ENCIT 2018

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0444
DEVELOPMENT OF AN EXPERIMENTAL DEVICE FOR THERMAL DIFFUSIVITY IDENTIFICATION OF METALLIC ALLOYS USING A PERIODIC TEMPERATURE FIELD

José Ricardo Ferreira Oliveira
Federal University of Uberlandia, Faculty of Mechanical Engineering, Experiment and Modelling Heat Transfer Laboratory. João Naves de Ávila Avenue, 2121, Zip Code 38900-402, Uberlandia City, Minas Gerais State, Brazil.
jose.ricardo@ufu.br

Luiz Roberto Rocha de Lucena
Federal University of Campina Grande, Department of Mechanical Engineering, Experimental Laboratory of Heat Transfer and Fluid Mechanics. Aprigio Veloso Street, 882, Zip Code 58429-140, Campina Grande City, Paraiba State, Brazil.
luiz.roberto@ufcg.edu.br

Rômulo Pierre Batista dos Reis
Federal University of Campina Grande, Department of Mechanical Engineering, Multidisciplinary Laboratory of Materials and Active Structures. Aprigio Veloso Street, 882, Zip Code 58429-140, Campina Grande City, Paraiba State, Brazil.
romulopierre@ufersa.edu.br

Carlos José de Araújo
Federal University of Campina Grande, Department of Mechanical Engineering, Multidisciplinary Laboratory of Materials and Active Structures. Aprigio Veloso Street, 882, Zip Code 58429-140, Campina Grande City, Paraiba State, Brazil.
carlos.araujo@ufcg.edu.br

Celso Rosendo Bezerra Filho
Federal University of Campina Grande, Department of Mechanical Engineering, Experimental Laboratory of Heat Transfer and Fluid Mechanics. Aprigio Veloso Street, 882, Zip Code 58429-140, Campina Grande City, Paraiba State, Brazil.
celso.rosendo@ufcg.edu.br

Abstract: *Thermophysical characterization of materials used in engineering is very important for realization of projects in a most areas of knowledge, where the phenomena linked to process of heat transfer have a great role. Thermal diffusivity is a very important thermophysical property in analysis of thermal energy diffusion problems. The objective of this work is the development of an experimental device for thermal diffusivity identification of metallic alloys, with operating principle based in Angstrom´s Method, which makes use of a periodic heat flow controlled by a power source, generating a periodic temperature field in the sample. The profiles of temperature field at certain points of the sample were captured by thermocouples, whose installation position in the sample are derived from the evaluating of sensitivity coefficients. Amplitude and phase of temperature-captured signals were obtained using graphic analysis software. A thermocouple is adopted as a reference. Ratio of the amplitude and phase lag between the thermal signals captured by the others thermocouples and by the reference thermocouple is therefore calculated. These results were inserted in mathematical models for thermal diffusivity identification. Samples used in this work were AISI 304 stainless steel and AISI 316 stainless steel. Thermal diffusivity values obtained for these materials, when compared with literature values, have a good agreement, within uncertainties range adopted.*

Keywords: *Experimental Device, Thermophysical Properties, Thermal Diffusivity, Angstrom´s Method, Periodic Temperature Field.*

1. INTRODUCTION

Appearance of new metal alloys, as a consequence of the process of technological advancement, attaches great importance to thermophysical characterization techniques, making them critical success factors in engineering projects [1]. This fact justifies the growing number of research and development of new techniques for the determination of thermophysical properties. Thermophysical property estimation is not an obvious task, and the problems are divided into two groups: design and solution of the mathematical model and experimental configuration [2]. There are several techniques for measuring thermophysical properties of materials. There are those who estimate the properties in isolation and those who estimate them simultaneously. In this context, the periodic techniques are assigned a great importance in measurements of thermophysical properties at low temperatures [3]. Among these, we highlight the technique proposed by Anders Jonas Angstrom, which printed a periodic heat flux in the test sample, provoking in this a periodic temperature field. An extremely important thermophysical property is thermal diffusivity. It reflects the relationship between the thermal energy that a medium can carry through the diffusion process and the energy it can store. In other words, thermal diffusivity shows how quickly heat can propagate in a given material. The objective of this work is the development of an experimental device to identify the thermal diffusivity of metallic alloys from the Angstrom's method. The samples used in this work are stainless steel AISI 304 and stainless steel AISI 316.

SIMBOLOGY

Symbol	*Description*	*Unit*	*Symbol*	*Description*	*Unit*
A	*Amplitude model*	-	χ		-
L	*Sample length*	*m*	ε	*Phase angles reference*	*rad*
t	*Time*	*s*	η		-
T	*Temperature*	*ºC*	Ψ	*Phase angle model*	*rad*
T_m	*Average temperature*	*ºC*	μ	*Uncertainty of thermal diffusivity*	m^2/s
x_n	*Thermocouple position in the sample*	*m*	σ	*Deviation from the literature*	-
α	*Thermal diffusivity*	m^2/s	ω	*Thermal frequency*	*rad/s*

2. MATHEMATICAL MODEL

In Figure 1, physical system that represents the problem presented in this work can be visualized.

