APPLIED QUANTITATIVE THERMOGRAPHY TO THE STUDY OF THERMAL ENERGY LOSSES IN THE EXTERNAL SURFACE OF OVENS CATENARY

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Abstract. *The present work has as objective to present the use of the Thermography as tool of quantification of the loss of energy of catenary ovens. The ovens used in this work possess useful volume between 400 and 1400 liters, being able to arrive at a temperature about 1300 °C. By using qualitative analysis of the thermic images it was possible to identify critical points in the ovens walls, which allowed to evaluate the behavior of the formulated refractory mass for the isolation in the construction of the ovens. Through the quantitative thermography, it was calculated the total thermal loss through the walls which made possible to infer the thermal efficiency of the ovens. It was adopted, for the calculation of thermal loss, the mechanisms of convection and radiation.*

Keywords*: Thermography,* C*atenary* O*vens, Quantification of the Thermal Losses*

1. INTRODUCTION

Thermography is generically defined as the technical of remote sensing that make possible temperature measurement and the construction of thermal images (thermogram), of component, machine or process, from infrared radiation naturally emitted for the bodies. However, the radiation measured for the camera doesn't depend just of object temperature but also varies in function of the emissivity, (Flir Systems, 2004). RoMiotto (2007), affirm that emissivity is the measure of the capacity of an object in absorbing, transmitting and to emit the infra red energy.

Recently Bezerra et al. (2006) proves that Infrared Thermography has an extensive application witch goes since a simple measured of temperature as well as defects localization in complex systems. However in these applications the thermography searches essentially the losses qualitative of the thermal damages of the processes.

The present work has as objective to present the use of the Thermography as tool of quantification of the energy loss of ovens, through of thermal losses calculation, of this form it is possible to know the efficiency thermal what it can result in a reevaluation of the covering of the oven.

2. CATENARY OVENS

The methodology used for the calculations of thermal quantification had been applied in two constructed catenary ovens in the Universidade Federal de São João Del Rei - UFSJ. Through of engineer adjusted of instrument and construction materials were constructed ovens prototypic that will be reproduced in many craftsman communities of Vale do Jequitinhonha.

The thermograms proceeding from these ovens had allowed the calculation of thermal loss beyond the identification of critical points of abnormal heating.

In the Fig. (1) the first constructed oven (Oven 1) that have a burn volume of the 600 liters, being able to arrive at a temperature of about 1100 °C.

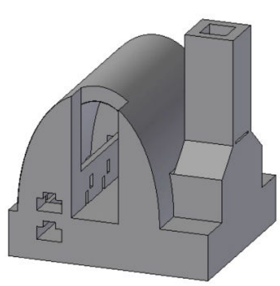

Figure 1. Catenary Oven 1

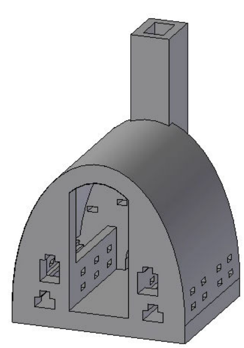

Figure 2. Catenary Oven 2

The Fig. (2) shows another oven constructed (Oven 2) with useful burn volume of the 1600 liters, being able to arrive at a temperature of about 1300 °C.

All the tests had been carried through with both the ovens contend ceramics articles in its interior. According to Norton (1952), about 20% of the supplied useful heat it is used for heating of the ceramics articles.

3. USED PROCEDURES

An infrared camera measures and reproduces through images the infrared radiation emitted from objects. The fact of radiation resulted of temperature and surface emissivity of an object makes possible the camera calculate and shows this temperature, (Flir Systems, 2004).

The radiation of the object and the reflected radiation also will be influenced by the effect of absorption of the atmosphere, of the environment where the object be.

For measure the temperature with precision it is necessary to compensate the effect of one definitive number of different sources of radiation that is made automatically for the camera through the configuration of the value of in the distance between the object and the camera, average temperature reflected by the object and mainly its emissivity.

3.1. Ovens Emissivity Determination

In the tests carried through in the catenary ovens the value of equal emissivity was used the 0.93, gotten from the procedure of attainment through an isolating ribbon settled in the surfaces of the ovens. Measured the temperature of the ribbon, using an equal emissivity the 0.95, was possible to adjust the emissivity of the walls of the ovens and to get the temperature of the same ones. Through the consultation the table of emissivitys offered by the RoMiotto (2007) is possible to find the value for return of 0.95 for a wave length between 7.5 and 13 µm, referring length to the Infrared Camera Flir E65.

