SENSITIVITY ANALYSIS APPLIED IN ESTIMATION OF GEOMETRIC PARAMETERS FROM DATA OBTAINED BY INFRARED THERMOGRAPHY DURING SAMPLE COOLING

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Abstract. *The main objective of this work is to perform a sensitivity analysis of geometric parameters of an inclusion in a gypsum board during the cooling process. Previous work showed experimental results of transient temperature distribution recorded by an infrared camera. Based on these experimental data and numerical simulations it was possible to estimate both thermophysical properties of the sample and geometric parameters of a steel inclusion in the sample. A differential of this paper is the sensitivity study before parameters estimation. In previous works the estimation was made only by fitting the experimental and numerical curves. It was not taken into account the best time to perform the experiments. In this work, new computational simulations are performed to determine the best time to capture the experimental data. These optimal times are determined from a sensitivity analysis of parameters to be estimated. Thus, from the study proposed here is possible to design optimal experiments, where the duration of measurements includes the best time found. As an example, it was estimated geometric parameters (radius, height and center) of a steel cylindrical inclusion in a gypsum board. The results were good and for the highest parameter sensitivity (height of inclusion) was found the lowest error of estimation.*

Keywords*: Sensitivity Analysis, Geometric Parameters, Infrared Thermography.*

1. INTRODUCTION

The infrared thermography is a technique for non-destructive testing to obtain thermal images of bodies. The two main types of thermography are active and passive. In active thermography it is necessary to heat the object with an artificial heat source. After heating, analysis of thermal behavior of the body during cooling is made. In passive thermography, the object is already heated by the process being studied, e.g. in an industrial furnace or human body. Qualitative analysis are made to detect areas with problems such as electrical installations or parts of body (human or animal). Quantitative analysis are those in which temperature data extracted from thermograms are used to calculate the heat losses in an equipment or as information to the solution of inverse heat conduction problems (IHCP), for example.

A frequent use of thermal imaging is the detection of failures. Dattoma et al. (2001) use the thermographic analysis to determine failures in wind turbine blades. Meola et al. (2004) present some experiments aiming at the discrimination of materials from their distinct thermal behavior detected by thermography.

Due to the relatively low accuracy of thermography, there is great concern about the importance of information processing. Some techniques and signal processing are presented by Rainieri and Pagliarini (2002) and Ibarra-Castaneda et al. (2004).

Among many works of parameter estimation, particularly thermophysical properties, are Douzane et al. (1999) and Huang and Tsai (2005). Two works can be detached: Huang and Chin (2000) in determining the thermal conductivity from thermography in a two-dimensional plate; and Niliot and Callet (1998), a review of methods for solving inverse problems. The difference is that this last work is being interested in boundary conditions instead of thermophysical and geometric parameters.

Since 2005, several studies have been conducted in the area of thermography in UFPE. Magnani et al. (2005) presented a study on the applicability of thermography in tropical regions. Some of them are: (a) visualization of thermal processes such as mixing of liquids at different temperatures and drying of a gypsum board; and (b) engineering applications, such as detecting loose covering of the building facade and infiltration air in a refrigerator. It was found that the tropical regions have a special feature during the night: there is a proximity between the temperatures of the human body and soil. Although thermography is widely used to detect people in temperate and cold climates, it presents difficulties in hot climates. Da Silva et al. (2006b) present some uses of thermography in detecting failures. Thermography can be used qualitatively to identify failures and different materials used in restoration of historical monuments, and viewing hot spots in electrical installations. And quantitatively, to determine heat losses of in some parts of a large industrial equipment. Da Silva et al. (2006a) show an energy analysis of a billet heating furnace with the aid of thermography. A comparison is made between: (a) the energy balance of the furnace simulated computationally and considering a single temperature for the entire outer wall; and (b) the energy balance achieved by the oven temperature data of thermal imaging equipment from outer wall. It was observed a difference between the two methods because the computational method do not take into account energy losses detected by thermography. Bezerra et al (2006) present a detailed study of the influence of parameters that must be set in an infrared camera to obtain reliable measurement results. Measurements were taken on a generator of radiation at various distances and temperatures. An important result was a low random error in measurements. It was observed that the relative humidity is an important parameter because it may have been responsible for variations in the results of thermography.

