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NUMERICAL / EXPERIMENTAL METHODOLOGY FOR DETERMINATION SIMULTANEOUS AND MONITORING OF THERMAL PROPERTIES AND INTERNAL TEMPERATURE OF EQUIPMENT IN SITU

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Abstract. *The temperature is a good indication of the operating state of equipment. However, the majority of the processes do not have thermal sensors in their internal part, being common the application of the measured temperatures in the outside for control. It is known, however, that this depends strongly on several parameters, increasing the uncertainties in the measurements. There are also several industrial areas, such as the petrochemical, steel and refrigeration industries, which depend on the continuous monitoring of the physical and dimensional characteristics of certain components, such as thickness or existence of crumbling in the internal walls of pipes, in order to define preventive and predictive maintenance of these parts. With the objective of determining the internal temperature of industrial equipment, this work proposes the development of a numerical-experimental technique and of non-invasive methods to arrive to estimate the internal temperature and thermophysical properties of materials. The work aims at the development of a technique with reduced computational cost, which allows the determination of the thermal properties of items such as equipment casings or ducts, even after installed and in operation, and the temperature on the internal surface of the monitored area. Such estimation makes use of experimental data involving the temperature and the heat flux monitored in accessible regions, on the external surface of the equipment, and application of a one-dimensional transient thermal model and inverse problems. The results show that the technique is promising both for the momentary determination of the characteristics of interest and as a tool for continuous monitoring of the temperature and thermal properties of the materials.*

Keywords: *Internal temperature, Thermal properties, Inverse problems, non-invasive methods, preventive and predictive maintenance*

1. INTRODUCTION

Several authors propose the use of thermal models to predict the internal temperature of equipment. With the use of a thermal model for an electric motor, Souza (2011) predicts the determination of operational failures, such as short-circuit and overload of the motor. Begot and Kauffmann (2008) uses inverse methods and temperature measurement to predict the temperature of fuel cells to provide higher performance and increased life-cycle. However, the thermal model strongly depends on the thermal properties of the component parts of the motor or fuel cell, these properties are sometimes unknown. Accordingly, it is necessary to use efficient techniques for determining the thermal properties of the materials involved. Borges (2008) proposes a non-destructive numerical/experimental technique for the simultaneous determination of thermal conductivity and diffusivity materials. The author makes use of experimental data, thermal modeling and techniques of inverse problems to achieve the proposed objectives.

Systems subjected to large temperature variations suffer from thermal fatigue, reducing the life of the related parties. This reduction develops, from the formation of fractures along the structures, to a variation in the thermal and mechanical properties of the materials involved. Rojacz *et al.* (2016) analyzed the effect of heat stress without wear of slag transport containers in the steel industry. By means of numerical-experimental, it was possible to estimate a temperature and a series of contents. In addition, the material fragility due to the degradation of the thermophysical characteristics of the materials due to the appearance of cracks and oxidation points.

Plastic compounds degrade from chemical, mechanical and thermal reactions (Singh and Sharma, 2008). In all cases, molecular changes occur that alter the physical characteristics of plastics. Gulmine and Akcelrud (2006) evaluated the influence of temperature on plastic electrical insulators. The authors studied and verified the influence of temperature increase on parameters such as dielectric strength and melting point of the insulation.

A technique that allows the estimation of the thermophysical properties in situ can be applied as a preventive and predictive maintenance tool, indicating the study of the conditions of housing of equipment and walls of ducts in the steel, petrochemical and refrigeration areas, for example. By evaluating the variation of conductivity and thermal diffusivity, it is possible to know, for example, if there was a reduction in the wall thickness of the ducts or bearing housings caused by wear processes or the incrustation of materials in the internal part of ducts.

Therefore, this work proposes the experimental validation of the technique for determination of the internal temperature together with the thermal properties, proposed by Mulina (2016), for two samples of conductivities and different thermal diffusivities, from parameters measured on the accessible surface.