3.2. Distance Between Ovens and Camera

The distance between object and the lens frontal of the camera is a used parameter to compensate the radiation absorbed between the ovens and the camera. The thermograms had been made with a lens of 24° and from distances between 1.5 and 7 meters, in accordance with the ideal vertical field of vision that varied between 0.5 and 2.2 meters. These values are in accordance with the relation between fields of vision and distance suggested by the Systems Flir (2004).

3.3. Reflected Average Temperature

The parameter of the average temperature reflected by the object is used to compensate the radiation reflected in the ovens and the radiation emitted for the atmosphere between the chamber and the ovens, (Flir Systems, 2004). As the emissivity of the surfaces of the ovens they are not low, the distances are not great and the external temperatures of the ovens are relatively distant of the environment, were not necessary to compensate the environment temperature.

3.4. Infrared Camera E-65 FLIR

The temperatures of the walls of the catenary ovens had been gotten by the thermograms proceeding from the Infrared Camera FLIR E65, Fig. (3). The camera possesss thermal sensitivity of 0.10°C to 30°C, Focal plane detector, microbolometer without refrigeration of 160 x 120 pixels and spectral amplitude between 7.5 and 13 µm. Recently SKF (2008) demonstrates that this equipment allows, among others things, the identification of a maximum temperature of 900°C.

Figure 3. Infrared Camera E-65 FLIR

For the assembly of some collected images software Image Builder was used. The support software ThermaCAM Reporter 7.0 was also used, it allowed the accomplishment of analyses more detailed of the thermograms and assembly of data bases for analysis.

3.5. Thermography Aplication Methods

According Rezende Filho (2007), the thermography can be qualitative or quantitative depending on the application. The Qualitative Thermography is used when it interests it is the profile and not them presented thermal values.

This is the characteristic that classifies the infra red thermography as one technique that supplies instantaneous report. The Quantitative Thermography defines the level of gravity of an anomaly.

Using qualitative analysis of the thermograms it was possible to identify critical points in the walls of the ovens, that are not possible to identify in a visual inspection, what it allowed to evaluate the behavior of the formulated refractory mass for the isolation in the construction of the ovens. In the construction of oven 1 fissures in the surface appeared of the walls, Fig. (4).

These imperfections had been, apparently, cured with the replacement of refractory mass, as it shows the Fig. (5).

Figure 4. Fissure in the wall of the Oven 1

Figure 5. Replacement of refractory mass

However, through the thermograms of the Fig. (6) it was possible to identify, through the areas clearest, damages due to the construction defects.

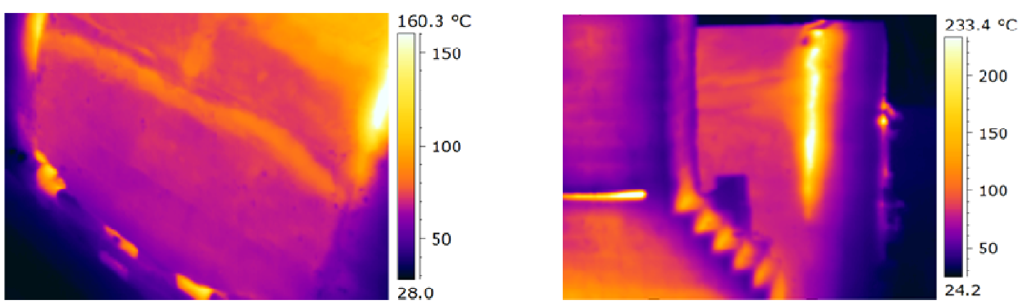

Figure 6. Critical points on Oven 1

Also critical points in the walls of Oven 2 had been identified. The Fig. (7) shows, by means of the areas clearest, few critical points caused by probable fictions in the internal covering. It can be considered as “critical points” the orifices of air circulation of the oven, since through these a bigger loss of thermal energy is had.