Infrared thermography applications in engineering and determination of geometric and thermophysical parameters of materials were part of the work of da Silva (2007). Qualitative applications of thermography are presented, as vizualization of: (a) basic phenomena as sheet of paper drying, (b) temperatures of fluids in heat exchangers, (c) natural gas flame, and (d) problems with the insulation of large industrial equipment (boilers, furnaces, etc.). The application relates to the quantitative determination of geometric and thermophysical parameters of materials. It was used the temperature data of thermal imaging to solve an IHCP.

Da Silva and Magnani (2006) used infrared thermography for detection of failures in gypsum boards. Experiments were performed with gypsum sample and gypsum samples with a steel cylindrical inclusion. After heated in oven, the temperature of the sample surface was recorded by an infrared camera during the cooling process. Comparing the temperatures of the two samples it was verified the sensitivity of the infrared camera to detect the inclusion.

In Magnani and da Silva (2007) it was presented an application of infrared thermography in determining the geometric and thermophysical parameters. The experiments were performed with the same samples and as the same way of da Silva and Magnani (2006) were. To determine the parameters, the cooling process was simulated computationally. From the adjustment between the curves of the numerical and experimental results could be estimated: (a) heat capacity and thermal conductivity of gypsum, (b) heat capacity of steel, (c) radius, height and center of the steel inclusion.

This paper is an extension of the work of Hora and Magnani (2009), where it was performed sensitivity analysis for the determination of thermophysical parameters of cylindrical inclusions in square boards. For parameter estimation problems, an important point of the process is sensitivity analysis. Sensitivity indicates how much the measured variable is changed according to variation in the parameter to be estimated. This study permits to find the best time to capture the experimental data and to assess the vulnerability of the IHCP to measurement errors. In the present study it was performed a sensitivity analysis to determine geometric parameters of an inclusion in a square board. The pairs sample/inclusion analyzed were: gypsum/steel, concrete/brass and steel/gypsum. A additional study was the estimation of radius, height and center of a steel cylinder included in a gypsum board, based on the sensitivity analysis performed for this sample.

2. METHODOLOGY

The work is divided into two stages: (a) sensitivity analysis of geometric parameters (radius, height and center of inclusion) for three pairs of samples with a cylindrical inclusion; and (b) estimation of geometric parameters of a steel inclusion in gypsum sample.

2.1. Sensitivity Analysis

Sensitivity analysis should be done before the solution of an IHCP. The study is important primarily because two factors. Firstly from sensitivity assessment it can be determined the best time to perform the experiments. The best time, also called optimum time is that which corresponds to the maximum value of sensitivity. It is guaranteed that at that moment, the parameter will be estimated to have maximum influence on the measured variable. Moreover, finding the best time it is possible to design optimal experiments where the execution period covers the time when the sensitivity is greater. The second factor is the identification of magnitude of the parameters sensitivities. If the sensitivity of a geometric parameter is high, it means that we need a small change in the geometric parameter to have a large variation in temperature. This indicates that the inverse problem is not sensitive to measurement errors and precise estimations of the parameters can be obtained. In cases of low sensitivity it is required a large variation in geometric parameters to obtain a small variation in mean surface temperature. In such cases, the parameter estimation is difficult because almost the same value of mean surface temperature can be obtained for a enormous range of geometric parameters values.

The sensitivity of each geometric parameter was calculated according to Eq. (1). It's an important relationship because it provides information how changes in (y) affects the value of (x). When used for parameter estimation, usually (x) is the measured variable (surface temperature in this case) and (y) is the parameter to be estimated (radius, height and center in this case).

$$S(x, y) = \frac{\Delta x}{\Delta y} . \frac{y}{x} \tag{1}$$

where:
S (x, y): sensitivity of *x* with respect to *y*;
x,y: parameters.

To illustrate how the sensitivities of the geometrical parameters were calculated, the Equation (2) gives the sensitivity of the mean surface temperature (T) with respect to the radius of the inclusion (r).

$$S(T\ ,r)=\frac{\Delta T}{\Delta r}\cdot\frac{r}{T} \tag{2}$$

where:
S (T, r): sensitivity of *T* with respect to *r*;
ΔT: change in mean surface temperature (°C);
Δr: variation of the radius (m);
T: mean temperature of the sample surface (°C);
r: radius of the inclusion (m).