2. DEVELOPMENT

Figure 1 presents a schematic of the thermal model to be studied. It is a theoretical model, equivalent to the problem to be solved to determine the internal temperature. The heat flux Q_h is dissipated in the casing of the equipment by convection and/or radiation, Q_i is the internal heat flux, generated by the equipment itself, and T_i is the variable of interest (internal temperature).

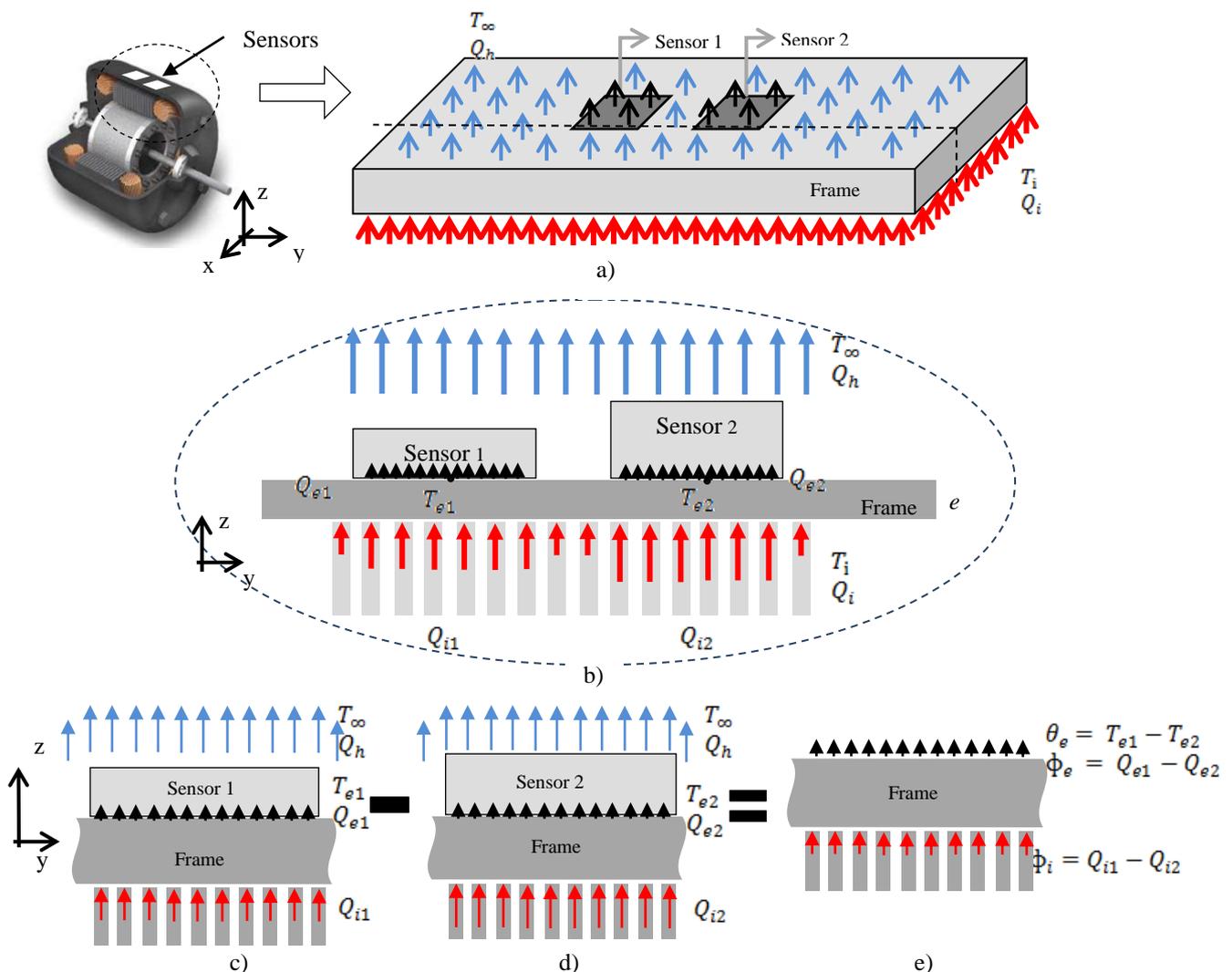


Figure 1. Equivalent thermal model for two thermal sensors. a) General thermal problem: the engine heat dissipation; b) 2D model with thermal sensors installed in the housing. c) Thermal problem Sensor 1; d) Thermal problem Sensor 2; e) Thermal problem "Difference Model". (Mulina, 2016)

The heat problem is presented in Fig. 1a in which it presents to the motor frame subjected to the boundary conditions of the internal heat flux type supplied by the motor, and heat losses by convection and radiative means to the

external surface. The proposed technique consists in installing two sensors on the external surface of the frame, as seen in Fig. 1b. The sensors were developed especially for the technique in order to measure the temperature and heat flux on the outer wall of the frame. Each sensor highlighted in Fig. 2, is composed of a heat flux transducer, a thermocouple and a cover. What differentiates the sensors is the thickness of coverage in each of them.

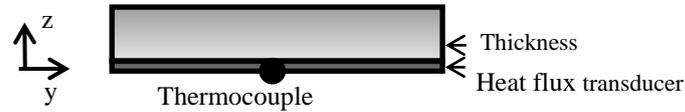


Figure 2. Scheme of thermal sensors (Mulina, 2016).