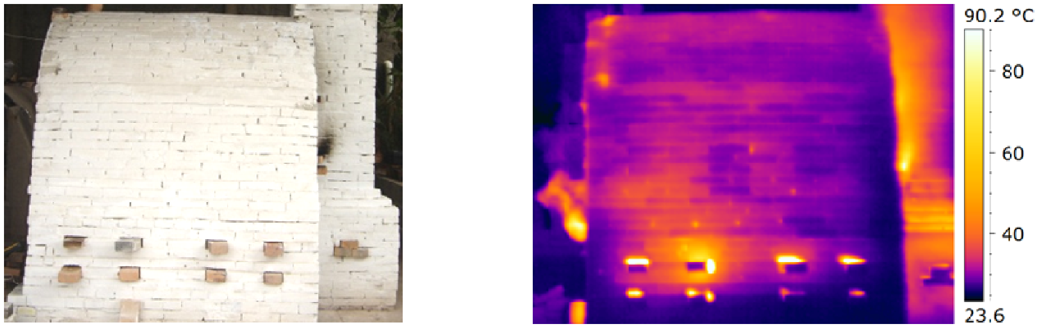

Figure 7. Critical points in the surface of Oven 2

Still it is possible to identify through the thermogram of the Fig. (7) an area, next the furnace (corner left lower of the thermogram), where the fuel was being deposited, what it was corrected with the distribution more homogeneously for the furnace.

Already by means of the quantitative thermography, it was calculated total thermal loss for the walls what it made possible to infer the thermal efficiency of the ovens. It was adopted, for the calculation of thermal loss, the convection and radiation mechanisms.

3.6. Convection and Radiation Mechanisms

For the calculation of thermal loss the method of convection and radiation mechanisms was adopted. From the temperature of the heating areas of the ovens walls, gotten for the thermograms, the lost amount of heat for the surface was calculated. That is possible through the Eq. (1), where Q_{Total} is the total amount of lost heat, $Q_{Convection}$ is the amount of lost heat for convection and $Q_{Radiation}$ is the lost amount of heat for radiation.

$$Q_{Total} = Q_{Convection} + Q_{Radiation} \tag{1}$$

The loss of energy for convection in the external wall of the oven was determined by the Eq. (2), through the distribution of temperatures of the thermograms, proceeding from the software of ThermaCAM Reporter 7.0, where $h_{Convection}$ the coefficient of transference of heat for convection, $T_{(x,\,z)}$ is the temperature (supplied for the thermograms) of each analyzed area, T_{air} is the temperature of air; and A is the area submitted to the analysis.

$$Q_{Convection} = \int_{Area} h_{Convection} \cdot \left(T_{(x,z)} - T_{air}\right).dA \tag{2}$$

The loss of energy for radiation in the external wall of the oven will be determined by the Eq. (3), respectively, through the distribution of temperatures of the thermograms, where σ is the Stefan-Boltzman constant equal to 5.67×10^{-8} (W/m² k^4), $\varepsilon\ (\lambda,T)$ it is the emissivity and T_{mr} is the radiating average temperature (average temperature reflected of the surfaces that changes heat for radiation with the external wall of the oven). In the calculations the T_{mr} is considered equal the ambient temperature.

$$Q_{Radiation} = \int_{Area} \sigma\,.\varepsilon(\lambda,T).\left(T^4{}_{(x,z)} - T^4{}_{mr}\right).dA \tag{3}$$

4. ANALYSIS OF THE EXPERIMENTAL RESULTS

For development of the mathematical models of heat exchange, the present work shows the described methodology for Ozisik (1990).

The quantification of the loss of energy has for objective to allow the control of the amount of heat changed for equipment with the environment, in function of its operational conditions and state of the covering. This data are of great importance to know its thermal efficiency or for the taking of decision how much to the exchange or repair of isolating coverings.

For the accomplishment of this task algorithms based on the convection theories and radiation had been developed, implemented in Excel. This applicatory one allowed, from the temperatures taken external for thermography, the calculation of the number of calories, changed with the environment in data period of time.

4.1. Quantification of Thermal Loss in the Ovens Catenary 1 and 2

In the analyses the ovens had been divided in five regions, VIEW A, B, C, D and the Chimney, in accordance with the Fig. (8).