The parameter (r) is varied to verify the influence in (T). Considering a 10% variation in the radius of inclusion, Δr = 0.1, the sensibility is:

$$S(T\ ,r)=\frac{\Delta T}{T}\cdot\frac{r}{0{,}1\,r}=\frac{Tf-T}{T}\cdot\frac{r}{0{,}1\,r}=10.\frac{\Delta T}{T} \tag{3}$$

In Equation (3) the term ΔT is the difference between the simulated mean surface temperature for the radius in the nominal value (T) and the simulated mean surface temperature with the change of 10% in the radius (Tf). The value of (Tf) is determined from simulations with the new value of the radius of inclusion. After the calculus of the mean surface temperatures for each time of the simulation, it is possible to construct the graph of sensitivity versus time.

2.1.1 Samples Analysed

In studies performed by Hora and Magnani (2009), six samples in form of square board were analysed: (a) gypsum sample; (b) gypsum sample with steel inclusion; (c) concrete sample; (d) concrete sample with brass inclusion; (e) steel sample; and (f) steel sample with gypsum inclusion. These materials were chosen for two reasons: (1) availability in the place of the studies, and (2) easy preparation of samples. The sample's size being studied is illustrated in Fig. (1).

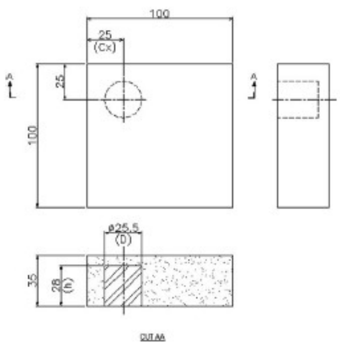
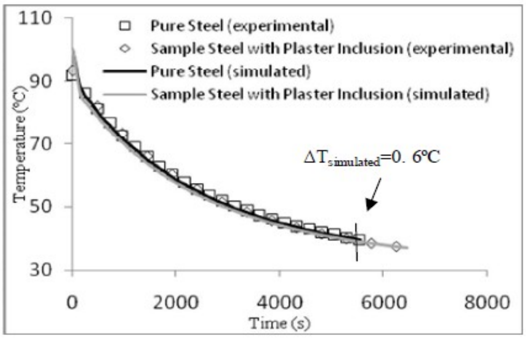
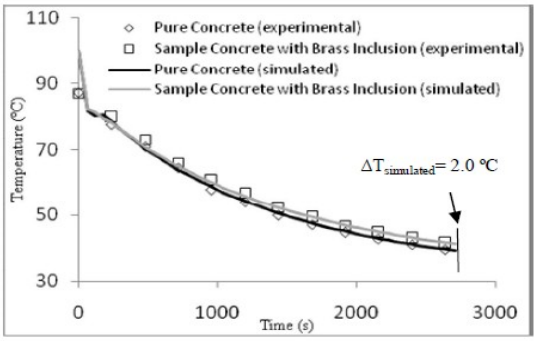


Figure 1 - Dimensions of the sample with inclusion (values in mm)

Simulations were performed to determine the effect of the cylinder included in the surface temperature of the board.Graphs of mean surface temperatures of samples with and without inclusion are shown in Figures (2) and (3). This analysis allowed to identify which samples could be used with an infrared camera resolution of 0.8 °C. Although the cylindrical inclusion of gypsum have a few influence (only by 0.6 °C) in the mean surface temperature of steel sample, it was performed to assess the drawback of this small deviation in the solution of inverse problems.

In the present work three pairs of sample/inclusion were studied: (a) gypsum sample with steel cylinder; (b) steel sample with gypsum cylinder; and (c) concrete sample with brass cylinder. These samples were the same of the work of Hora and Magnani (2009). For each sample, an analysis of the sensitivity of geometric parameters was done. The simulations were done with geometric parameters in the nominal values of the sample and with these parameters changed 10% to analyze the influence of this variation in the surface temperature of the sample.





(a) (b)

Figure 2 - Comparison between the evolutions of the experimental and simulated surface temperatures: (a) samples of steel and steel/gypsum, (b) samples of concrete and concrete/brass (extracted from Hora and Magnani (2009)).

