A STUDY ON THERMAL CONTACT RESISTANCE AND UNCERTAINTY ANALYSIS IN THERMAL PROPERTIES ESTIMATION OF METALLIC MATERIALS

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Abstract. *A study of the thermal contact resistance and the uncertainty analysis that happens in the simultaneous estimation of thermal conductivity and volumetric heat capacity is presented. The purpose of performing this work is the lack of information in published papers when experimental procedures are carried out. Several papers do not present these analyses, which are indispensable in an experimental viewpoint, and when these influences are taken into account, only values are presented; in other words, how the analyses were carried out and what method was used are not explained. So, the analyses in the present work are done in an one-dimensional experiment, where a symmetric assembly is applied. The sample is located between the resistive heater and the insulation. The thermal contact resistance is calculated by considering two influences: the first is the gap between the resistive heater and the sample, and the second is the kapton layer of the resistive heater. Good results are obtained in this analysis, because these influences result in a temperature difference around 0.2 ºC, which is equal to the uncertainty of the thermocouple. The uncertainty analysis is based on the uncertainty propagation procedure by analysing the thermal contact resistance, experimental, and numerical errors. The uncertanty analysis is satisfactory, because the obtained result is lower than 5 %.*

Keywords*: thermal contact resistance, uncertainty analysis, thermal properties estimation, heat conduction.*

1. NOMENCLATURE

F	objective function, ºC^2
L	sample thickness, m
P	parameter to be analyzed
$R''_{c,1}$	thermal contact resistance of the thermal compound, ºCm^{2}W^{-1}
$R''_{c,2}$	thermal contact resistance of the kapton layer, ºCm^{2}W^{-1}
T	numerical temperature, ºC
T_0	initial temperature, ºC
U	uncertainty, %
t	time, s
x	Cartesian coordinate, m
X	sensitivity coefficient
Y	experimental temperature, ºC
Greek Symbols	
α	thermal diffusivity, m^{2}s^{-1}
λ	thermal conductivity, Wm^{-1}K^{-1}
ρc_p	volumetric heat capacity, Wsm^{-3}K^{-1}
ϕ	imposed heat flux, Wm^{-2}
ϕ_a	average of imposed heat flux, Wm^{-2}
Subscripts	
j	index of points
i	index of parameter
m	total number of points

2. INTRODUCTION

Nowadays, there are several techniques to determine the thermal properties of any materials. These techniques can determine these properties separately or simultaneously; moreover, most of these estimations occur quickly, reliably and accurately. Thus, to do this estimation, an experimental assembly is necessary. Therefore, when experiments are performed, there are several errors happening. These errors are related to the equipment used to measure the temperature, the power supply, thermal contact resistance, and others. So, these errors are intrinsic to the process. Since, there is no way to avoid these errors; the correct procedure is to perform a controlled experiment and to quantify these errors. However, papers like Ghrib *et al*. (2007), Borges *et al*. (2008), Le Goff *et al*. (2009), Kravvaritis *et al*. (2011), Sanjaya *et al*. (2011), and others performed an experiments and did not mention these errors and in other papers, these errors are mentioned and quantified (Jannot *et al*., 2006, Jannot *et al*., 2009, Xamán *et* al., 2009, Jannot *et al*., 2010, Thomas *et al*., 2010), but the procedure and method adopted are not described.

In the present work, a study of the uncertainty analysis and the thermal contact resistance is done by using an experiment to simultaneously estimate the thermal properties. This method is based on a one-dimensional thermal model. A symmetrical assembly is used, where the sample is located between the resistive heater and the insulator. To determine the properties, an objective function, based on the square difference between the numerical and experimental temperature plus the thermal contact resistance influence, is minimized. The study of the thermal contact resistance contains the influence of the kapton layer in the resistive heater and the gap between the resistive heater and the sample.

The uncertainty analysis is done taking into account the influence of the thermal contact resistance and the errors from the numerical and experimental temperatures.