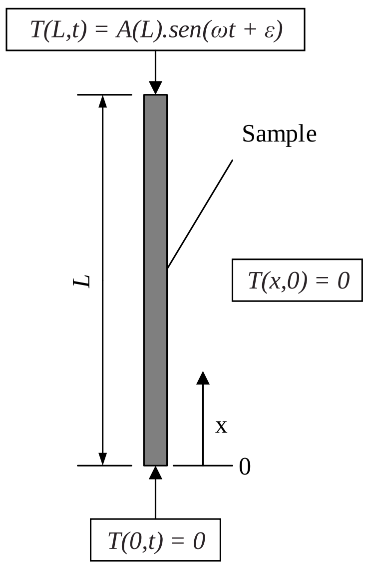


Figure 1. Physical system of this work

To arrive at the mathematical model that represents the physical system of Fig. 1 it is admitted that the experiments are carried out with the use of thermal insulation in contact with the lateral area of the sample, thus increasing the radial thermal resistance, ensuring that the heat flow occurs in the axial direction. In this case, the Biot number would assume values much smaller than 1 [4] for the experimental conditions in question, implying, therefore, that the temperature in each section of the sample is uniform during the transport of energy, so that the conduction heat transfer along the sample is one dimensional. It is further assumed that the thermal diffusivity variation with temperature is negligible and that the medium is isotropic with constant properties. Thus, considering a sample of length L, the mathematical model, the initial condition and the conditions of the problem are given respectively by:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

$$T(x,0) = 0\,; \qquad 0 \le x \le L \tag{2}$$

$$T(L,t) = A(L)\sin(\omega t + \varepsilon) \tag{3}$$

$$T(0,t) = 0 \tag{4}$$

A periodic heat flux with a given frequency was imposed on the upper part ($x = L$) which causes a periodic temperature field in the sample. The lower end was maintained at a constant temperature by being in contact with a fluid at which the temperature was controlled through a thermoregulator bath. The solution of this model was proposed by [3], and can be seen in Eq. (5):

$$T(x,t) = A(x)\, sin(\omega t + \varepsilon + \Psi) + 2\pi\alpha \sum_{n=1}^{\infty} \frac{n(-1)^n[\alpha n^2\pi^2 \, sin(\varepsilon) - \omega L^2 \, cos(\varepsilon)]}{\alpha^2 n^4 \pi^4 + \omega^2 L^4} \, sin\left(\frac{n\pi x}{L}\right) e^{-\left(\frac{\alpha n^2 \pi^2 t}{L^2}\right)} \tag{5}$$

Alternatively, periodic permanent temperature field solution was obtained when this regimen was reached [3]. For this, it is assumed that the transient variations of the temperature field cease when time increases (the transient term of Eq. (5) disappears when $t \to \infty$) such that in long times the condition of periodic regime is reached permanent. This solution is given by Eq. (6), whose deduction is in [5].

$$T(x,t) = A(x)\, sin(\omega t + \varepsilon + \Psi) \tag{6}$$

$$A = \left|\frac{sinh[x\beta(1+i)]}{sinh[L\beta(1+i)]}\right| = \left[\frac{cosh(2\beta x) - cos(2\beta x)}{cosh(2\beta L) - cos\, 2\beta L}\right]^{1/2} \tag{7}$$

$$\Psi = arg\left\{\frac{sinh[x\beta(1+i)]}{sinh[L\beta(1+i)]}\right\} \tag{8}$$

$$\beta = \sqrt{\frac{\omega}{2\alpha}}$$

3. METHODOLOGY

3.1 Experimental device

Figure 2 shows a schematic diagram of the experimental device developed for this work.

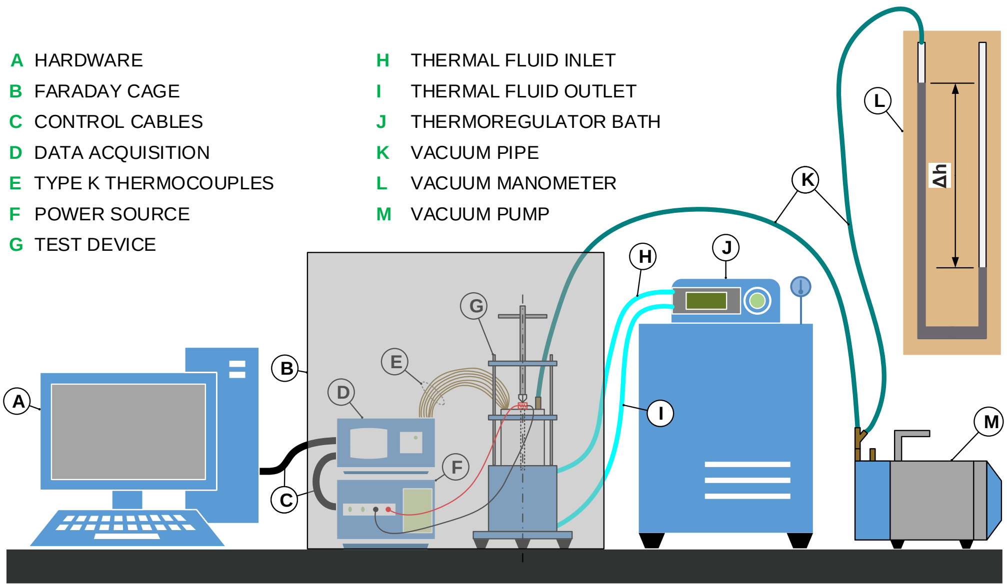


Figure 2. Experimental device

The device shown in Fig. 2 is comprised of the data acquisition, heating, cooling, vacuum, sample and test device systems. Test device has a cylindrical shape. It is where the sample is during the experiment. It can be seen in in Fig. 3.