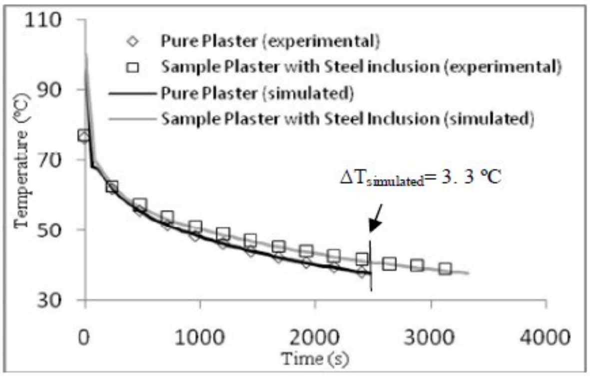


Figure 3 - Comparison between the evolutions of the experimental and simulated surface temperatures for the samples of gypsum and gypsum/steel (extracted from Hora and Magnani (2009)).

2.2. Geometric Parameters Estimation

The technique proposed here for estimating the parameters basically consists in recording the surface temperature of a sample during its cooling with an infrared camera, computationally simulate the phenomenon and change geometric parameters to minimize the deviation between the experimental and numerical results. To estimate geometric parameters of gypsum sample with steel cylinder, experimental results of Hora and Magnani (2009) were used. The experiments consisted of: (a) heating the sample in an oven to temperature of 100 º C; (b) remove from oven and place on a base; (c) recording the thermal images of the samples cooling with an infrared camera (Model S45 FLIR Systems); and (d) processing the thermograms for the extraction of data from surface temperature of the sample. For the recording of the thermal images the emissivity considered is 0.95. This value is relative to the emissivity of a black plastic ink that was used to paint the surface of the sample.

Figures (4) (a) and (4) (b) show how the sample was positioned at the base and as the infrared camera was positioned over the sample and the inclusion, respectively.

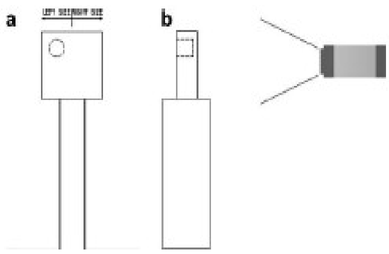
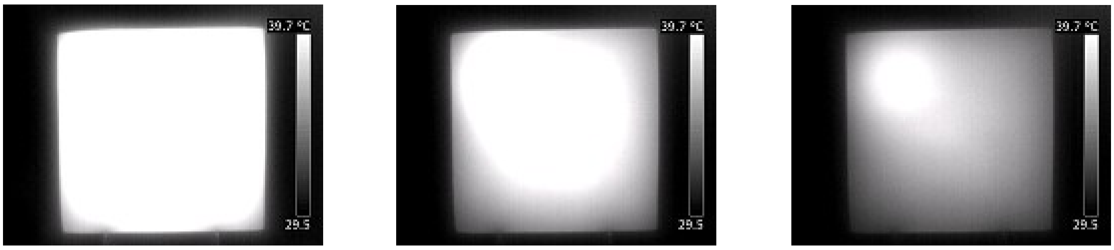


Figure 4 - (a) Positioning of the sample at the base, (b) Positioning the camera in relation to the sample.

Figure (5)(a)-(c) shows thermal images of gypsum sample with steel inclusion in 15, 30 and 45 minutes, respectively, after the beginning of sample cooling. It can be noticed that the cylinder is well highlighted as it approaches the end of the experiment at 3.300s. In these themograms lighter regions represent higher temperatures.

Thermograms of sample cooling were processed for extraction of temperature data by two computer programs. The first program extracts the data from the thermogram as gray scale and .GIF format, associates each image pixel at a temperature and builds an array with the values of surface temperature of the sample. The second uses the data from arrays of temperature and makes the calculation of the mean surface temperature of the board.



(a) (b) (c)

Figure 5 – Thermal images of the cooling of gypsum sample with steel cylinder: (a) 15 minutes, (b) 30 minutes (c) 45 minutes.

In this paper, the index used to determine the parameters is the mean surface temperature of the sample been cooled. To determine the surface temperature, simulations of the sample cooling in the form of square board with cylindrical inclusions were performed.