The installation of the thermal sensors of different thickness alter locally the thermal exchanges between the frame and the environment, as presented in Fig. 1b. Because the sensors have different thicknesses, temperature and heat flux at the contact interface between the sensor and the frame vary. The same reasoning applies to the internal heat flux in the region below the sensors, as highlighted in Fig. 1b. The thermal variations caused by the presence of the sensors can be treated as one-dimensional and such behavior can be proved by means of computer simulations. Due to the presence of the cover on the heat flux and temperature sensors, heat exchange between the frame and the environment changes, this defines the sensor as active.

In order to validate the technique developed by Mulina (2016), a set of experiments were carried out in order to evaluate the performance of a carcass with low thermal conductivity of polyvinyl chloride (PVC), and in cases with higher thermal conductivity, in this case, steel DIN 38MnSiVS5. The choice of such materials was based on the vast scientific literature that reports its thermal properties.

2.1. CASE STUDY: APPLICATION OF THE TECHNIQUE IN PVC SAMPLE

In order to confirm the feasibility of the technique, an experiment was carried out with a sample of non-conductive thermal properties, in the case of polyvinyl chloride (PVC). The sample size and other experimental parameters are presented in Table 1. Figure 3 shows the experimental setup and arrangement of the sensors on the upper surface of the sample.

Table 1. Experimental parameters

<i>Sample</i>		
Material		PVC
Sample dimensions [m]	X	0.3
	Y	0.3
	Z	0.025
<i>Experimental data</i>		
Interval of acquisition [s]		4.12
Duration of the experiment [s]		4219
Number of acquisition points in time		1024
Average temperature [°C]		27
Dimensions of electrical resistance [mxm]		0.3 x 0.3
Experimental average heat flux imposed on the lower surface [W/m ²]		100