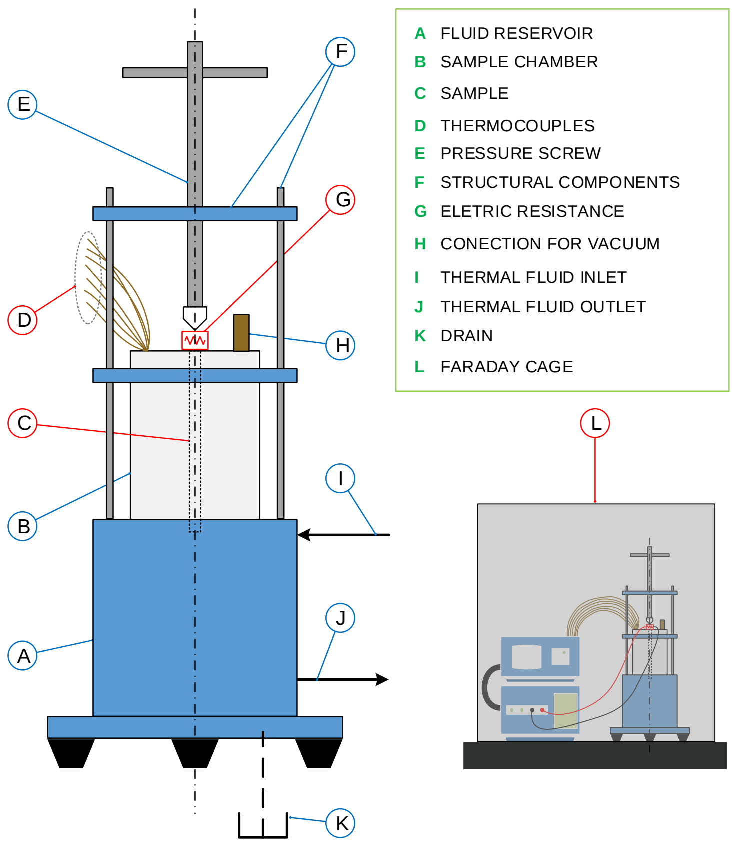


Figure 3. Test device details

According to Figure 3, sample chamber consists of a thin-walled stainless steel tube with a height of 123 mm and a diameter value of 100 mm was dimensioned from the concept of critical insulation radius. This is due to the possibility of the experiment being carried out either with vacuum or with thermal insulation inside the chamber. In this way, the dimensioned diameter was one for which the radial heat loss by the thermal insulation presented a negligible value. Sample chamber also includes two PVC closure closures that have a centralized bore of 12.7 mm, even the sample diameter . In the top cover there are two more holes: one with a diameter of 3 mm, where the thermocouples will pass and the other one with a diameter of 10 mm, for the installation of a vacuum connection inside the chamber. In the lower lid, in contact with the lower face of the sample and with the cooling fluid, there is a 2 mm thick copper disk, installed to prevent the entry of this fluid into the sample chamber by capillarity. It was assumed that this disk, because of the high thermal conductivity of the copper, is isothermal with respect to the cooling fluid. The chamber with the sample inside it is mounted on the fluid reservoir, where the cooling fluid circulates, at 0 ° C. It is worth mentioning, from Fig. 3, that the test device, data acquisition and power source during the experiments were housed inside a metal cage, based on the Faraday Cage principle. This cage was used to minimize the effects of disturbances caused by electromagnetic interference from eddy currents, known as Foucault currents.

3.2 Thermocouple installation and calibration

Fourteen type K thermocouples, $0,1 \times 10^{-3}$ m in diameter, were installed along the sample. The option for this type of thermocouple is due to the fact that it presents a linear behavior in its characteristic curve voltage versus temperature in a wide range, when compared to the other types of thermocouples. Anchorage of the thermocouples in the samples was done through the capacitive discharge welding process. This technique has the advantage of ensuring a perfect contact between the thermocouples and the points where it is desired to measure the temperatures and to reduce the response time that could come from a thermal contact resistance between the thermocouples and the test piece [6]. Welding sites of the thermocouples in each sample were defined from studies of sensitivity coefficients.

Sensitivity coefficient is a parameter that represents the intensity of variation of the mathematical model due to a small disturbance in the parameter analyzed. In other words, it is the partial derivative of the mathematical model in relation to said parameter. The greater its value, the easier and more accurate the identification of the parameter analyzed [7]. Sensitivity coefficient presented in the dimensionless form allows a better interpretation of the relative variations [8].

Equations (9) and (10) are, respectively, the dimensionless coefficients of sensitivity of the ratio of amplitudes and of the lag with respect to the thermal diffusivity.

$$\eta = \frac{\alpha}{A(x,L,\omega,\alpha)} \times \frac{\partial A(x,L,\omega,\alpha)}{\partial \alpha} \tag{9}$$

$$\chi = \frac{\alpha}{\Psi(x,L,\omega,\alpha)} \times \frac{\partial \Psi(x,L,\omega,\alpha)}{\partial \alpha} \tag{10}$$

Thermal diffusivity values, available from [4], were used to study the sensitivity coefficients of AISI 304 and AISI 316 stainless steels. Figures 4.a and 4.c refer respectively to the η and χ values for the AISI 304 stainless steel sample, in the same way as Fig. 4.b and Fig. 4.d are for the AISI 316 stainless steel sample. Regions with red color are those with the highest values of sensitivity coefficient in dimensionless form, whereas regions with the purple color are those with the lowest values of this parameter.