Therefore, the aim of this work is to present a study of the thermal contact resistance and uncertainty analysis applied on the simultaneous estimation of the thermal conductivity and volumetric heat capacity of AISI 304 Stainless Steel, seeking to clarify the lack of information in the published papers.

3. THEORETICAL ASPECTS

3.1. Thermal model

The heat diffusion equation for the problem presented in this work is shown in Fig. 1. Considering the constant thermal properties and the time domain it can be written as:

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{\rho c_p}{\lambda}\frac{\partial T(x,t)}{\partial t}, \quad t > 0 \tag{1}$$

subject to the boundary conditions:

$$-\lambda \frac{\partial T(x,t)}{\partial x} = \phi(t) \text{ at } x = 0, \quad t > 0 \tag{2}$$

$$\frac{\partial T(x,t)}{\partial x} = 0 \text{ at } x = L, \quad t > 0 \tag{3}$$

and the initial condition:

$$T(x,t) = T_0 \text{ at } t = 0 \tag{4}$$

The numerical temperature is obtained by solving the one-dimensional diffusion equation using the finite difference method with an implicit formulation. To solve this equation, the Gauss-Seidel method was used. The parameters used in this method are: time interval equal to 0.1 s, number of points equal to 11 and grid of around $1.1\text{x}10^{-03}$ m. In order to confirm whether this numerical solution is correct, a comparison between the numerical and analytical solutions was made and a good agreement was checked. The analytical solution was obtained by using the Green's Function (Beck *et al.*, 1992).

Figure 1 shows the proposed one-dimensional thermal model, consisting of a sample located between a resistive heater and an insulator. To ensure the unidirectional heat flux, the sample thickness is much smaller than its other dimensions. In addition, all the surfaces, except the heated surface (x = 0), were isolated.

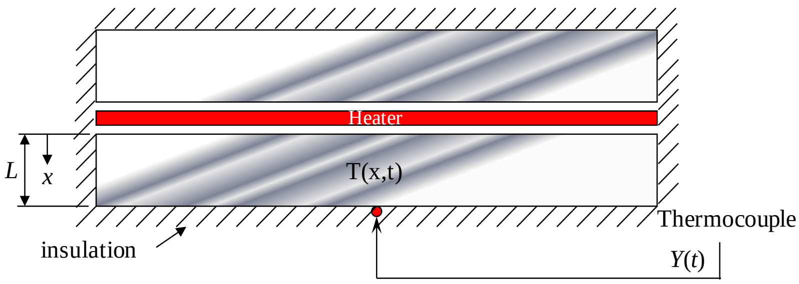

Figure 1. One-dimensional thermal model.

3.2. Analyses of the best region to determine the properties λ and ρc_p

Studies of the sensitivity coefficient for each sample were performed in this work to determine the best region for estimating the properties as well as the best configuration of the experimental setup. The best region is the set of points which presented sufficient sensitivity to determine the thermal properties accurately. This study provides information such as: the correct position of the thermocouples, the experimental time, and the time interval of the imposed heat flux incidence. The higher the coefficient values, the better the chance of obtaining the properties reliably, considering that the coefficients do not present correlation.

The sensitivity coefficient is defined by the first partial derivative of the temperature in relation to the parameter being analyzed (λ or ρc_p), written as follows:

$$X_{ij} = P_i \frac{\partial T_j}{\partial P_i} \tag{5}$$

In this work, only two properties were analyzed. Therefore $i = 1$ for λ and $i = 2$ for ρc_p, and j varies between 1 and m.

Furthermore, several analyses of the objective function were performed to guarantee sufficient information from the analyzed region to estimate the properties simultaneously. One can verify this information if the minimum value of the objective function is found. This objective function is represented by Eq. (6) in the next section.