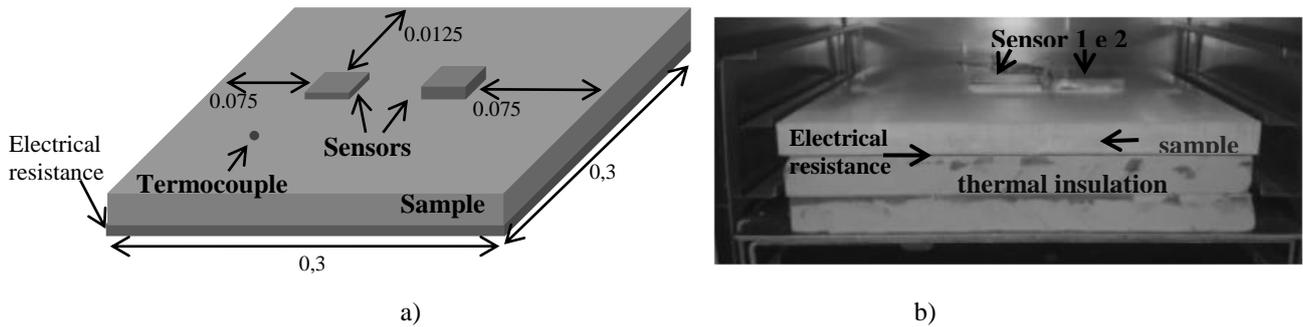


Figure 3. PVC sample evaluated: a) Dimensions and arrangement of sensors and b) Experimental assembly.

The dimensions of the sensors and materials employed are described in Table 2.

Table 2. Sensor characteristics.

Material		Copper
Thermal diffusivity [m^2/s] * 10^7		142
Thermal conductivity [$W/(mK)$]		398
Dimensions of the sensor 1 [m]	x	0.05
	y	0.05
	$z(e_1)$	0.002
Dimensions of the sensor 2 [m]	x	0.05
	y	0.05
	$Z(e_2)$	0.006

The values of temperature and heat fluxes measured experimentally by the thermal sensors 1 and 2, installed on the upper surface, are presented in Fig. 4.a and 4.b. Fig. 5.a and 5.b shows the differences between the heat fluxes and the experimental temperatures, respectively.

It should be noted that in this experiment the sensors were previously positioned in the sample that was at room temperature. Then the electric resistance was switched on.

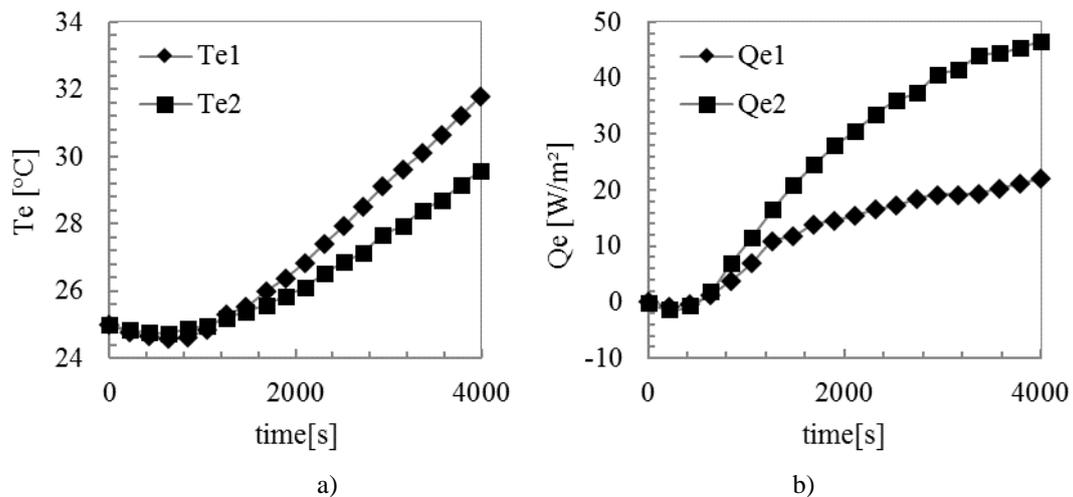


Figure 4. Experimental data: a) Temperatures and b) Heat flux and on the upper surface of the PVC sample.

