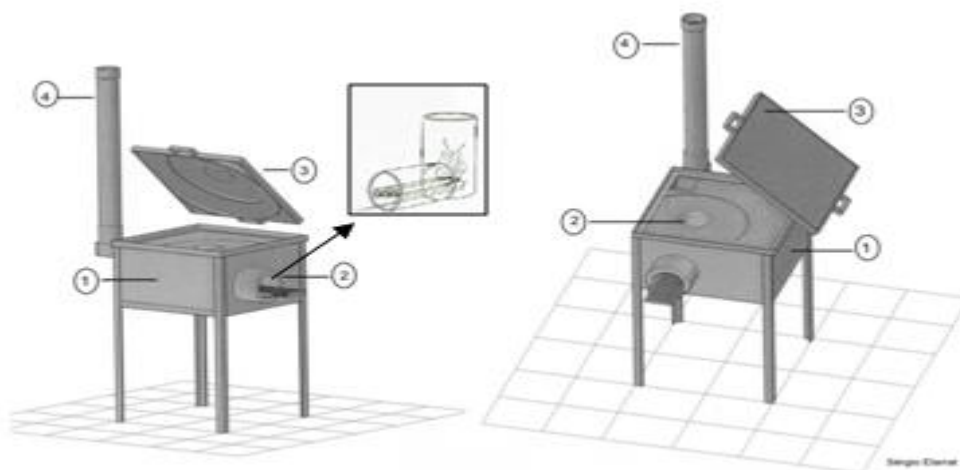


Figure 1. (1) Shows the Ecofogão's refractory ceramic base; (2) Combustion chamber-type rocket stove; (3) Metal plate with fin on the underside for directing the combustion gases and (4) Chimney.

Such stove has been tested following the Water Boiling Test (WBT) method proposed by the Shell Foundation. In addition to, temperature profile on plate surface was monitored and gas emissions in the chimney was quantified. Still and MacCarty (2008) summarized the three phases of WBT as follows.

The first phase, cold-start high-power test, begins with the stove at room temperature and uses a previous weighted bundle of wood or other fuel to boil a measured quantity of water in a standard pot. Energetic efficiency is evaluated from the amount of biomass consumed, water mass boiled and time. At the end, the boiled water is replaced with a fresh pot of cold water to perform the second phase of the test.

Second phase, hot-start high-power test, follows immediately after the first test while stove is still hot. Again, the test uses a previous weighted 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.

Third phase follows immediately from the second. Here the test determines the amount of fuel required to boil a measured amount of water during 45 minutes. This step simulates the long cooking of legumes throughout much of the world. The data collected during the three phases of the WBT is used for calculating the stove efficiency.

This paper presents experimental results carried out in a metallic multiple use wood stove with rocket combustion chamber. Results show the energetic fuel characterization, hot gases temperature distribution under the iron plate, the gases emissions concentration and an investigation results to find out cause for high concentration of sulfur dioxide in eluded gases. In order to find the source of sulfur dioxide, study was carried out to examine the cast iron plate and grill through a metallographic analysis using an optical microscope and a scanning chemistry using an optical spectrometer, while the grid was examined using a scanning electron microscope (SEM), a semiquantitative analysis by energy dispersive spectroscopy (EDS).

2. MATERIALS AND METHODOS

2.1. Energy Characterization of Firewood.

The fuel adopted was the wood Jatobá and its energetic characteristics was done 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 Jatobá wood energy characterization.

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	CalorimeterBomb	IkaWerke C2000
Ultimate Analysis	Equipment Operation Manual	Equipment Operation Manual	Ultimate 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.