3.3. Thermal conductivity and volumetric heat capacity simultaneous estimation

To estimate the two properties it is necessary to use an objective function. Usually, the objective function is simply the square difference between the temperatures (Adjali and Laurent, 2007; Borges *et al.*, 2008). However, since the thermal resistance contact is a systematic error, this influence needs to be considered in the analysis, because this value is constant and permanent. So, this influence was included in the objective function with the purpose of considering an initial error, therefore, the objective function will never be equal to zero. Thus, the objective function used in this work is based on the square difference between the experimental and numerical temperatures plus the influence of the thermal contact resistance. This equation can be written as:

$$F = \left[\left(R''_{c,1} + R''_{c,2}\right)\phi_a\right]^2 + \sum_{j=1}^{m}\left(Y_j - T_j\right)^2 \tag{6}$$

Thus, it is known that the optimal values for λ and ρc_p, respectively, which minimize the objective function, are the values of the properties to be estimated. To obtain these values, the BFGS (Broydon Fletcher Goldfarb Shanno) sequential optimization technique, presented in Vanderplaats (2005), was used. This technique is a particularity of the variable metric methods. The advantages of this technique are its fast convergence and facility for working with many design variables. Because it is a first order method, it is necessary to know the gradient of the objective function.

4. EXPERIMENTAL PROCEDURE

Figure 2 shows the experimental apparatus used to determine the properties of AISI 304 stainless steel. The dimensions of the plates are 49.9 x 49.9 x 10.9 mm^3. The resistive kapton heater has a resistance of 15 Ω and dimensions of 50.0 x 50.0 x 0.2 mm^3. The resistive kapton heater was used for its thinness, allowing for faster overall warming. To provide the necessary heat flux, this heater was connected to a digital power supply Instrutemp ST – 305D-II. This experimental apparatus can be used from environment temperature up to 200 ºC, but it is necessary to change the insulation.

In this work, different intensities of heat flux were used in the same experiment as an attempt to achieve the best condition to estimate the properties simultaneously in accordance with the analyses of the sensitivity coefficients. To achieve this heat flux condition, the digital power supply had a configuration that allowed work in parallel, series or independent connections. Thus, it is possible to apply different intensities of heat flux by a combination of two buttons. Therefore, the following procedure was adopted: the series condition was used to provide the highest heat flux in the first period of the experiment, and, in the second part, the parallel condition was used to supply the lowest heat flux. A symmetrical assembly was used to minimize the errors when measuring the heat flux on the sample surface. In addition, the current and voltage values were measured with the calibrated multimeters Instrutherm MD-380 and Minipa ET-2042C, respectively.

Since the contact between the resistive heater and the sample was imperfect, the silver thermal compound Arctic Silver 5, which presents a thermal conductivity around 8.89 $Wm^{-1}K^{-1}$ (Arctic Silver Incorporated, 2011), was used to avoid the air interstices present in the assembly. The great advantage to this compound is its high thermal conductivity, when compared to the air. Also, to improve the contact between the components, weights were placed on top of the isolated heater-samples set. To ensure a unidirectional heat flux and minimize the effect of convection caused by the air circulating in the environment, the heater-samples set was isolated with polystyrene plates. Temperatures were measured using type K thermocouples (30AWG;0.254 mm in diameter) welded by capacitor discharge in the middle of the bottom surface and calibrated by using Marconi MA 184 bath temperature calibrator with a resolution of ± 0.01 K. This thermocouple was connected to an Agilent 34980A data acquisition, controlled by a microcomputer. To obtain better results, all experiments were performed in a temperature controlled room.

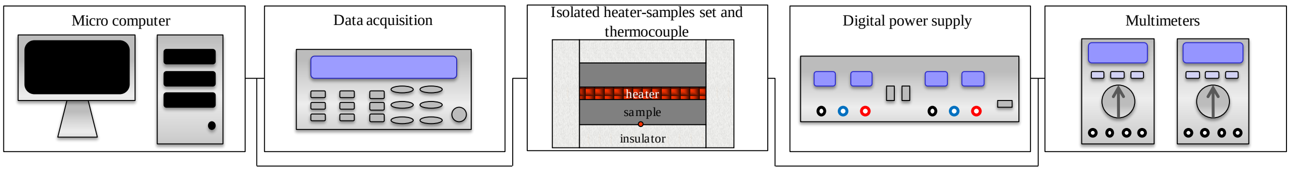

Figure 2. Sketch of the experimental apparatus used to determine the properties.