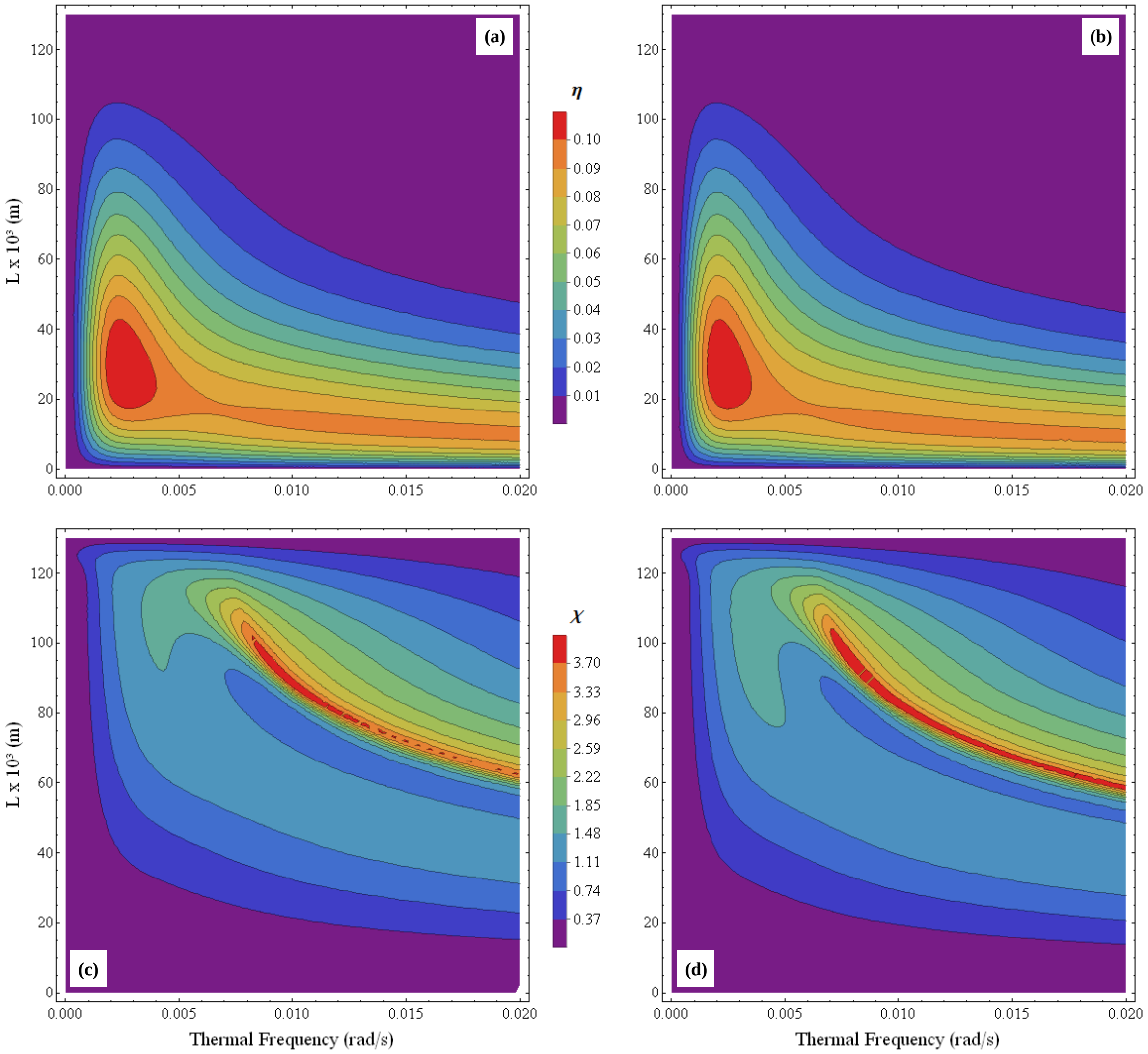
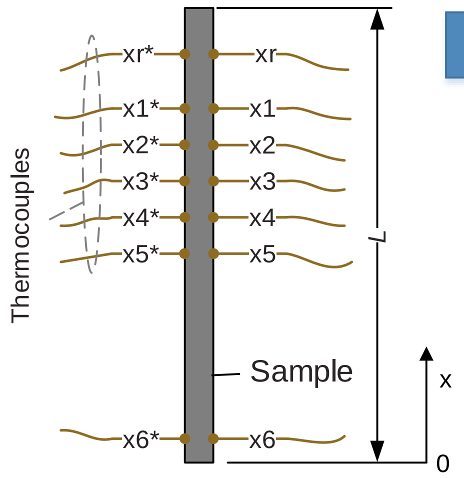


Figure 4. Sensitivity coefficient in dimensionless form

Figure 5 shows the identification adopted for each thermocouple and their arrangement along the sample, as well as the position of each thermocouple in relation to the origin adopted. To identify the thermal diffusivity, reference thermocouple "xr" and the thermocouples "x1" to "x5" were used, the thermocouple "x6" being used only to observe the behavior of the attenuation of the amplitude of the periodic oscillations of temperature. Thermocouples marked with (*) are the reserve thermocouples, and would be used if the respective thermocouple exhibited any defects during the experiment. The total length (L) of each sample is 150 x 10^{-3} m. The electrical resistance is in contact with the sample on the opposite side to the one that is the origin adopted. It is worth mentioning that, to avoid possible two-dimensional effects of heat transfer due to the proximity of the electric resistance, the reference thermocouple (xr) and its substitute (xr*) were installed at a certain distance from that component. In calculations for thermal diffusivity identification, the sample length was considered as the distance between the origin adopted and the location of installation of the reference thermocouple.



Thermocouples position (L x 10³ m)

Thermocouples	Sample AISI 304	Sample AISI 316
xr, xr*	130	130
x1, x1*	120	110
x2, x2*	115	105
x3, x3*	110	100
x4, x4*	105	95
x5, x5*	100	90
x6, x6*	5	5

Figure 5. Thermocouples identification and position in the sample

In order to minimize the errors of the temperature values to be measured, calibration procedures of the installed thermocouples are performed before the experiments for thermal diffusivity identification. These procedures, which were carried out in a metallic container, initially with melting ice and then with boiling water according to Fig. 6, consist of the lifting of thermocouples calibration curves, which were used to correct the temperature measured [in the thermal diffusivity identification experiments] in real temperature values.