To cooling modeling, initial temperature of sample is set to 100 ° C and the thermophysical properties of materials are considered constant and uniform. In determining the coefficients of natural convection correlations were used those of Kreith (2000) for vertical, horizontal upper and lower horizontal surfaces of the board. These correlations are showed in Appendix A.

Because manipulation to remove samples from oven to base, convection coefficient is increased by ten times at the beginning of the simulation due to forced convection at that moment. It was verified that this increase in the coefficient of convection at the very beginning has no effect on the distribution of final temperature of the sample surface. Mathematical modeling is discretized using finite volume method with a regular and uniform grid, using fully implicit discretization of time. The coefficients of natural convection are calculated at each step of time according to the distribution of surface temperature.

From the fit between experimental and numerical curves, radius, height and center of the inclusion were estimated. This fit was done separately for each parameter, keeping the others constant. Then, new simulations were performed to find the deviation of the estimation. The parameters estimated were varied to obtain a difference of 1 ° C (accuracy of the infrared camera), in the best time, between the experimental and simulated mean surface temperatures.

3. RESULTS AND DISCUSSION

3.1 Sensitivity Analysis

Figure (6) illustrates the sensitivity of the mean surface temperature of the sample respected to the radius of inclusion, S (T, r).

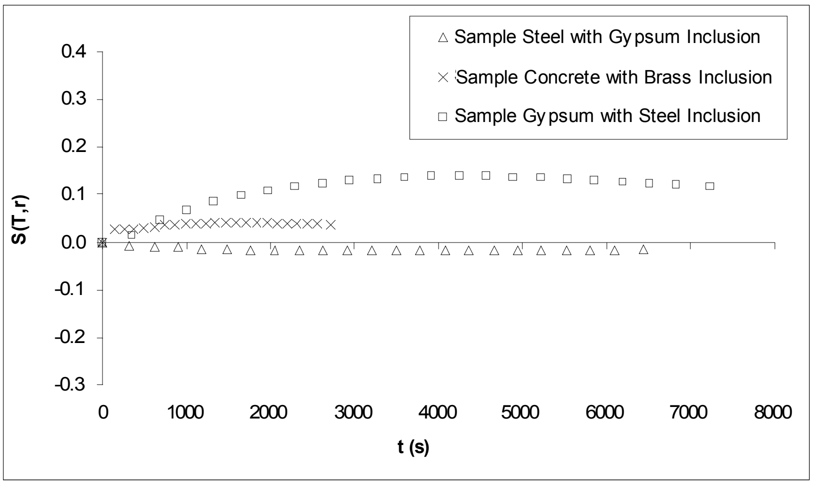


Figure 6 - Sensitivity analysis for the radius of inclusion.

One can observe in Fig. (6) that the pair sample/inclusion that has greater sensitivity is gypsum/steel. The best time for the determination of this parameter is 4.146s after the begining of the cooling where the sensitivity reaches a value of 0.1378. The sample of concrete with brass cylinder has a lower sensitivity than the sample of gypsum with steel, reaching in 1512s the value of 0.0414. The pair steel/gypsum had the lowest sensitivity to mean surface temperature, reaching a value of -0.0181 at time 3466.8s. Positive values of the radius sensitivity signify that the mean surface temperature of the sample increases when this parameter is increased. Negative values signify that the mean surface temperature of the sample decreases when the radius is increased.

Figure (7) shows the sensitivity respected to the height of the cylinder inclusion, S(T,h). It can be seen that the pair gypsum/steel has greater sensitivity than others one. The sensitivity reached a value of 0.3559 at time 1.221s. The pair concrete/brass showed the value of 0.0495 for sensitivity in 1417.5s. Notice that for steel sample with gypsum inclusion, the sensitivity remains low also for height, reaching a value of -0.0099 at time 2856.9s.