5. RESULTS ANALYSES

Forty experiments were performed to simultaneously estimate the thermal conductivity and the volumetric heat capacity of AISI 304 stainless steel. Each experiment lasted 160 s, and the heat flux was imposed from 0 to 140 s. From 0 to 20 s, the imposed heat flux was approximately 2640 Wm^{-2}; from 20 to 140 s, the imposed heat flux was around 660 Wm^{-2}. The time interval used to monitor the temperature was 0.1 s. To guarantee the hypotheses of constant thermal properties, this configuration for the heat fluxes was chosen to keep the temperature difference lower than 5 K. This temperature difference is based on the difference between the final and initial temperatures which are measured having the thermocouple on the same position of the sample.

The sensitivity analyses were performed to determine the best region to estimate the properties. These analyses were performed by using the values of λ and ρc_p obtained from Borges *et al.* (2008) and the parameters described above. In addition, several analyses of the objective function (Eq. 6) with the sensitivity coefficient analyses were performed to determine the properties in the selected region. This selected region corresponds to a set of points which provides accurate thermal properties estimation. Since this estimation presents an accurate result, it can be said that this region of points presents enough influence to determine these properties.

Figure 3 shows the sensitivity coefficients and imposed heat flux at $x = L$ for λ and ρc_p, and Fig. 4 presents the values of the objective function.

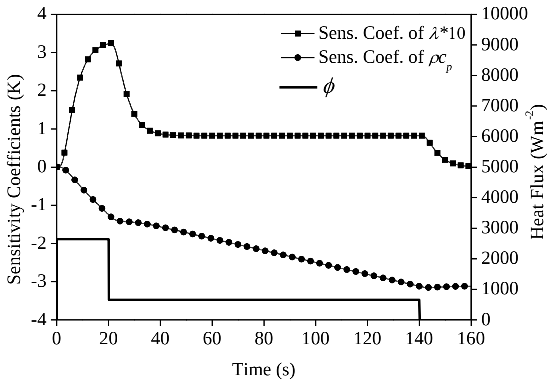

Figure 3. Sensitivity Coefficients and imposed heat flux.

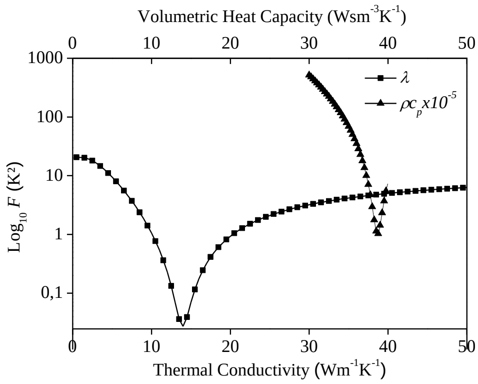

Figure 4. Objective Function Values (*F*).

X_1 represents the sensitivity coefficient for λ and X_2 represents the sensitivity coefficient for ρc_p, both on the isolated surface. The former is multiplied by a factor to improve the visualization of the curve. In Figure 3, one can see that X_1 increases during the first 20 s and remains constant thereafter until the change of heat flux; and X_2 increases proportionally with the temperature.

Because of this behavior, the highest heat flux was imposed in the first period of time, resulting in high sensitivity for λ. The lowest heat flux was imposed in the second part to increase the sensitivity for ρc_p and maintain the sensitivity for λ. This procedure was done, because it is necessary to control the magnitude relation between X_1 and X_2, to guarantee that the estimation would take place for both properties. That is, if one coefficient is much larger than the other, the estimation, by using minimization, will occur only for that property presenting the higher coefficient. Hence, Figure 4 shows that, since a minimum value was found for each property, enough influence exists to determine simultaneously the properties in the region analyzed. Figure 4 was obtained by minimizing the difference between the experimental and numerical temperatures. This numerical temperature was obtained by varying the value of one property while the other property was kept constant. Thus, the minimum value, of the objective function is found when the temperature difference presents the lowest value for both the property. Analyzing Fig. 4, it can be seen, that there is a different minimum value for each property, however the estimation occurs at the same time for the properties by using the same objective function.