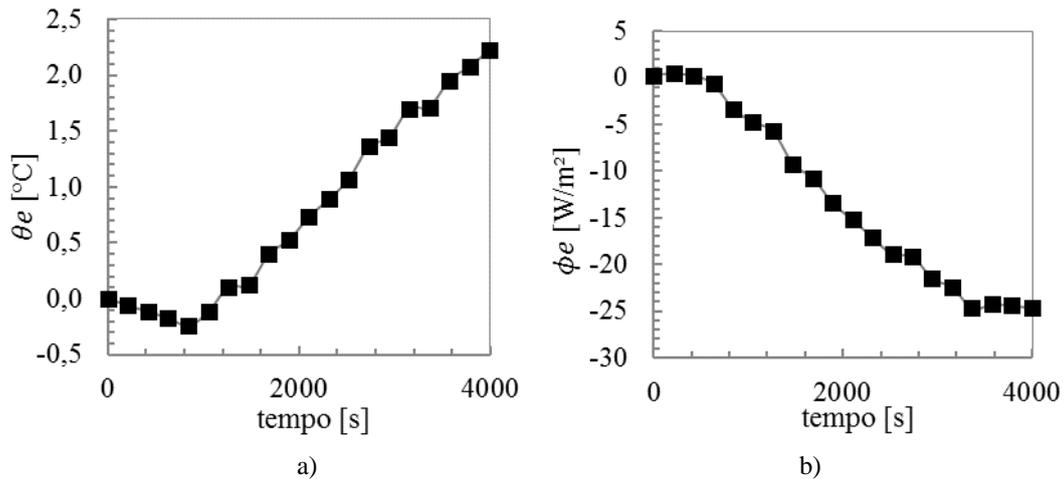


Figure 5. Signs applied to the Difference Model: a) Temperature and b) External heat flux.

2.1.1. DETERMINATION OF THE THERMOPHYSICAL PROPERTIES OF THE PVC SAMPLE

Applying the technique described by Mulina (2016) in the temperature and heat flux signals obtained, the thermophysical properties presented in Table 3 were estimated for the PVC sample.

Table 3. Estimated values for α and k and comparisons with data available in the scientific literature.

	Presente Trabalho (a 25°C)	Borges (2008) (a 30°C)	Goodfellow (2014) (a 23°C)	IPT (2004) (a 26°C)	Efunda (2016)
α [m^2/s] $\times 10^7$	1.19 (± 0.158)	1.157	1.143	-	-
k [W/(mK)]	0.18 (± 0.002)	0.159	0.12 – 0.25	0.16	0.125 - 0.167

It is noteworthy that the sample evaluated is the same as that used by Borges (2008). In general, the results confirm the feasibility of the technique proposed in the present work.

2.1.2. DETERMINATION OF THE INTERNAL TEMPERATURE IN PVC SAMPLE

Once calculated as thermal properties, and as internal and external contour conditions, it is possible to determine the internal temperature of the shell. Fig. 6a and 6b show, respectively, the internal temperature behavior, experimental and calculated from the parameters found for the technical proposal, for a standard experiment using the PVC sample.