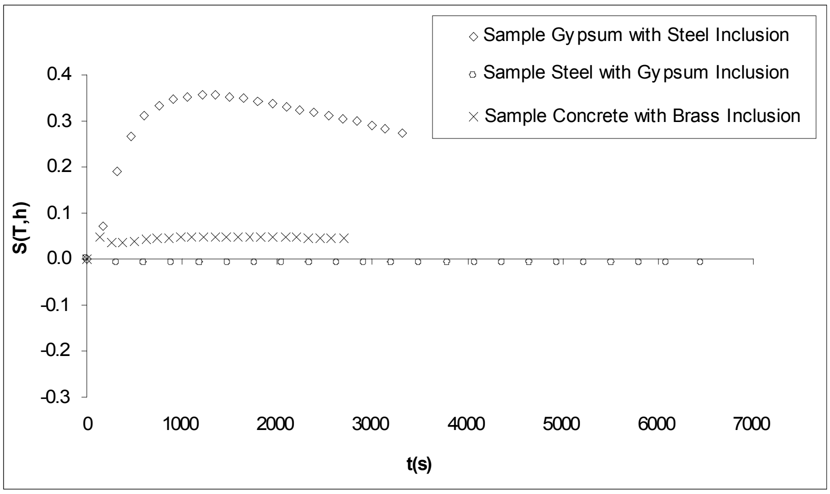


Figure 7 - Sensitivity analysis for the time of inclusion.

Figures (8) and (9) show the sensitivities of the center of the inclusion S (T,c). Two studies were performed (a) varying the center of the inclusion in the diagonal direction upwards, in other words, increasing both abscissa and ordinate (Figure (8)); and (b) varying the center of the inclusion in diagonal downward direction, i.e., by decreasing both abscissa and ordinate (Figure (9)).

In Figure (8) positive values of the sensitivity of the center signify that the mean surface temperature of the sample increases when this parameter is increased, and negative values signify the mean surface temperature of the sample decreases when the center is increased. For gypsum/steel sample, the best time was 4212s and the sensitivity was - 0.2435; for concrete/bass sample in the best time of 918s the sensitivity was - 0.0327, and for steel/gypsum sample in the best time of 2889s the sensitivity was 0.0076.

In Figure (9), positive values signify an increase in mean temperature of sample surface when the center coordinates are reduced, and negative values indicate that sample mean surface temperature decreases when the center coordinates are decreased. For gypsum/steel sample, the sensitivity was - 0.1028 in the best time of 2988s; for concrete/ brass sample in the best time of 283.5s the sensitivity was – 0.0170; and for the steel/gypsum sample, in the best time 3434.7s the sensitivity was 0.0059.

What happens is that the sensitivities for the gypsum/steel and concrete/brass samples are greater when the center moves diagonally upward. The steel/gypsum sample presented almost the same sensitivity when it varies the center diagonally upward as diagonally down. This fact is important when deciding how to vary the center to perform the sensitivity analysis.

Figures (6) to (9) show that thermophysical properties of the samples and the inclusions influence the sensitivities of the geometric parameters. The pair gypsum/steel had a higher sensitivity than the other concrete/brass and steel/gypsum in all parameters studied. This is due a high heat capacity of the gypsum and the high thermal conductivity of steel. Although the brass has a thermal capacity value close to steel, the thermal conductivity of concrete is much greater than gypsum. This decreases the influence of inclusion in the surface temperature of the sample of concrete with bronze. In the pair steel/gypsum, conductivity and heat capacity of gypsum are very low when compared to steel, making almost imperceptible the inclusion. I.e., the influence of gypsum inclusion is almost zero. This type of configuration sample/inclusion generates a sensitivity very small and difficult to estimate the parameters.

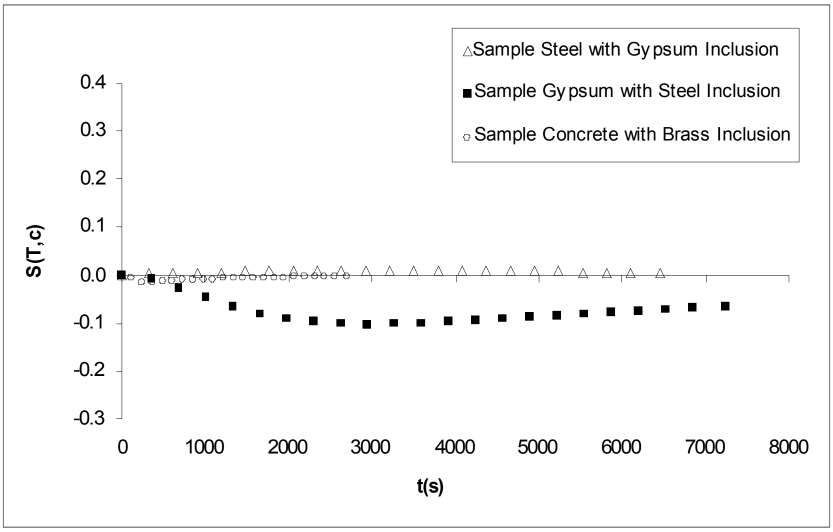


Figure 8 - Sensitivity analysis for the center with increasing coordinates.