2.2. The Temperature distribution under the iron plate

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

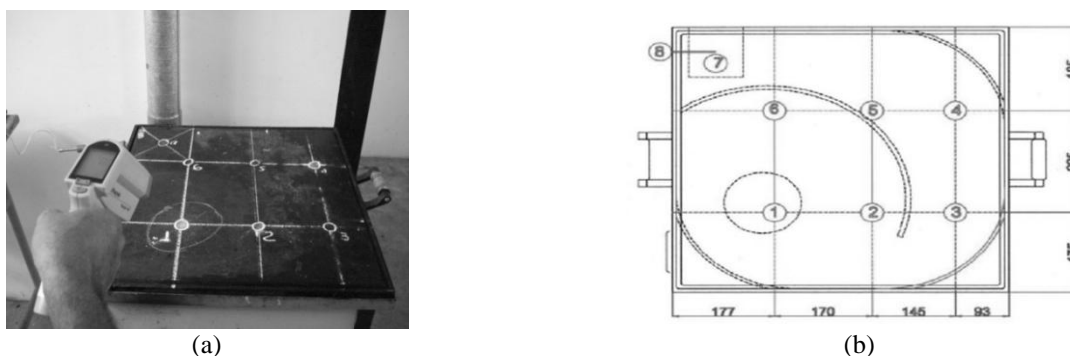


Figure 2. (a) shows point locations where the plate surface temperature were measured with the pyrometer laser and (b) shows the points set up and the distance between them.

Once known surface plate temperature, using a turbine digital anemometer (Figure 3), the air velocity was measured at the combustion chamber entrance as well as gases velocity at chimney outlet. This obtained information were used as boundary condition for computer simulation to characterize the flow and gas temperature under the cast iron plate. The following assumptions were adopted for numerical calculation:

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



Figure 3. Turbine digital anemometer acquiring velocity data and gas temperature.

2.3. Gases composition

The flue gas composition was carried out using a Tempest 100 gas analyzer. During phase 3 of WBT, Tempest 100 took samples every 15 minutes at 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 here are the results of the arithmetic average of these data.

2.4. Sulfur dioxide investigation.

Test samples were removed from both, the plate as the grate, Figure 4. Samples from the plate was used to metallographic analysis with an optical microscope and chemical scanning (optical emission spectrometer SPECTRO-MAX DIN 31051), while the sample of the grid went through a scanning electronic microscope LEO 1450 VP.

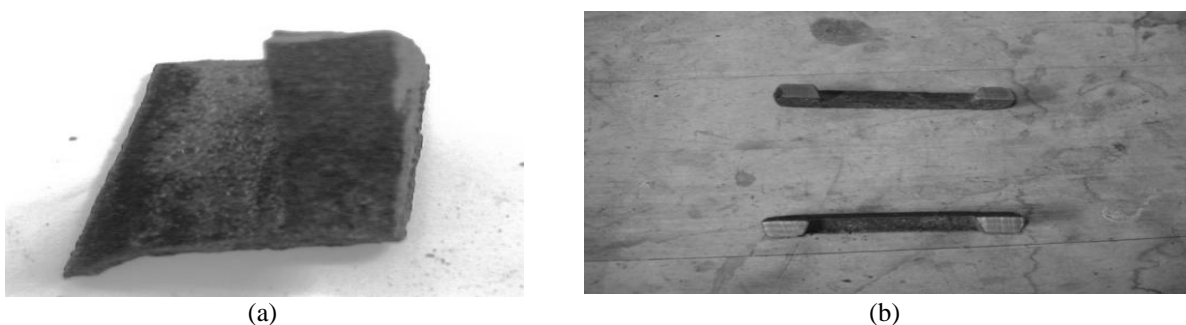


Figure 4. (a) Test sample of the plate; (b) Test sample of the grid.

Cast iron plate samples were obtained in rectangular shape made with a grinder. Samples had one of its surface flatted and duly polished up to achieve a smooth finish and mirror to observe its microstructure. For this, the following material was used:

- Grinder BOSCH GWS 14-180, on 220 V;
- A stone grinding of beef cattle;
- A stone emery sandpaper-type;
- An apron and a face mask (NR-6);
- Sandpaper Manuals (120, 220, 320, 600);
- Running water;
- Liquid soap mixed with alumina;
- An abrasive polishing.

After grinding and polishing, microstructure analysis was obtained with an optical microscopy. The sample was attacked with a Nital solution 1% in ethanol for a time of 10 seconds. After three chemical attacks, sample drying was made with a piece of cotton and warm air.