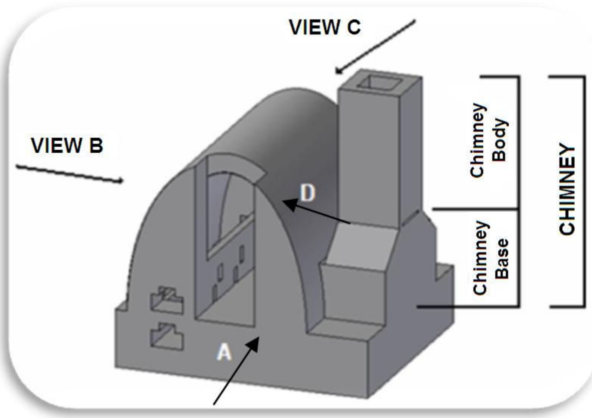

Figure 8. View A,B,C,D and the Chimney

The chimney, analyzed separately of the oven walls, was divided in two parts, the Body of the Chimney and the Base of the Chimney, Fig. (8). The Base of the Chimney of Oven 1 still was subdivided in five regions, VIEW A', B', C', D' and E', as it demonstrates the Fig. (9), already the Base of the Chimney of Oven 2 was subdivided in six regions, VIEW A", B", C", A" Inclined, B" Inclined and C" Inclined, Fig. (10).

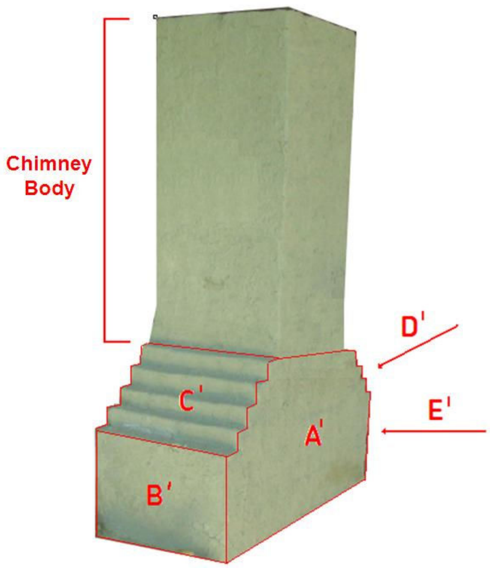

Figure 9. Chimney View, Oven 1

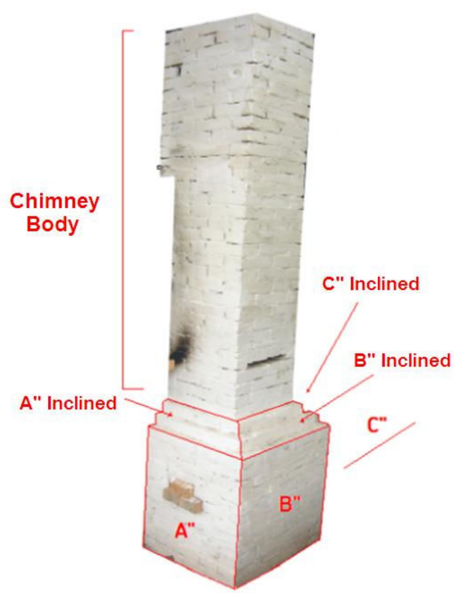

Figure 10. Chimney View, Oven 2

The View C', D', A" Inclined, B" Inclined and C" Inclined had been analyzed taking in consideration an angle of equal inclination 45°. In the case of views B and D of both the ovens equal inclination was also considered 60°. The temperatures used for the calculations of thermal exchange correspond to the average temperatures of each view.

For the development of the mathematical models the walls of the ovens had been considered vertical plates. The regimen adopted for the calculations must be of Free Convection, according to criterion for the establishment of the described regimen of convection for the Tab. (1), where *Gr* is the Grashof number and *Re* is the Reynolds number, (Incropera, 1993).

Table 1. Criterion for Establishment of the Convection Regimen

Criterion	Convection Regimen
$Gr/Re^2 >> 1$	Free
$Gr/Re^2 \approx 1$	Combined
$Gr/Re^2 << 1$	Forced

Free or Natural convection does not suffer action from external Operatrizes Forces, (Incropera, 1993). The speed of the wind in the place of construction of the ovens is worthless. Exactly considering an equal speed the 1 m/s, speed raised for the environment, the relation enters the Grashof number (*Gr*) and of Reynolds (*Re*), for Oven 1, it would be greater that 1 for any one of the seen, that in accordance with the Tab. (1) still would belong to the free regimen of convection.