Finding the optimum time for an experiment means to optimize both planning and implementation. That is, if the experiment is performed in a period that does not include the best time, the sensitivity is not high enough to minimize the error of the estimation. And if the experiment is done in a long period, which exceeds the best time, it will occurs the lost of time and will generate data that won't be used in estimating the parameters.

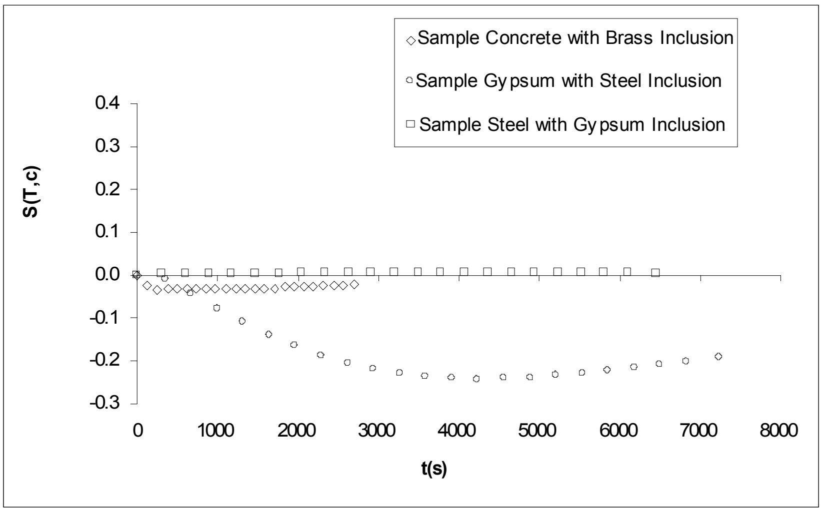


Figure 9 - Sensitivity analysis for the center with reduced coordinates

Table (1) shows a summary of the sensitivities values for the geometric parameters of the samples analysed.

Table 1 - Values of geometric parameters sensitivities.

Geometric Parameters	Samples Analysed					
	Gypsum/Steel		Concrete/Brass		Steel/Gypsum	
	Best Time (s)	Sensitivity	Best Time (s)	Sensitivity	Best Time (s)	Sensitivity
Radius	4146	0.1378	1512	0.0414	3466.8	-0.0181
Height	1221	0.3359	1417.5	0.0495	2856.9	-0.0099
Center with increasing coordinates	4212	-0.2435	918	-0.0327	2889	0.0076
Center with reduced coordinates	2988	-0.1028	283.5	-0.0170	3434.7	0.0059

For this study, to estimate the radius, height and center, the experiments can be performed up to: (a) 4176 s for the sample of gypsum with steel inclusion, (b) 1512 s for the sample of concrete with brass inclusion, and (c) 3466.8 s for the sample of steel with gypsum inclusion. But if it is necessary to estimate only one of the geometrical parameters, this time may be even lower, depending on the sensitivity of each parameter.

3.2 Geometric Parameters Estimation

Table (2) presents the results of geometric parameters estimation of the steel inclusion in the gypsum board. The experiments of Hora and Magnani (2009) on gypsum board with steel cylinder included had a duration of 3.300s. It was observed in the sensitivity analysis of the present work that the optimum time to perform the estimation of radius and center was 4000s after the begining of the sample cooling. Nevertheless, the experimental data might be used because the value of the sensitivities in best times were no more than 5% of those found in the last time of the experiments conducted by Hora and Magnani (2009).

It can be seen in Table (2) that the minor deviation occurred in determining the height. This is due to higher sensitivity when compared to other parameters. It means that an increase in the height of the cylinder has a greater capacity to cause a variation in the mean temperature of the sample surface than the radius and center. This proves the effectiveness of a sensitivity study before carrying out experiments that generate information for the solution of inverse problems of heat conduction.