The chemical scanning used the method of optical emission spectroscopy (OES), which is a non-intrusive means of plasma investigation. Determining the wavelength, or either, the radiation frequency, one can determine the chemical species responsible for emission. This frequency is characteristic of each species and depends on their energy levels (UNESP, 2011).

Scanning electron microscope (SEM) used energy dispersive spectroscopy (EDS) to perform the grid analysis. This method consist on imping an electron beam, coming from the tungsten filament, on sample surface, exciting atoms outer electrons making them move for an upper energy level. Upon electrons return to its initial energy level, they release the acquired energy as light emission with wavelength in the x-rays spectrum. A detector installed in the vacuum chamber of SEM measures the energy released. Since the electrons of a given atom have distinct wavelengths, it is possible to determine which chemicals are present at that location (DEGEO-UFOP, 2011).

3. MATHEMATICAL EQUATIONS

The LHV was calculated subtracting the steam condensing heat 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 HHV plus Proximate and Ultimate Analysis.

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

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 water saturated vapor and liquid and enthalpies at atmospheric pressure.

4. RESULTS

4.1. Energetic characterization

The results of the energy characterization are presented in Table 2. This table leads to the empirical chemical formula for the testing fuel, Jatobá as eq. 2

$$C_{4,374}H_{5,476}O_{2,464}N_{0,124}Ash_{0,024} \quad (2)$$

Table 2. Results of the energy characterization of Jatobá wood.

Property	Results	Property	Results
HHV (kJ/kg)	20,350.83	%C	52.54
LHV (kJ/kg)	19,125.59	%H	5.52
%Humidity	9.4	%O	39.42
%Volatile	79.06	%N	1.74
%Ash	0.37	%Ash	0.78
% Carbon content	20.57	Bulk density (kg/m ³)	200

4.3. Temperature distribution on the hot plate

The temperature distribution collected by the pyrometer laser is shown in Figure 5.