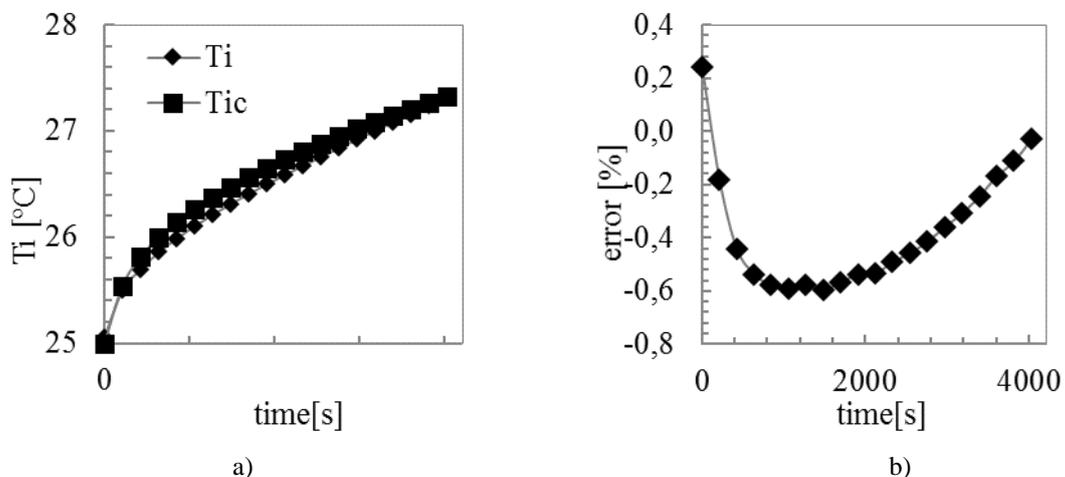


Figure 6. Internal temperatures $T_i(t)$: a) Experimental and calculated. b) Relative error.

2.2. CASE STUDY: APPLICATION OF THE TECHNIQUE IN STEEL DIN 38MNSIVS5 SAMPLE

For the evaluation of the technique in materials with metallic properties, samples of steel DIN 38MnSiVS5, produced by the company Villares, were used and its composition of this steel detailed in Table 4.

Table 4. Composition of the microalloyed steel DIN 38MnSiVS5.

Composition	C	Si	Mn	S	P	Cr	V	N
%	0,38	0,68	1,50	0,06	0,022	0,18	0,11	0,006

The choice of this material is due to the fact that the samples used had their thermophysical properties determined by Souza (2009) applying different technique. Due to the geometric limitation imposed by the samples used, the experimental setup was performed differently, according to Fig. 7, where S1 and S2 are the thermal sensors installed on the samples of the same dimensions.

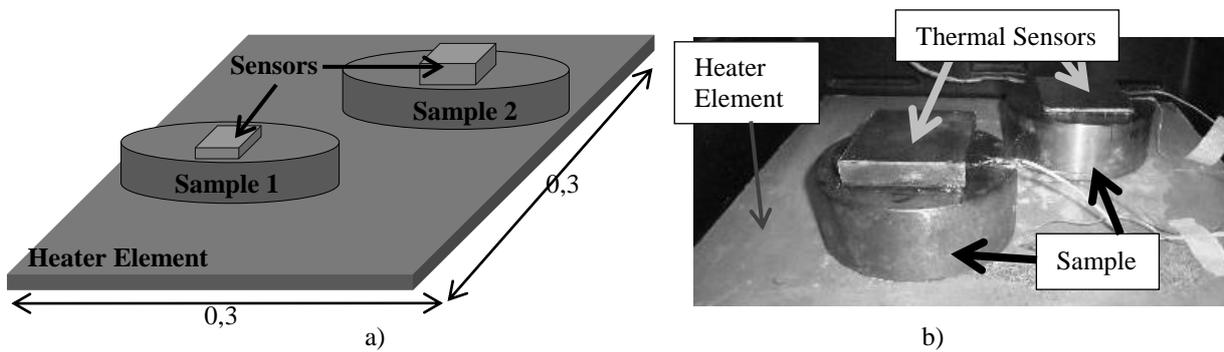


Figure 7. Experiment carried out for steel. a) Scheme. b) Experimental setup.

The dimensions of the samples and the sensors, and the experimental parameters applied to the experiments, are described in Table 5.

Table 5. Experimental parameters for the steel DIN 38MnSiVS5.

<i>Sample</i>		
Material	STEEL DIN 38MnSiVS5.	
Sample dimensions [m]	\varnothing	0,05
	Z	0,0386
<i>Experimental data</i>		
Interval of acquisition [s]	1	
Duration of the experiment [s]	635	
Number of points	635	
Average temperature [°C]	25	
Dimensions of resistance [mxm]	0.3 x 0.3	

Figure 8.a e 8.b shows the signals referring to temperatures and, and heat fluxes and obtained experimentally on the external surface of the samples. Likewise, Fig. 9.a e 9.b details the heat and temperature flux values applied to the technique.