Another objective of the sensitivity analysis is to determine the number of points in the curve which should be used to estimate the properties. To be considered in properties estimation, these points should present values different from zero, which indicate applied heat flux. So, the sets of points which do not present applied heat flux should be disregarded in the estimation. Also, a thermal inertia analysis of the heater was carried out to verify whether this inertia can cause an influence in the experiments. This analysis was performed by using an assembly which contains heat flux sensors, similar to Borges *et al.* (2006). Therefore, it is possible to quantify this thermal inertia in time. These tests were done by applying the same experimental conditions and the results present a delay of almost 2 seconds to achieve the real value of heat flux. Thus, the set of points which corresponds to this delay was disregarded in the thermal properties estimation.

To determine whether the conditions explained above resulted in good experiments, another analysis was performed based on Dowding *et al.* (1995). According to these authors, the best condition and design for the experiment were achieved when the sum of the sensitivity coefficient for λ and ρc_p plus the temperature difference were equal to zero ($X_1 + X_2 + Y - Y_0 = 0$). This is valid when the boundary condition of imposed heat flux on the top surface and insulation on the bottom surface is used. In other words, if this proposed condition is reached, the reliability of the obtained results can be guaranteed. Figure 5 shows the obtained results of this analysis considering the above experiment.

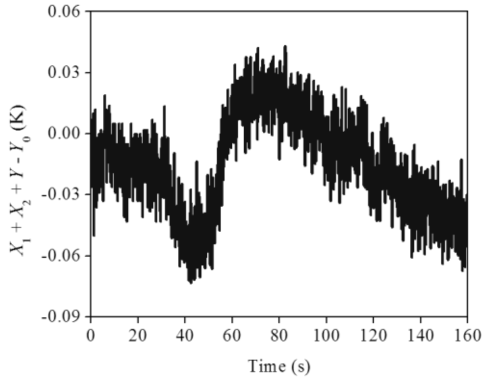

Figure 5. Analysis of the best condition and design for AISI 304 stainless steel.

It can be seen that the highest difference was around 0.07 K. Then, when this value is compared with the mean temperature of the experiment, which is 23.5 ºC, it can be concluded that this little difference does not interfere in the estimation results. Therefore, based on this analysis, it is possible to claim that the experiments were well performed.

Figure 6 presents the distribution of experimental and numerical temperatures for the sample at $x = L$ and the imposed heat flux at $x = 0$. The numerical temperature is achieved by employing the values of the estimated properties, λ and ρc_p, from one of the accomplished experiments. These temperatures present good agreement, which can be proved by analyzing the temperature residuals shown in Fig. 7. These residuals are calculated by the difference between the experimental and numerical temperatures divided by the experimental temperature. The maximum value found was around 0.5 %, which represents a temperature difference lower than 0.12 K and this difference is lower than the thermocouple uncertainty. This difference will be considered as the imperfection of the thermal insulation in the uncertainty analysis. Thus, one can find good agreement between the obtained results and the literature on AISI 304 stainless steel.

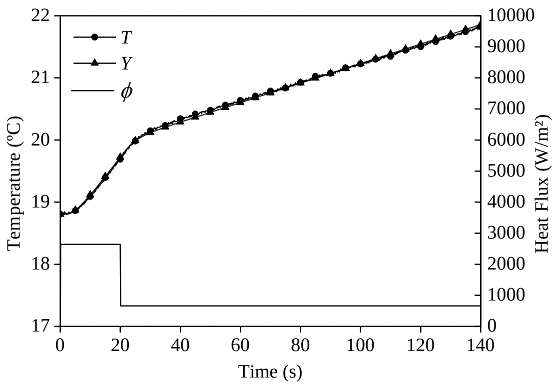

Figure 6. Numerical (T) and Experimental (Y) Temperatures with Heat Flux (ϕ).