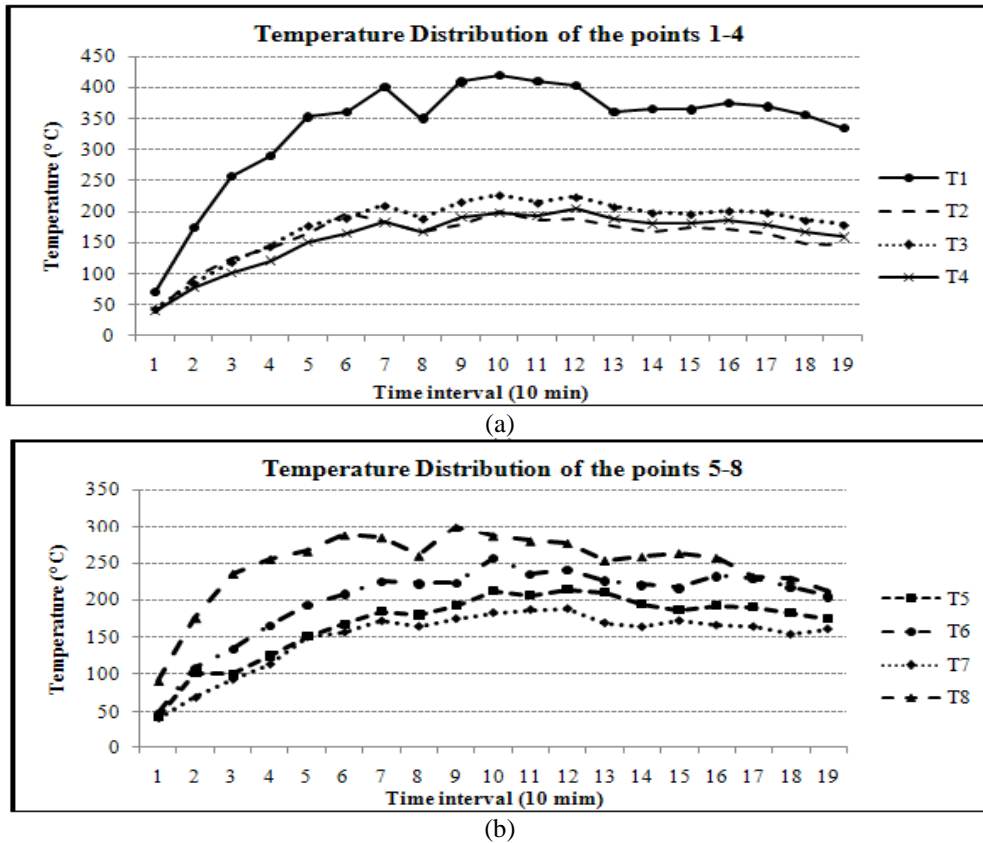


Figure 5. (a) diagram that shows the temperature of the points 1-4 on the plate
 (b) diagram that show the temperature of the points 5-8.

This figure shows that point 1, located at rocket-stove chamber exit, has the highest temperature readings, with a peak of 420 °C. Point 8, temperatures of hot gas at the chimney entrance is in the range 250-300 °C. Figure 5 shows that the stove plate does not have a uniform temperature as consequence of flow orientation promoted by the fin under the plate. It causes temperatures differences around 200 °C.

4.3. Hot gases temperature distribution under the iron plate

Figure 6-b shows the calculation results for the gas velocity under the plate. There may be noted the effect of centrifuge force that concentrates the gas on the outer wall of the fin and leaves stagnation areas under the plate and bottlenecks for gas flow. The average hot gases speed is around 7 m/s. Figure 6-a has gas temperature distribution under the plate and how such temperature distribution is uneven. At burner exit, point 1, it is close to 450 °C whereas in fin external surface is close to 200 °C.

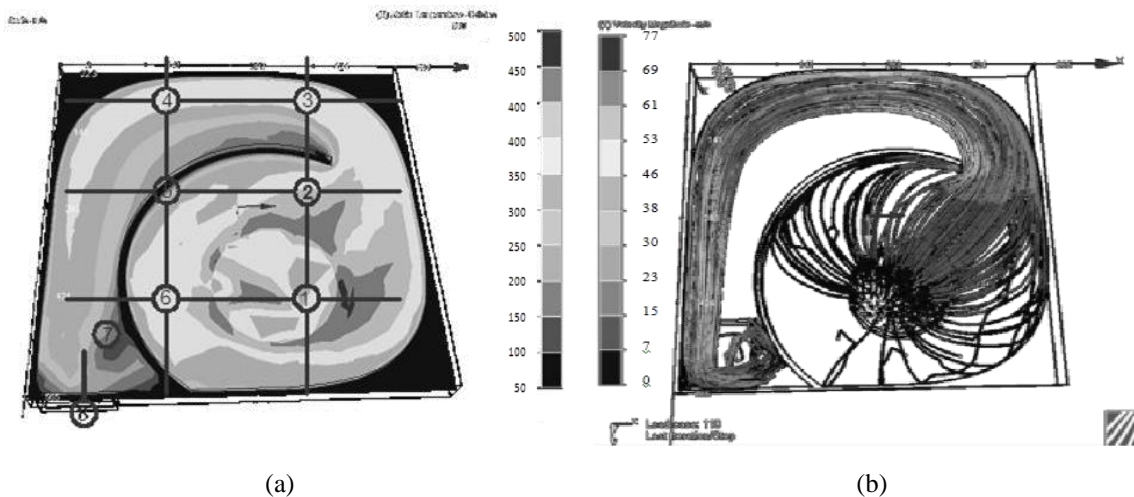


Figure 6. (a) Temperature distribution for the hot gases and (b) Results for hot gases velocity

4.4. Species concentration to flue gases

Using data obtained with Tempest 100, it is observed that the CO concentration was around 0.6%, while CO₂ and O₂ were around 4 and 16% respectively, as shown in Figure 7. The same test showed that the concentration of NO and NO_x were approximately 37.5 and 37.1 ppm, besides presenting a high SO₂ concentration that was around 135.8 ppm. These results indicates that combustion is occurring at very high air excess but the most intriguing is the sulfur source once the fuel does not have sulfur as seen at Table 2. Once the stove plate and its grate are made of cast iron, an investigation on these as source of sulfur was performed.