With temperature of the environment and the temperature of the surface of the ovens, the Thermal Expansion Coefficient calculation is possible (β, ^{-1}K), express for the Eq. (4) where T_f is the Film Temperature (arithmetic mean enters the temperature of the wall of the oven and the environment temperature).

$$\beta = \frac{1}{T_f} \tag{4}$$

The calculation of the number Reynolds (*Re*) is described for the Eq. (5) where v is the Speed of the Draining (speed of the wind, m/s), L is the height of the catenary and υ is the Viscosity Kinematics of the Fluid in question (air, m^2/s). As the regimen of convection submitted for the catenary ovens it is of Free Convection the Reynolds number was used in this case as only indicating of the type regimen.

$$Re = \frac{v.L}{\upsilon} \tag{5}$$

The Grashof number (*Gr*) is calculated by the Eq. (6) where g is relative to the Gravity Force considered equal the 9,81 m/s^2, T_w the Walls Average Temperature of the Ovens (K) and T_∞ is considered the Ambient temperature (K).

$$Gr = \frac{g.\beta.L^3(T_W - T_\infty)}{\upsilon^2} \tag{6}$$

The Grashof number represents the reason between the push and the force viscose that acts in the fluid, the same exerts paper of the Reynolds number in the forced convection.

The Rayleigh number (*Ra*) represented by the Eq. (7) where *Pr* is the Prandtl number.

$$Ra = Gr.\Pr \tag{7}$$

Through the number of *Ra* the number of *Nu* (Nusselt) more appropriate is determined in accordance with the theory that better describes the behavior of the ovens, Eq. (8) where c and n are constant of the Tab. (2), that they vary in accordance with draining regimen (Laminar/Turbulent), (Ozisik, 1990).

$$Nu = c.Ra^n \tag{8}$$

Table 2. Constat c and expoente n of the Eq. (8)

Draining Type	*Ra* Domain	*c*	*n*
Laminar	10^4 a 10^9	0,59	1/4
Turbulent	10^9 a 10^{13}	0,10	1/3

The *Ra* behaves, in this in case that, as a “contour condition”, that it determines which the draining regimen, in the case of the walls of Oven 1 and to 2 (View, B, C and D) the regimen of draining is turbulent. Already in the case of the chimney of Oven 1 and 2 the regimen is Laminar to plate for the Base of the Chimney and Turbulent for the Chimney Body. This behavior if kept for all the functioning conditions.

Through the value of Nu the Convective Coefficient (*h*) was calculated adjusted, Eq. (9) where k represents the Thermal Conductivity of the Fluid (W/m.K), what allowed, from the Eq. (2), the calculation of the amount of heat changed with the way by means of the convection ($Q_{Convection}$).

$$h = \frac{Nu.k}{L} \tag{9}$$

The described procedures for this calculation had been carried through for all the views of the evaluated ovens. Pr, k and υ are determined thermophysical properties of the fluid from T_f.

With the calculation of the $Q_{Convection}$ the $Q_{Radiation}$ (3), it was possible to get, through the Eq. (1), the total amount of lost heat for the surfaces of each analyzed view. What it allowed the calculation of the rate of heat loss for each view in relation to the supplied energy, for the burning of the fuel. According to Chiti (1992), in a typical burning they are expenses 5 kg of firewood for the moment, liberating of 17.500 the 22.500 kcal/h, for Pinus. The average value of 20.000 kcal/h what it corresponds 23.260 W of supplied heat, for Oven 1 was adopted. In the calculation of the heat supplied Oven 2 the real value of fuel flow was used, with a average of 33,8 kg consumed for the moment (first hour 43,2 kg, second 28 kg, third 48 kg and fourth 84 kg), considering an average PCI of the used wood equal 5000 kcal/kg. All fuel mass (wood) was weighed, in way to be to get the fuel flow for the feeding of Oven 2.

The addition of all the referring rates of energy loss to each view, resulted in the Total Rate of Heat Loss for the surfaces of the ovens, equal 16.7% for the walls and 10.9% for the surfaces of the chimney, values for an only readiness with internal temperature between 800°C and 900°C for Oven 1, case are considered the inclination of the walls of Views B and equal D 60° the Rate of Loss will be equal 15.33%. The referring thermograms to Oven 2 had been collected in four different readinesses what it allowed the construction of the curve represented for the Fig. (11), where have it in accordance with Total Rate of Heat Loss the alteration of the internal temperature, at the moments (intervals of time of approximately 1 hour) called Hour 1 (270°C), Hour 2 (430°C), Hour 3 (530°C) and Hour 4 (600°C). Until moment 3, the Loss Rate in accordance with increases the increase of the internal temperature.