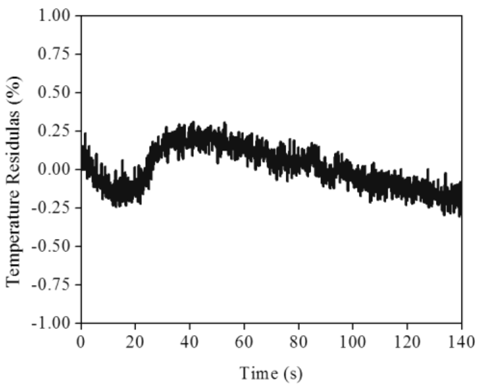

Figure 7.Temperature residuals.

Table 1 presents the standard deviation (S.D.), the difference (the percentage difference between the mean and the literature value) and the mean value of λ and ρc_p for AISI 304 stainless steel.

Table 1. Results obtained for the AISI 304 stainless steel.

Property	Present work	Incropera *et al.* (2007)	S. D.	Difference (%)	Mean Temperature (ºC)
λ ($Wm^{-1}K^{-1}$)	14.7	14.90	± 0.16	1.36	23.5
ρc_px10^{-6} ($Wsm^{-3}K^{-1}$)	3.9	3.87	± 0.04	0.77	

The estimated values of λ and ρc_p are in good agreement with those values found in the literature.

6. THERMAL CONTACT RESISTANCE

The thermal contact resistance was analyzed with the purpose to find out if there is a significant influence during the temperature measurements. This study was divided into two parts: the first part considered the thermal resistance caused by the applied thermal compound; the second part took into account the influence of the kapton layer present in the resistance heater.

The analysis of the influence of the thermal compound was performed by using the Profile Projector Carl Zeiss MP320, which was able to measure the distance between the resistive heater surface and the sample surface. As mentioned in the experimental procedure, the authors decided to use the Arctic Silver 5 thermal compound to avoid the air gaps. Thus, the distance measured is the thickness of the thermal compound applied.

In accordance with Narumanchi *et al.* (2008), who measured the thermal contact resistance of many thermal compounds, including the Arctic Silver 5, the thermal contact resistance is dependent on its thickness. Based on this information, it is possible to evaluate the thermal contact resistance. The thickness measured in our assembly is 0.035 mm, which correspond to a thermal contact resistance of 45x10^{-6} m^{2}ºCW^{-1}.

This value of thermal resistance will result in a temperature difference, and this difference is proportional to the applied heat flux. In this work, the heat flux average is 1650 Wm^{-2}, which corresponds to a temperature difference of 0.07 ºC.

The influence of the kapton layer was also analyzed. This analysis was done by using the same idea of the thermal compound analysis. An Optical Microscope Jenavert Zeiss (2000x) with the Image Analyzer Olympus Model TVO.5XC-3 was used to measure the thickness of the kapton on the heater. The kapton layer presents a thickness of 10.64 x10^{-6} m. Since the thermal conductivity of the kapton is 0.12 Wm^{-1}ºC^{-1} (MatWeb, 2012); a thermal contact resistance equal to 88.67x10^{-6} m^{2}ºCW^{-1} was obtained. By considering the applied heat flux average, 1650 Wm^{-2}, this thermal contact resistance corresponds to a temperature difference of 0.15 ºC.

7. UNCERTAINTY ANALYSIS

An uncertainty analysis was done to verify whether the obtained results were reliable. This analysis was based on the uncertainty propagation procedure. In this procedure it is necessary to decide which errors will be analyzed. Therefore, the following errors were considered: temperature measurement, the imposed heat flux, measurement instruments, thermal contact resistance, imperfection of thermal insulation, and the numerical errors (BFGS and finite difference method. Therefore, the uncertainty analysis can be done by the sum of these considered errors in accordance with the theory of error propagation extracted from Taylor (1988).