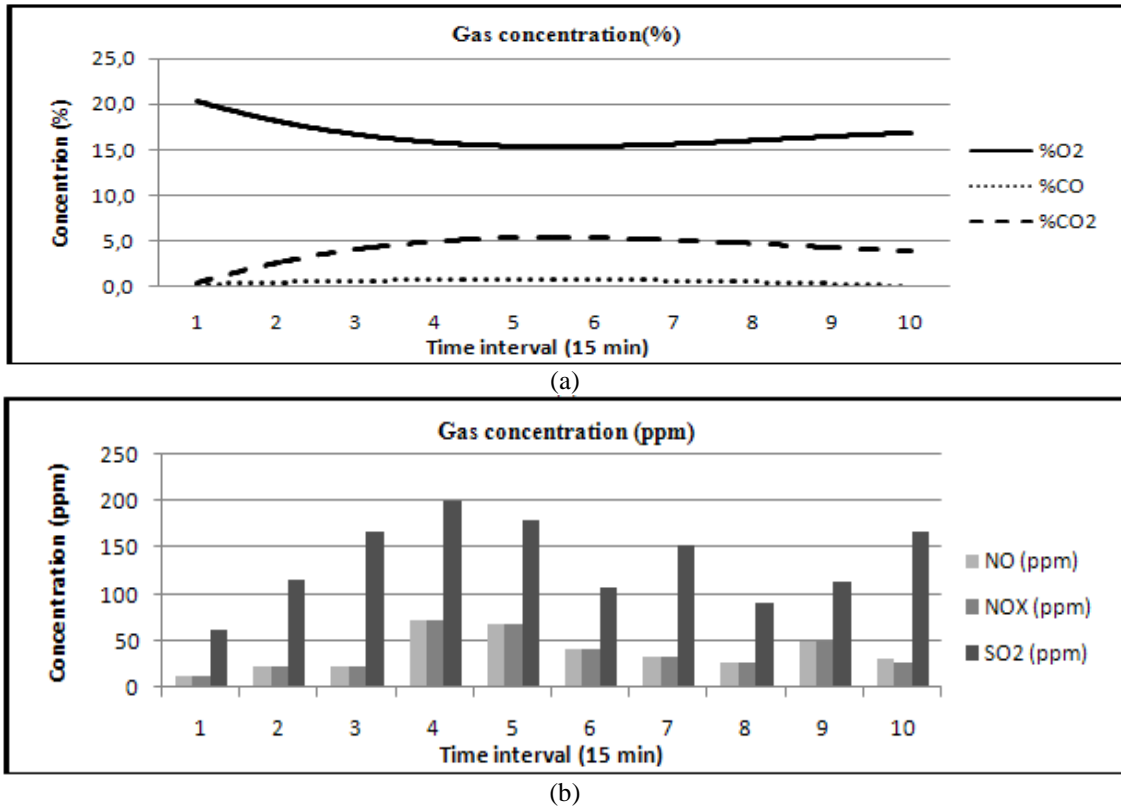


Figure 7. (a) concentration (%) of O₂, CO₂ and CO and (b) concentration (ppm) of NO, NO_x and SO₂.

4.5. Analysis of the metal parts of Ecofogão

4.5.1. Analysis of the sample from plate

A microscopic image at Figure 8 shows that sample is made of cast iron once was found vermicular graphite. The whitish areas indicating the presence of other chemicals that are in higher concentrations than defined in the cast iron standard.