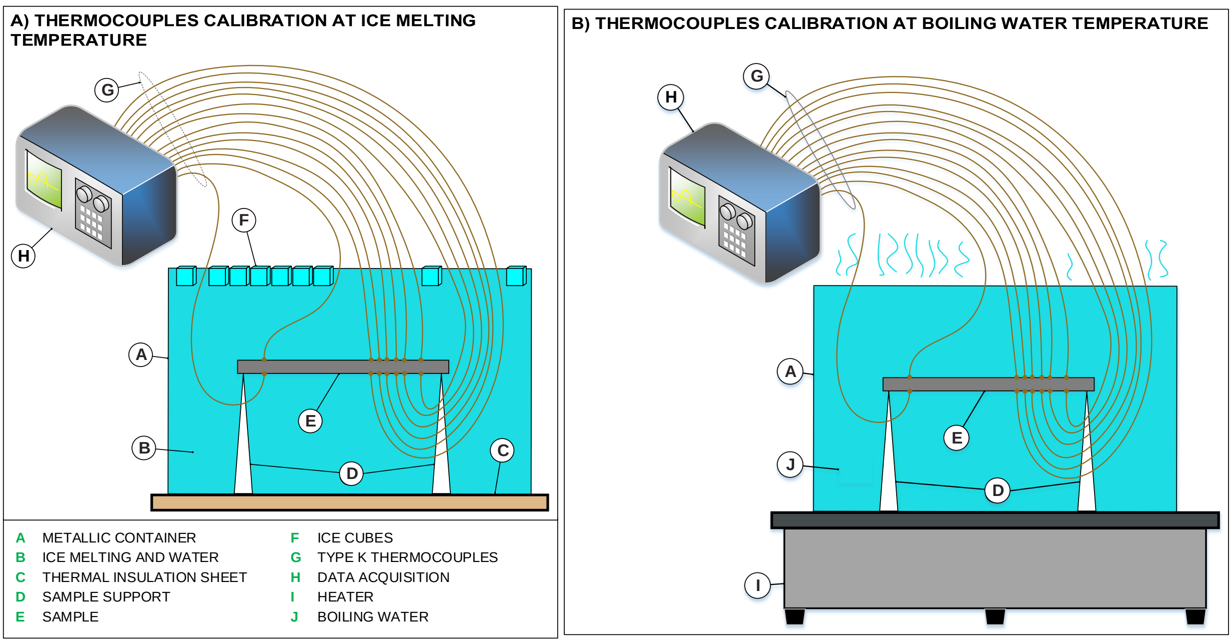


Figure 6. Thermocouples calibration

4. RESULTS AND DISCUSSIONS

A total of 9 experiments were carried out: 6 were made with AISI 304 stainless steel (3 with vacuum in the sample chamber and 3 with thermal insulation) and 3 with AISI 316 stainless steel (with thermal insulation in the sample chamber). The values of ω: 4,5 x 10^{-3}, 8,5 x 10^{-3} and 15,5 x 10^{-3} rad/s were adopted. Figure 7 shows the temperature profile due to the periodic heat flux, for ω = 8,5 x 10^{-3} rad/s. The values of A and Ψ were identified from the moment at which the transient perturbation connected to the initial condition is dissipated. Such instant was termed as the initial instant (t = 0 s) of the Permanent Periodic Regime.

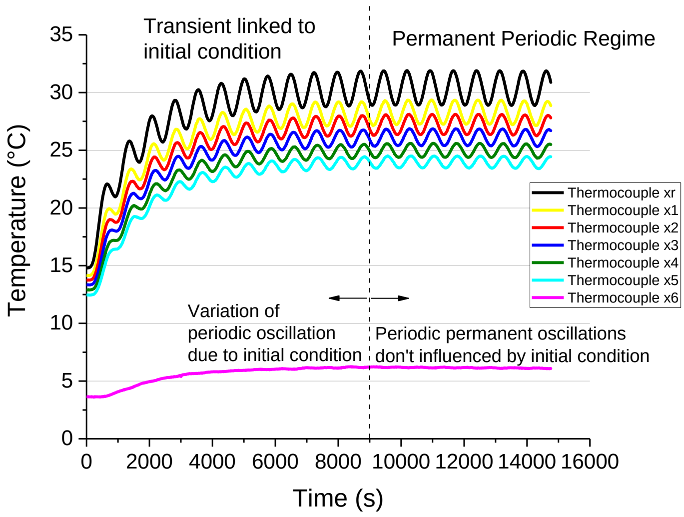


Figure 7. Sample temperature profile due to a periodic heat flow

Temperature curves shown in Fig. 7 prove what was shown by [3] for the resulting temperature field in a sample subjected to a periodic heat flux: as time increases, the transient perturbation is dissipated, and thermal field becomes a field with permanent periodic oscillations. The "Permanent Periodic Regime" is then constituted, and for the case shown in Fig. 7, such condition is reached after 5000 s from the beginning of the experiment.

Figures 8a, 9a and 10a show temperature profiles measured in the Permanent Periodic Regimen for ω = 8.5 x 10^{-3} rad/s. Figures 8b, 9b and 10b show the variation of T_m throughout the sample. Figures 11a, 12a and 13a show the values of A versus ω. Figures 11b, 12b and 13b show values of Ψ versus ω.