When analyzing the experimental temperature for the AISI 304 stainless steel, the thermocouple error, the thermal contact resistance, the acquisition data error, and the imperfection of thermal insulation were considered. Thus:

$$U_Y^2 = U_{aquisition data}^2 + U_{thermocouple}^2 + U_{contact resistance}^2 + U_{thermal insulation}^2 \quad (7)$$

When considering the numerical temperature, the multimeters errors, which were used to measure the current and voltage values and the numerical error of the finite difference method were used. Therefore:

$$U_T^2 = U_{current multimeter}^2 + U_{voltage multimeter}^2 + U_{FDM}^2 \quad (8)$$

Finally, the uncertainty of the estimation can be calculated based on the objective function, which is composed of the experimental and numerical temperature and the BFGS method. Hence:

$$U_{final}^2 = U_Y^2 + U_T^2 + U_{BFGS}^2$$
$$U_{final}^2 = U_{aquisition data}^2 + U_{thermocouple}^2 + U_{contact resistance}^2 + U_{thermal insulation}^2$$
$$+ U_{current multimeter}^2 + U_{voltage multimeter}^2 + U_{FDM}^2 + U_{BFGS}^2 \quad (9)$$

After the final uncertainty has been defined, it is necessary to quantify the partial uncertainty. To define these values, the authors decided to consider each uncertainty divided by the mean value of the analyzed parameter. For example, the uncertainty of the thermocouple is equal its error (0.2 ºC) divided by the mean temperature (23.5 ºC). Thus, uncertainties are:

$$U_{aquisition\ \ data} = \frac{0.5}{23.5} = 2.13\ \% \qquad (10)$$

$$U_{thermocouple} = \frac{0.2}{23.5} = 0.85\ \% \qquad (11)$$

$$U_{contact\ resistance} = \frac{0.07+0.15}{23.5} = 0.94\ \% \qquad (12)$$

$$U_{thermal\ \ insulation} = \frac{0.12}{23.5} = 0.51\ \% \qquad (13)$$

$$U_{current\ multimeter} = \frac{0.01}{0.7} = 1.42\ \% \qquad (14)$$

$$U_{voltage\ multimeter} = \frac{0.1}{11} = 0.91\% \qquad (15)$$

$$U_{BFGS} = \frac{0.1}{23.5} = 0.43\ \% \qquad (17)$$

$$U_{FDM} = \frac{0.1}{23.5} = 0.43\ \% \qquad (18)$$

$$U_{final}^2 = 2.13^2 + 0.85^2 + 0.94^2 + 0.51^2 + 1.42^2 + 0.91^2 + 0.43^2 + 0.43^2$$

$$U_{final} = 3.10\ \% \qquad (19)$$

As it can be seen, the uncertainty value is in accordance with that found in the literature, because the presented value is lower than 5 %.

8. CONCLUSIONS

This paper presents a study of thermal contact resistance and uncertainty analysis in the simultaneous estimation of the thermal conductivity and the volumetric heat capacity of AISI 304 Stainless Steel. Good results were obtained for the properties estimation. The thermal contact resistance analysis was performed by considering the gap between the resistive heater and the sample, and the kapton layer of the resistive heater. The uncertainty analysis was carried out by taking into account the thermal resistance contact, experimental and numerical errors. Goods results were obtained for both analyses, since the thermal contact resistance resulted in a temperature difference around 0.2 ºC, and the uncertainty analysis presented a value of 3 %. A future proposal is to perform these analyses by considering thermal properties estimation by varying the initial temperature.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

Adjali, M.H. and Laurent, M., 2007. “Thermal conductivity estimation in non-linear problems”. International Journal of Heat and Mass Transfer Vol. 50, pp. 4623-4628.

Arctic Silver Incorporated, Arctic Silver® 5 High-Density Polysynthetic Silver Thermal Compound, Available at: http://www.arcticsilver.com/as5.htm, Access date: May 30, 2011

Beck, J., Cole, K., Haji-Sheikh, A. and Litkouhl, B., 1992. Heat Conduction Using Green's Function. Taylor & Francis p 552.