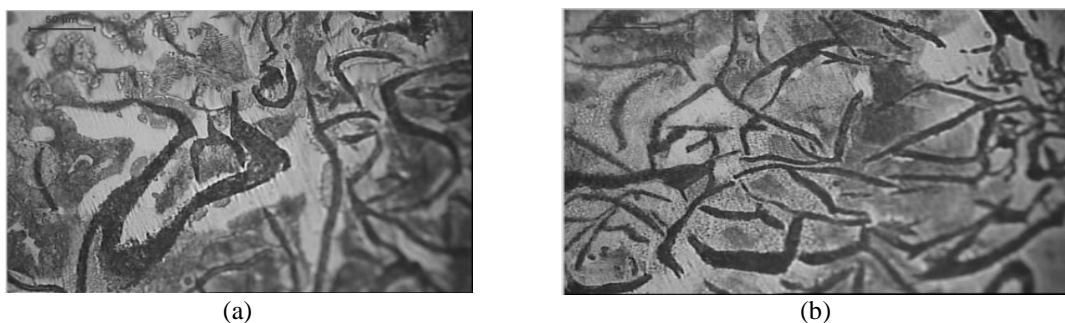


Figure 8. (a) Microstructure of the center of the plate with of fifty times. (b) Microstructure of the end plate with increase of fifty times.

Element concentrations in cast iron plate was determined by a chemical scanning and presented in the Table 3.

Table 3. Chemical elements of cast iron plate by scanning chemical.

	Carbon (C)	Silicon (Si)	Manganese (Mn)	Sulfur (S)	Phosphorus (P)	Chrome (Cr)	Nickel (Ni)
Specification of the elements according to the manufacturer (%)	2.5-4	1 – 3	0.3 – 1	0.05 – 0.25	0.1 - 1	-	-
Mean of the elements on the plate by OES	>3.80	4.70	0.22	0.55	0.06	1.23	0.0055

4.4.2. Analysis of the sample from the grate

In the grate sample was performed a semiquantitative analysis by energy dispersive spectroscopy (EDS). This approach has as the lower limit of detection of 1000 ppm. Results are in the Figure 9.

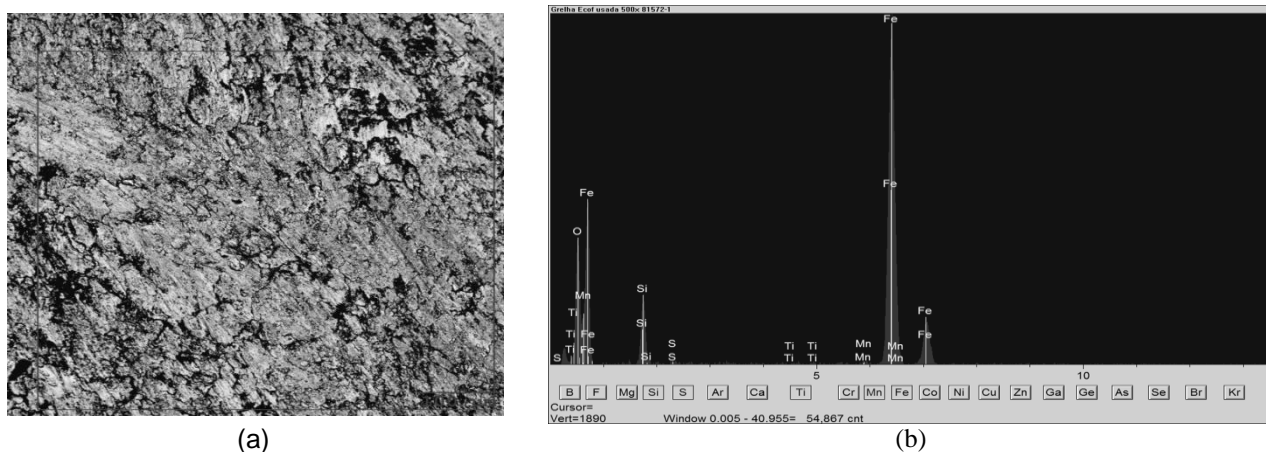


Figure 9. (a) microstructure of the grate (zoom =100); (b) concentration of the grate's elements with EDS.

The EDS showed that there is presence of sulfur in the surface layer of the grate. The measured values for elements concentrations are shown in the Table 4.