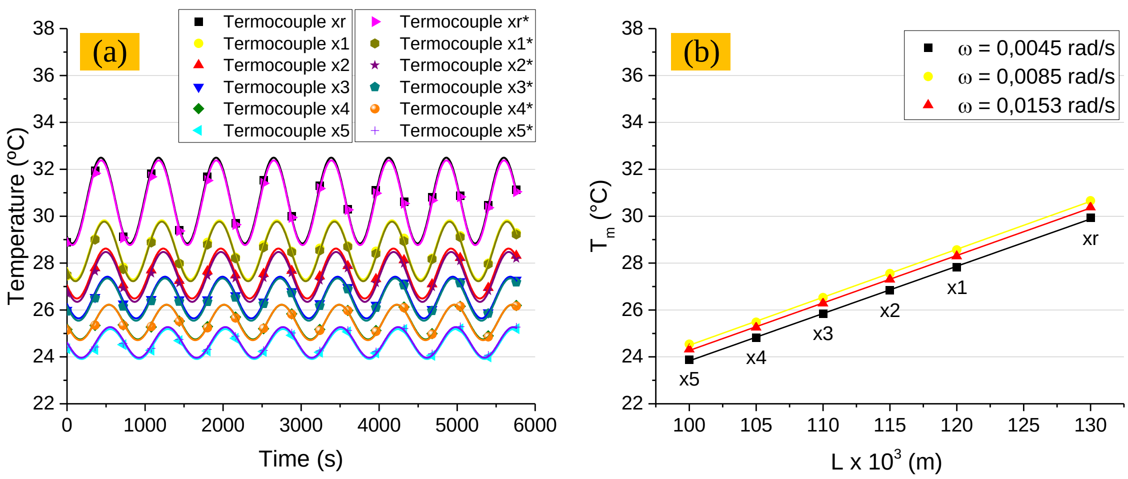


Figure 8. (a): Permanent Periodic Regimen ω = 8.5 x 10^{-3} rad/s; (b): T_m **x** L; AISI 304 stainless steel with vacuum.

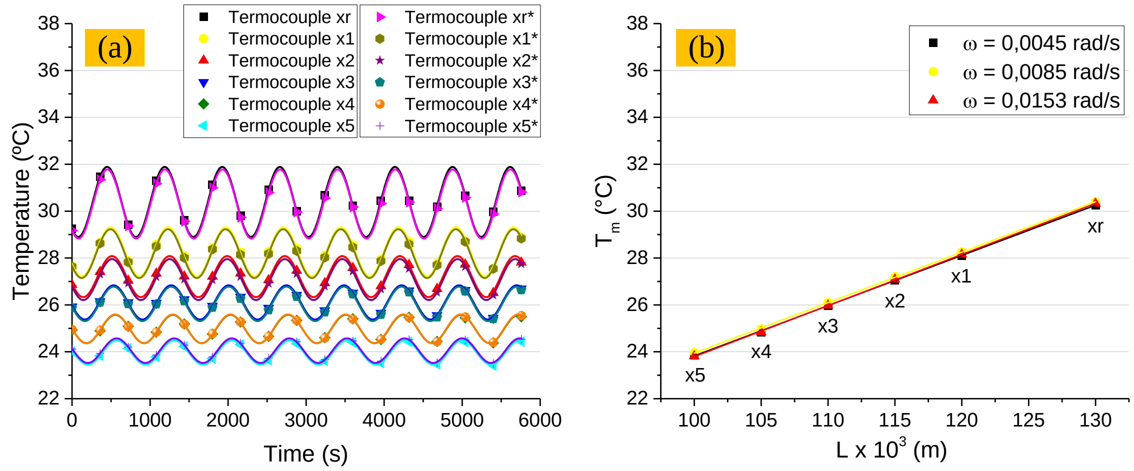


Figure 9. (a): Permanent Periodic Regimen ω = 8.5 x 10^{-3} rad/s; (b) :T_m **x** L; AISI 304 stainless steel with insulator

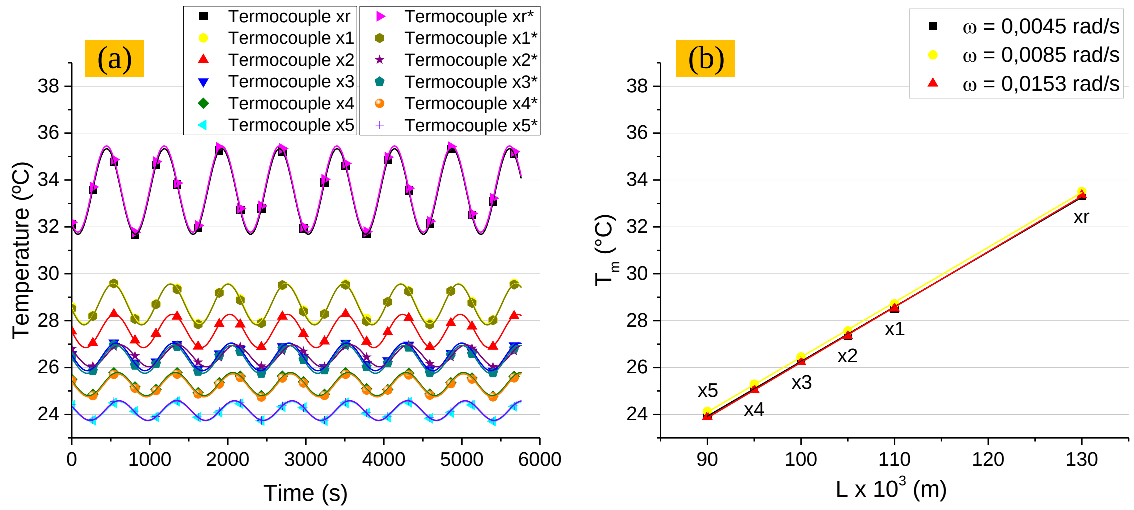


Figure 10. (a): Permanent Periodic Regimen ω = 8.5 x 10^{-3} rad/s; (b): T_m **x** L; AISI 316 stainless steel.