Borges, V.L., Lima e Silva, S.M.M. and Guimarães, G., 2006. “A dynamic thermal identification method applied to conductor and non conductor materials”. Inverse Problems and Sciences Engineering Vol. 14, pp. 511-527.

Borges, V.L., Souza, P.F.B. and Guimarães, G., 2008. “Experimental determination of thermal conductivity and diffusitivity using a partially heated surface method without heat flux transducer”. Inverse Problems in Science and Engineering Vol. 16, pp. 1047-1067.

Dowding, K.J., Beck, J., Ulbrich, A., Blackwell, B. and Hayes, J., 1995. "Estimation of thermal properties and surface heat flux in carbon-carbon composite". Journal of Thermophysics and Heat Transfer Vol. 9, pp. 345-351.

Ghrib, T., Yacoubi, N. and Saadallah, F., 2007, "Simultaneous Determination of Thermal Conductivity and Diffusivity of Solid Samples using the Mirage Effect Method". Sensors and Actuators, Vol.135, pp. 346-354.

Incropera, F.P., DeWitt, D.P., Bergman, T.L. and Lavine, A.S., 2007. Fundamentals of Heat and Mass Transfer. John Wiley & Sons, USA p 997.

Jannot, Y., Acem, Z. and Kanmogne, A., 2006, "Transient Hot Plate Method with Two Temperature Measurements for Thermal Characterization of Metals". Measurement Science and Technology, Vol.17, pp. 69-74.

Jannot, Y., Degiovanni, A. and Payet, G., 2009, "Thermal conductivity measurement of insulating materials with a three layers device". International Journal of Heat and Mass Transfer, Vol. 52, pp. 1105-1111.

Jannot, Y., Felix, V. and Degiovanni, A., 2010, "A centered hot plate method for measurement of thermal properties of thin insulating materials". Measurement Science and Technology, Vol. 21, pp. 1-8.

Kravvaritis, E.D., Antonopoulos, K.A. and Tzivanidis, C., 2011, "Experimental determination of the effective thermal capacity function and other thermal properties for various phase change materials using the thermal delay method". Applied Energy, Vol. 88, pp. 4459-4469.

Le Goff, R., Delaunay, D., Boyard, N., Jarny, Y., Jurkowski, T. and Deterre, R., 2009, "On-line temperature measurements for polymer thermal conductivity estimation under injection molding conditions". Internation Journal of Heat and Mass Transfer, Vol. 52, pp. 1443-1450.

Matweb, Kapton, Available at: www.matweb.com, Access date: February 16, 2012

Narumanchi, S., Mihalic, M., Kelly, K. and Eesley, G., 2008. "Thermal Interface Materials for Power Electronics Applications" In Proceedings of the 11th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems. Florida, United States, pp. 1-13.

Sanjaya, C.S., Wee, T. and Tamilselvan, T., 2011, "Regression analysis estimation of thermal conductivity using guarded-hot-plate apparatus". Applied Thermal Engineering, Vol. 31, pp. 1566-1575.

Taylor, B.N., 1988. The Physical Constants. Physics Letter B p 204.

Thomas, M., Boyard, N., Lefèvre, N., Jarny, Y. and Delaunay, D., 2010, "An experimental device for the simultaneous estimation of the thermal conductivity 3-D tensor and the specific heat of orthotropic composite materials". International Journal of Heat and Mass Transfer, Vol. 53, pp. 5487-5498.

Vanderplaats, G.N., 2005. Numerical Optimization Techniques for Engineering Design. McGraw Hill, USA, p 465.

Xamán, J., Lira, L. and Arce, J., 2009, "Analysis of the temperature distribution in a guarded hot plate apparatus for measuring thermal conductivity". Applied Thermal Engineering, Vol. 29, pp. 617-623.

11. RESPONSIBILITY NOTICE

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