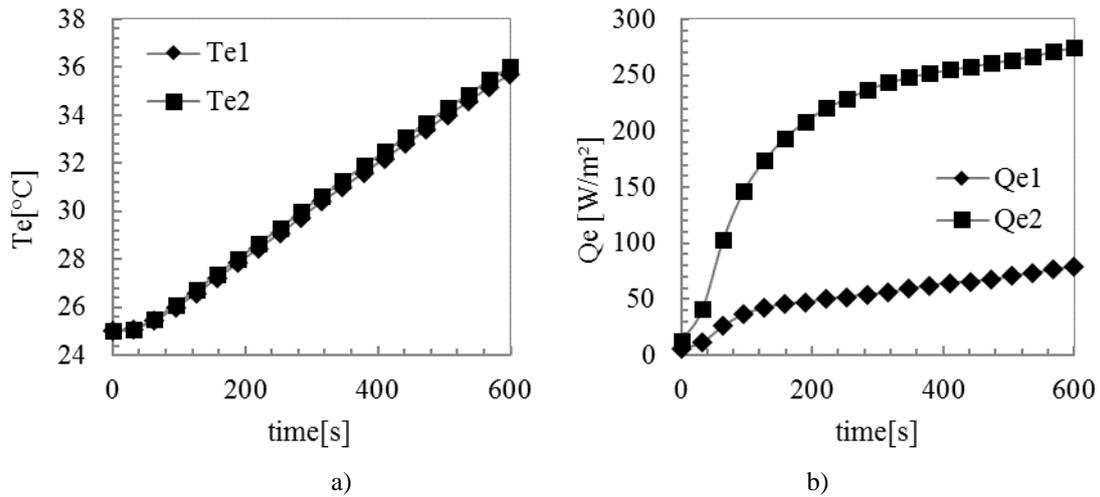


Figure 8. Experimental parameters obtained. a) Temperature. b) Heat flux

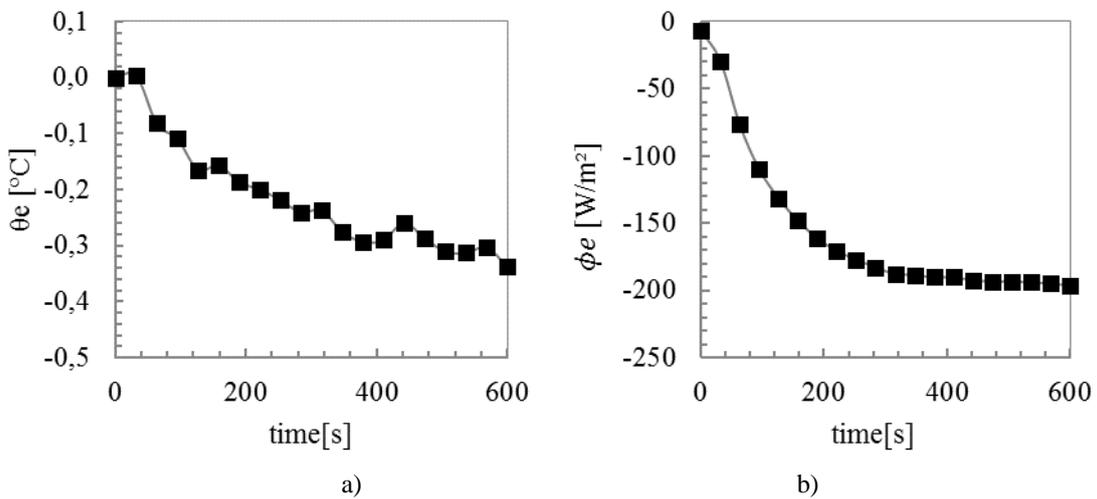


Figure 9. Differences applied to the Difference model: a) Temperature and b) Heat flux.

2.2.1. DETERMINATION OF THE THERMOPHYSICAL PROPERTIES OF THE STEEL DIN 38MNSIVS5 SAMPLE

The mean values of diffusivity and thermal conductivity are presented in Table 6, together with a comparison between the values obtained in this work with values found in the literature (Souza, 2009).