Table 4. Chemical elements of the cast iron plate by semiquantitative analysis by EDS.

	Carbon (C)	Silicon (Si)	Manganese (Mn)	Sulfur (S)	Titanium (Ti)	Oxygen (O)	Iron (Fe)
Average concentrations of elements (%)	8.230	3.996	0.692	0.223	0.187	13.414	81.479

5. Conclusion

The result of the gases analysis obtained from the Tempest 100 has shown that the concentrations of NO_x and CO are below the recommended benchmark of 360 and 500 ppm, respectively (Standard 382 of CONAMA, December 26, 2006). The emitted gases showed a high concentration of oxygen, which indicates that the stove worked with a high coefficient of excess air. The gases analysis also showed high emissions of sulfur dioxide.

Although grate and plate have sulfur in its composition, the high concentration of sulfur dioxide present in gases emission originated from the grate. Observing the physical structure of the stove was identified that the grid has suffered a major deterioration, which is a consequence of exposure to high temperatures of the grate. According to data obtained by scanning electronic microscope, sulfur is present in low concentrations on the grate surface, which should come from the smelting process. Due to the high content of silica present in the grate, which is derived from the melting sand, there was the weakening of the material and its deteriorating prematurely, what caused the high concentration range of SO₂.

The chemical analysis of the cast iron plate showed that it contained high concentrations of silicon, about 235% more than the reference concentration of 2% (as shown in Table 3). This demonstrates an exacerbated graphitization of

the material. However, the high concentration of sulfur that was expected, it was not found. This was within the specified. From metallographic analysis, it was found a type of vermicular graphite quantitatively high, confirming the graphitization action of silicon. This action causes the weakening of the structure of the plate to large temperature variations.

Analyzing, the temperatures calculated with the software and those obtained with the pyrometer laser and thermocouple, it was observed that 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 for the plate. Based on results from calculation, 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.

The formation of an area with a large temperature difference between the region surrounding the flip, combustion chamber exit (high temperature zone) and chimney inlet (low temperature), coupled with the high content of silicon present in the composition of material caused a crack on the plate, as predicted by research. The crack is shown in the Figure 10.

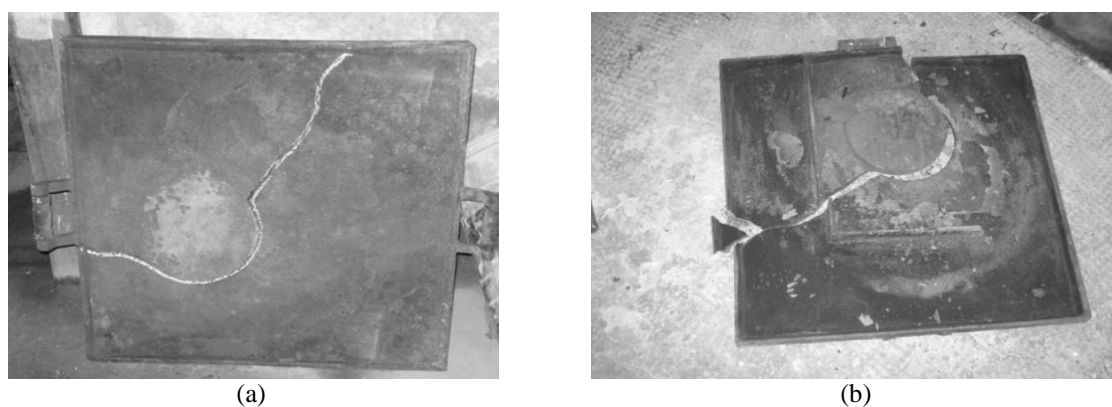


Figure 10. (a) Crack in cast iron plate - top view; (b) Crack in cast iron plate - bottom view.

Since the plate and the grid have high silicon content, both showed damage caused to their exposure to high temperatures variations, in order to address this problem it was recommend that the material used to design these components has a chrome-nickel alloy on its structure and with that withstand this high variations.

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