Table 2 - Values of geometric parameters for the inclusion of steel.

Parameter	Best Time (s)	Found Value (m)
Radius	4.176	0,009525 ± 24,95 %
Height	1.221	0,026 ± 11,54 %
Center (x,y)	4.212	(0,2 ± 25%;0,7 ± 7,42)

4. CONCLUSIONS

In previous works it wasn't done a sensitivity analysis before the estimation of unknown, parameters were estimated only from the fit between experimental and numerical curves. In this paper it was performed a sensitivity analysis of the geometric parameters with respect to the mean surface temperature of samples with cylindrical inclusions for three pairs sample/inclusion: gypsum/steel, concrete/brass and steel/gypsum. This preliminary study was important to determine the best times of measuring and to design optimal experiments for the estimation of unknown parameters. From the determination of the optimal times, the estimation errors could be minimized due to the high sensitivity in these times. And the duration of the experiments could also be optimized with this information. As an example, it was estimated the geometric parameters of an inclusion of steel in a gypsum board using the best experimental times. The results were good, and it could be seen that the estimation of parameters in the best time provides a minor deviation. The geometric parameter that presented highest sensitivity and smallest error of estimation was the height of inclusion. Others, radius and center, had lower sensitivities and larger errors.

3. ACKNOWLEDGEMENTS

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5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

APPENDIX A – CORRELATIONS FOR THE COEFFICIENTS OF NATURAL CONVECTION FOR A FLAT PLATE

The Rayleight number (Ra) used is shown in Eq. (A.1).

$$Ra = \frac{g\beta \Delta T L^3}{\nu\alpha} \tag{A.1}$$

where:
g: acceleration of gravity (m/s²);
β: temperature coefficient of volume expansion (1/K);
$\overline{\Delta T}$: average temperature difference between the plate and the fluid (ºC);
L: characteristic lenght of the surface (m);
ν: kinematic viscosity (m²/s).

The Nusselt number (Nu) for a blend of fully laminar and fully turbulent heat transfer is given by Eq. (A.2).

$$Nu = ((Nu_l)^m + (Nu_t)^m)^{1/m} \tag{A.2}$$

where:
Nu_l : Nusselt number for fully laminar heat transfer;
Nu_t : Nusselt number for fully turbulent heat transfer;
m: blending parameter that depends on the body shape.

For vertical surfaces of the board and Rayleight number (Ra) in the range $1 < Ra < 10^{12}$, the correlations are given by Equations (A.3) to (A.6).

$$Nu^T = \overline{C_l}.Ra^{1/4} \tag{A.3}$$

$$Nu_l = \frac{2}{(\ln(1+2/Nu^T))} \tag{A.4}$$

$$Nu_t = \frac{C_t^V Ra^{1/3}}{(1+1.4\text{x}10^9 Pr/Ra)} \tag{A.5}$$

where:
Pr: Prandtl number;
C_t^V : function for turbulent heat transfer.

$$C_t^V = \frac{0.13\text{xPr}^{0.22}}{(1+0.61\text{Pr}^{0.81} Pr)^{0.42}} \tag{A.6}$$

For horizontal upper surface of the board and Rayleight number Ra ≥ 1, the correlations are given by Equations (A.7) to (A.10).

$$Nu^T = 0.835.\overline{C_l}.Ra^{1/4} \tag{A.7}$$

$$Nu_l = \frac{1.4}{(\ln(1+1.4/Nu^T))} \tag{A.8}$$

$$Nu_t = C_t^H Ra^{1/3} \tag{A.9}$$

where:
C_t^H : function for turbulent heat transfer;

$$C_t^H = 0.14\frac{1+0.0107\text{Pr}}{1+0.01\text{Pr}} \tag{A.10}$$

For horizontal lower surface of the board and Rayleight number Ra < 10^{10} and Prandtl number Pr ≥ 0.7, the correlations are given by Equations (A.11) to (A.13). In this case, only laminar flows is considered.

$$Nu^T = H_l.Ra^{1/5} \tag{A.11}$$

$$H_l = \frac{0.527}{(1+(1.9/Pr)^{0.9})^{0.22}} \tag{A.12}$$

$$Nu = \frac{2.45}{(\ln(1+2.45/Nu^T))} \tag{A.13}$$