Table 6. Comparison between values of α and k .

	Mulina (2016) (a 25 $^{\circ}\text{C}$)	Souza (2009) (a 30 $^{\circ}\text{C}$)	Chaudhuri <i>et al.</i> (2002)
α [m^2/s] $\times 10^6$	9.88 (± 0.34)	9.62	-
k [$\text{W}/(\text{mK})$]	38.69 (± 1.24)	40.58	27 – 41

2.2.2. DETERMINATION OF THE INTERNAL TEMPERATURE IN STEEL DIN 38MNSIVS5 SAMPLE

Figure. 10 shows the experimental and calculated temperatures for the experiment with the micro-alloyed steel. The internal experimental temperature presented is the arithmetic mean between the measured temperatures on the inner face of each sample.

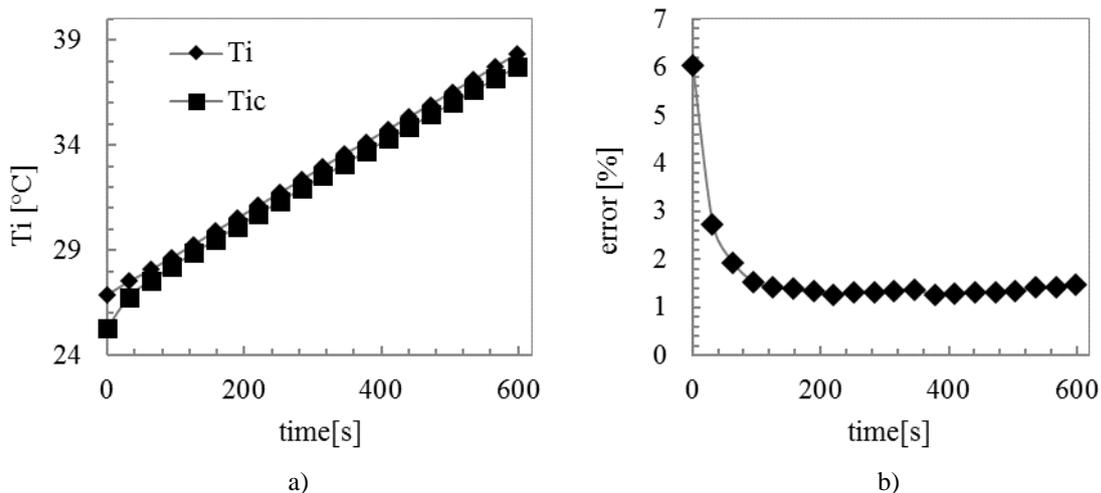


Figure 10. Temperature of the inner face: a) Experimental and calculated. b) Relative error.

It is possible to identify a good agreement between the experimental and calculated values by means of the technique, confirming the viability of the methodology in the measurement of the internal temperature of materials with metallic and non-metallic properties.

3. CONCLUSIONS

This paper presents a numerical/experimental technique for determination of thermal properties and internal temperature of industrial equipment

From the definition of the thermal problem, design of auxiliary thermal problems, experimental data, use of a Difference Model and techniques of inverse problems in heat transfer, it was estimated the variables of interest from two simulated experiments.

By means of analyzing the results, it was noted a good consistency between the simulated and experimental data, which confirmed the potential and feasibility of use of the technique for insulating and metallic materials.

Based on the scientific literature, it appears that the majority of techniques available makes use of samples and controlled laboratory experiments for estimating simultaneously the thermal properties of materials. The advantage of this technique compared to others is the possibility of its use in the field, directly on the material being studied.

Finally, it is considered that the present work took just one step forward to the great challenge that is to determine simultaneously the thermal properties and internal temperature of industrial equipment. Experiments are being prepared in the laboratory to confirm the viability and further enhance the technical proposal.

4. ACKNOWLEDGEMENTS

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