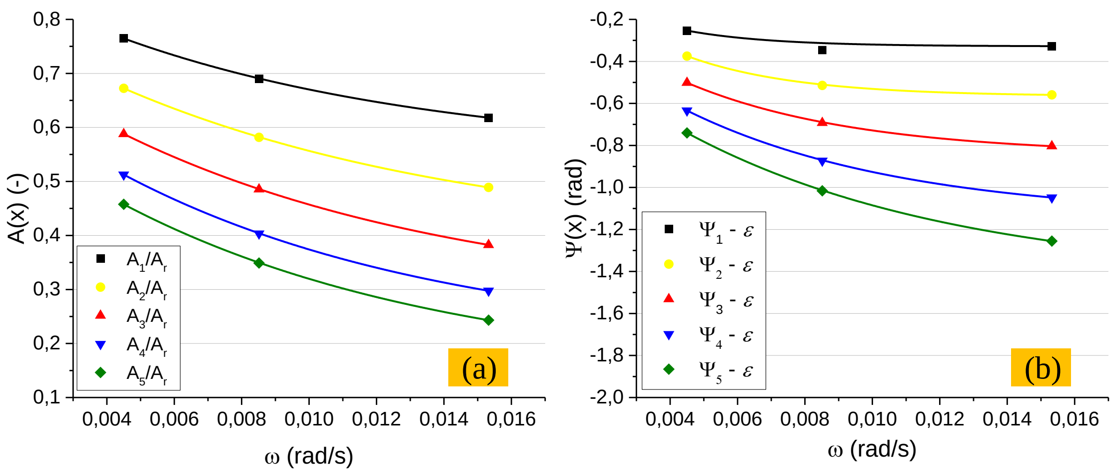


Figure 11. (a): A(x) *versus* ω; (b): Ψ(x) *versus* ω; AISI 304 stainless steel with vacuum.

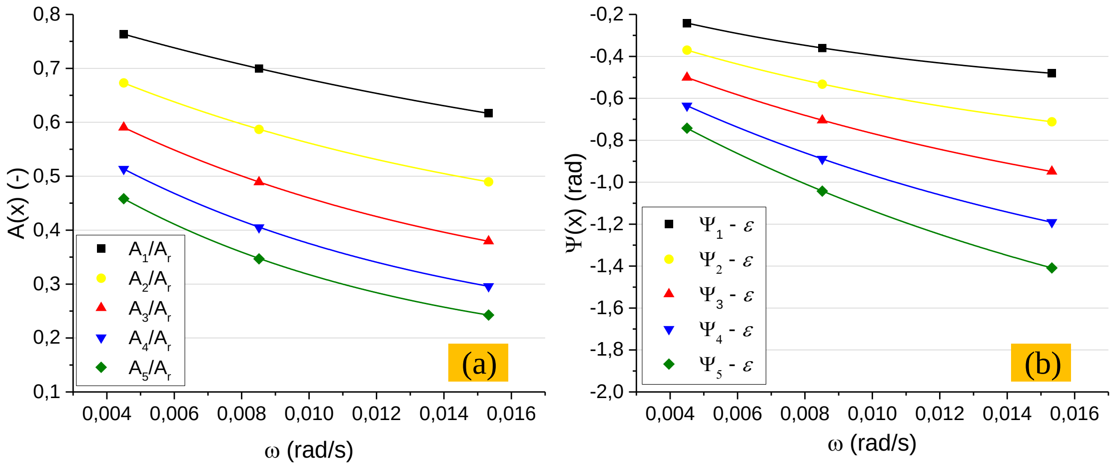


Figure 12. (a): A(x) *versus* ω; (b): Ψ(x) *versus* ω; AISI 304 stainless steel with thermal insulator.

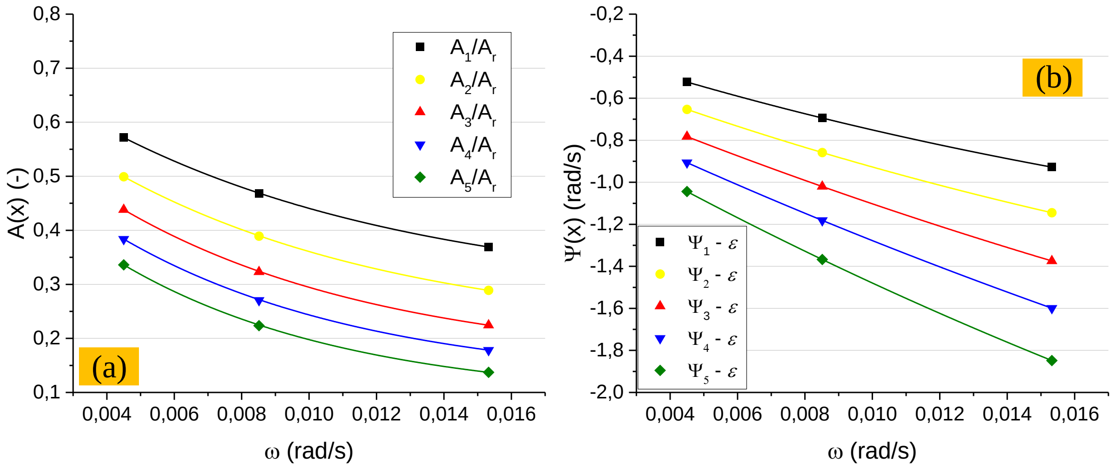


Figure 13. (a): A(x) *versus* ω; (b): Ψ(x) *versus* ω; AISI 316 stainless steel.

One-dimensional heat transfer hypothesis is proved through Figures 8a, 9a and 10a. For this hypothesis to be considered valid, the temperatures recorded by each pair of thermocouples (holder and reserve) must have approximate values, i.e., the temperature distribution must be uniform across the sample over time, and this was observed in the figures mentioned.

In Figs. 8b, 9b and 10b an increasing linear behavior of T_m as the thermocouple moves away from the origin with an excellent curve fit. This shows that the values actually considered are in the permanent periodic regime. In the AISI 304 stainless steel, it is verified that in the case of the use of thermal insulation in the sample chamber, regardless of the thermal frequency, the curves are practically the same, they overlap, which is theoretically expected behavior. However, the same behavior is not observed when using the vacuum, which gives greater reliability to the results when using thermal insulation.