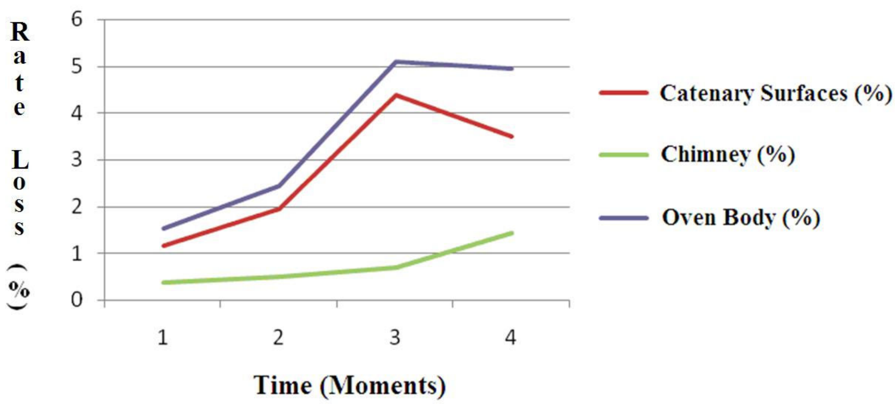

Figure 11. Rate of heat loss in relation to the increase of the oven 2 internal temperature

According to Fig. (11), after moment 3, exactly with the addition of 84 kg of mass until moment 4, has a decrease of the Total Loss Rate, which had to the increase of the ambient temperature and mainly which had to a fall in the temperatures of the oven walls (proceeding from the thermograms). It adds this fact the determine of the displacement of the biggest points of temperature for the region of the oven chimney, also with fire the visual flare perception leaving for the same one, allowing to infer an increase of the heat loss for the chimney, fact this demonstrated with the values of the temperatures of the Tab. (3) and green curve analysis (losses for the chimney) of the Fig. (11).

Table 3. Chimney Temperature Increase

Moment	Temperatures (°C)						
	A”	B”	C”	A” Incl.	B” Incl.	C” Incl.	Body Chimney
3	41,9	44,6	45,9	63	70,9	68,6	45,73
4	75,5	79,9	79,4	110,2	111,6	117,1	72,93

This behavior if must to a probable asymmetry in the construction of the Chimney that at the moment between 3 and 4, “banished” part from by vol. useful the present heat of the catenary, what it explains the fact of the maximum project temperature of Oven 2, about 1300°C, not to have been reached. Exactly taking in consideration the consequences of this asymmetry, Oven 2 presented Total Rate of Thermal Loss in the four operational conditions, in accordance with the Tab. (4) for the surfaces of the catenary, chimney and all the oven body, very lesser in relation to the results demonstrated for Norton (1952) and Olsen (1983).

Table 4. Rate of Heat Loss for the Oven 2 Surfaces

Rate of Heat Loss(%)	Moment			
	1	2	3	4
Catenary Surfaces	1.157	1.9344	4.385	3.497
Chimney	0.368	0.492	0.696	1.425
Oven Body	1.525	2.4264	5.081	4.922

According to Norton (1952), the heat loss of catenary ovens more efficient that uses for the burn 5 kg of firewood for hour, is generally equal 18% of loss for the walls. This information demonstrates that the methodology used for analysis of the thermal losses in the two archetypes of ovens was adjusted and that the techniques and materials used in the construction of the Oven 1 and Oven 2 reveal sufficiently satisfactory.

5. CONCLUSION

With conceptual beddings firmly established, this work is dedicated to the development of useful instrument for the thermal loss quantification in ovens.

The accomplishment of thermal images of the external oven wall is an efficient aid, as much for the detention of defective areas, not considered in the simulation of the energy balance, how much for the possibility to quantify the energy losses of these areas. This procedure allows to the taking of decision how much to the repair or substitution of the covering of an oven.

The analysis of the thermal behavior of such ovens, through the thermograms, makes possible the determination of the operational limits and degree of possible covering deterioration. Through the analysis of the thermograms it is possible to diagnosis the behavior of the formulated masses that had been used as isolation of the catenary ovens aiming at its optimization. The implementation of the used methodology allowed to quantify the energy loss and to know the efficiency thermal of the ovens surfaces evaluated.

6. ACKNOWLEDGEMENTS

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