The graphs obtained for *A(x)* versus *ω* (Fig. 11.a, 12.a and 13.a) shows that the amplitude of the model decreases exponentially with the increase in thermal frequency. Curves obtained for *Ψ(x)* versus *ω* (Fig. 11.b, 12.b and 13.b) shows that the phase lag between the temperature signals increases exponentially with increasing thermal frequency. Such behaviors were presented by [3] and obtained experimentally by [8].

The values of *A* and *Ψ* of each experiment, determined from the relation of the temperature profiles captured by thermocouples x_1 to x_5 in relation to those captured by thermocouple x_r, were inserted in their respective models, Eq. (7) and (8). Thus, for each experiment, 5 thermal diffusivity values through Eq. (7) and 5 values were identified through Eq. (8). From these values, the mean value of α and the standard uncertainty μ (α) were obtained and presented in Tab.1.

Table 2 shows comparisons between values obtained in this work with values available in the literature [10]. It is understood that the values identified herein are within a range of acceptable deviation from the literature.

Table 1. Thermal diffusivity values obtained experimentally.

ω	AISI 304 (vacuum)		AISI 304 (thermal insulator)		AISI 316	
	$[\alpha_A \pm \mu(\alpha)]$	$[\alpha_\Psi \pm \mu(\alpha)]$	$[\alpha_A \pm \mu(\alpha)]$	$[\alpha_\Psi \pm \mu(\alpha)]$	$[\alpha_A \pm \mu(\alpha)]$	$[\alpha_\Psi \pm \mu(\alpha)]$
$4,5 \times 10^{-3}$	3,22 ± 0,03	3,63 ± 0,04	3,23 ± 0,04	3,72 ± 0,06	2,97 ± 0,03	3.36 ± 0,02
$8,5 \times 10^{-3}$	3,26 ± 0,06	3,58 ± 0,04	3,34 ± 0,03	3,39 ± 0,04	3,01 ± 0,02	3,63 ± 0,04
$15,3 \times 10^{-3}$	3,34 ± 0,03	4,49 ± 0,13	3,31 ± 0,04	3,39 ± 0,02	3,11 ± 0,01	3,62 ± 0,02

Table 2. Thermal diffusivity values comparison with literature [10].

Stainless Steel	$[\alpha_A \pm \mu(\alpha)] \times 10^6$ (m²/s)	$[\alpha_\Psi \pm \mu(\alpha)] \times 10^6$ (m²/s)	[10]	σ_A (%)	σ_Ψ (%)
AISI 304 - vacuum	3,34 ± 0,03	3,63 ± 0,04	3,77	-11,41	-3,71
AISI 304 - t. insulator	3,34 ± 0,03	3,72 ± 0,06		-11,41	-1,33
AISI 316	3,11 ± 0,01	3.36 ± 0,02	3,46	-10,12	-2,89

5. CONCLUSIONS

This work aimed to the development of an experimental device to identify the thermal diffusivity of metal alloys. For calibration of this device, the AISI 304 and AISI 316 stainless steels were used, which are materials whose thermal diffusivity values can be found in the literature. The method of operation of the device is based on the Angstrom's method, in which a periodic heat flux is used in the sample, resulting in a periodic temperature field, being the differential of this method the fact that there is no need to know the intensity of the heat flow. The experiments performed on the samples resulted in thermal diffusivity values that have a good agreement with the literature, showing that the device is able to identify the thermal diffusivity of various metallic materials.

6. ACKNOWLEDGEMENTS

The authors acknowledge CNPq and CAPES for the financial support for this work.

7. REFERENCES

[1] CAROLLO, L. F. S.; LIMA E SILVA, A. L. F.; LIMA E SILVA, S. M. M. **Applying different heat flux intensities to estimate temperature-dependent thermal properties of metals**. In: 23RD ABCM INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING. Rio de Janeiro: 2015.

[2] BORGES, V. L. **Desenvolvimento do Método de aquecimento plano parcial para determinação simultânea de propriedades térmicas sem o uso de transdutores de fluxo de calor.** Tese de Doutorado - Uberlândia-MG: Universidade Federal de Uberlândia, 2008.

[3] CARSLAW, H. S.; JAEGER, J. C. **Conduction of heat in solids**. 2. ed. Oxford: Clarendon Press, 1959.

[4] INCROPERA, F. P.; DE WITT, D. P. **Fundamentos de Transferência de Calor e Massa**. 5. ed. Rio de Janeiro: LTC, 2003.

[5] FERREIRA OLIVEIRA, J. R. **Identificação da difusividade térmica de ligas metálicas utilizando um campo de temperatura periódico**. Dissertação de Mestrado - Campina Grande-PB: Universidade Federal de Campina Grande, 2017.

[6] BEZERRA FILHO, C. R.; LIMA E SILVA, S. M. M.; LAURENT, M.; RAYNAUD, M. **Determinação da difusividade térmica utilizando um sinal periódico**. In: 15TH BRAZILIAN CONGRESS OF MECHANICAL ENGINEERING. Águas de Lindóia-PR: 1999

[7] RAYNAUD, M. **Conception optimale des experiences**. Lyon: Centre de Thermique de l'INSA de Lyon, 1995.

[8] BEZERRA FILHO, C. R. **Etude des resistances thermiques de contact en regime periodique**. Tese de Doutorado - Lyon: L'Institut National des Sciences Appliquees de Lyon, 1998.

[9] BUREAU INTERNATIONAL DES POIDS ET MEASURES (BIPM). **Evaluation of measurement data - Guide to expression of uncertainty in measurement**. JCGM 100:2008, GUM 1995 with minor corrections. 1. ed., 2008.

[10] CAROLLO, L. F. S.; LIMA E SILVA, A. L. F.; LIMA E SILVA, S. M. M. **Applying different heat flux intensities to simultaneously estimate the thermal properties of metallic materials**. Measurement Science and Technology, n. 23, 2012.

8. RESPONSIBILITY NOTICE

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