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Experimental Determination of the Convective Coefficient of Heat Transfer Using the Global Capacitance Method

Fernanda da Silva Machado[1], Thaís Roberta Campos[2], Túlio Pinheiro Duarte[3], Felipe Raul Ponce Arrieta[4], Pedro Américo Almeida Magalhães Júnior[5]

[11] Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: machadofernanda484736@gmail.com
[2] Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: trcampos@sga.pucminas.br
[3] Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: tulio-p.duarte@outlook.com
[4] Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: felipe.ponce@pucminas.br
[5] Department of Mechanical Engineering, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brazil
Email: paamjr@gmail.com

Abstract**—***The heat transfer coefficient (h) is an extremely important variable in the evaluation of convective heat transfer, however, its determination is a great challenge due to the various factors that influence it: fluid viscosity, fluid density, specific heat of the fluid, thermal conductivity of the fluid, coefficient of volumetric expansion, fluid velocity. The objective of this work is the experimental determination of the convective heat transfer coefficient by means of the global capacitance method. Three test bodies, two cylindrical bodies and one spherical body were used. These specimens were individually heated in a stove, and heating was monitored by means of a thermocouple and a data logger. The results showed a good concordance between the values of h obtained experimentally and the literature.*

Keywords—Convective Coefficient, Global Capacitance, Heat Transfer, Transient Conduction

I. INTRODUCTION

Heat transfer is defined as the transmission of energy due to a temperature difference in a medium or between different means. There are three modes of heat transfer: conduction, convection, and radiation. The heat transfer by convection is classified in natural convection and forced convection, according to the nature of the fluid flow. Natural or free convection is defined when fluid movement occurs as a result of only the differences in specific mass caused by temperature gradients. When the flow of the fluid is induced by external agents, such as a pump, the process is called forced convection. [1]

The coefficient of heat transfer by convection or film coefficient, h, according to Newton's law of cooling, is the key point to obtain the amount of heat transferred from a surface to a fluid or vice versa. H is, in fact, a complex function that depends on the fluid flow, the physical properties of the fluid medium and the geometry of the system in question. In the case of the physical properties of the fluid and its flow, we can mention: dynamic fluid viscosity, fluid density, specific heat of the fluid, thermal conductivity of the fluid, coefficient of volumetric expansion, fluid velocity, acceleration of gravity and temperature difference between the surface and the fluid. With regard to geometry we can cite the characteristic dimension, dimension that dominates the phenomenon of convection. **Error! Reference source not found.**

One of the major challenges remains the determination of the average coefficient of convective heat transfer (h), for each process condition, which plays a decisive role in the processes involving heat transfer between a fluid and a solid. One of the most common causes of error in the calculation of the temperature of products is originated by the value adopted for this coefficient. In the literature there are recommended ranges for this value, but they do not adequately characterize the particular process. [3]

Considering the numerous variables that influence the calculation of h, there are no tables to obtain the convective coefficient. In general, in most engineering applications, h is determined experimentally and from empirical correlations. The importance of calculating the convective coefficient for a given specific situation, within a precision range, is essential for an adequate dimensioning of the thermal demands in question. **Error! Reference source not found.**

The phenomenon of transient conduction occurs in numerous engineering applications and can be analyzed using different methods. The nature of the procedure is closely related to the hypotheses made for the process. If, for example, temperature gradients inside the solid can be neglected, the global capacitance method can be used to determine the temperature variation over time. That is, it is assumed that during the transient process the temperature of the system is uniform, but it is not constant.[4] The objective of this work is the determination of convective coefficient in convection of solid bodies using the heating transient, applying the global capacitance method.

II. GLOBAL CAPACITANCE METHOD

Global capacitance method is based in the hypothesis that solid temperature is uniform in the space, for all time during transient process. That assumption means that temperature gradients inside solid are despicable.

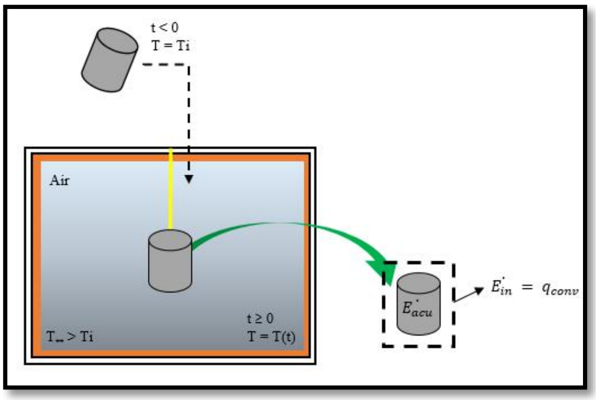

Fig.1: Heating a solid inside a stove

By Fourier Law, thermal conduction in the absence of a temperature gradient implies in existence of an infinity thermal conductivity. That assumption is impossible. However, the assumption is approximated if the resistance to conduction inside solid to be little in comparation to resistance to heat transference between solid and proximity [5].

By neglecting the temperature gradients inside the solid, it is not possible to analyze the problem using the heat equation, this because the heat equation is a differential equation that describe temperature spacial distribution inside the solid. An alternative is to determine the transient answer by formulation of an overall energy balance at solid [5].

Considering the situation in Fig.1*: Heating a solid inside a stove*, where a solid with uniform initial temperature Ti is heated inside a stove with higher temperature T∞ > Ti. If the heat process begins at time t = 0, the solid temperature will increase for times t > 0, until it reaches T∞. This increase is due to convective heat transfer at the solid-air interface. The overall energy balance must relate the rate of heat input at surface with the rate of variation of internal energy:

$$\dot{E}_{in} = \dot{E}_{acu} \qquad (1)$$

or

$$hA_s(T_\infty - T) = \rho V c_p \frac{dT}{dt} \qquad (2)$$

Setting the temperature difference as:

$$\theta = T - T_\infty \qquad (3)$$

and recognizing that (dθ/dt) = (dT/dt), if T∞ is constant, we have:

$$\frac{\rho V c_p}{hA_s}\frac{d\theta}{dt} = -\theta \qquad (4)$$

Separating variables and integrating from the initial condition at which t = 0 and T(0) = T:

$$\frac{\rho V c_p}{hA_s}\int_{\theta_i}^{\theta}\frac{d\theta}{\theta} = -\int_0^t dt \qquad (5)$$

in which:

$$\theta_i = T_i - T_\infty \qquad (6)$$

Making the integrations, it follows that:

$$-\ln\frac{\theta}{\theta_i}\frac{\rho V c_p}{hA_s} = t \qquad (7)$$

The importance of the global capacitance method is its inherent simplicity for the resolution of transient heating and cooling problems, in its use it is necessary to determine under what conditions it can be employed with satisfactory accuracy. When Biot number (B_i) is much less than 1 (B_i << 1), the resistance to conduction inside the solid is much less than the resistance to convection through the boundary layer in the fluid. Thus, the hypothesis of uniform temperature distribution at the intersection of the solid is reasonable for the Biot number to be small [5]. Generally, the following relation is used to validate the use of the global capacitance method:

$$B_i = \frac{h\,L_c}{k} < 0{,}1 \qquad (8)$$

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For convenience, it is common to define the characteristic length (L_c) as the ratio of the volume of the solid to its surface area:

$$L_c = \frac{V}{A_s} \quad (9)$$

III. MATERIALS AND EXPERIMENTAL PROCEDURE

For the accomplishment of the tests three test bodies were used, whose geometric characteristics and thermodynamic properties are presented in Table.1*: Geometric and thermal properties of test body 1*; a Magnus brand stove which reaches a maximum temperature of 300 ° C; a Novus Field logger data logger and T-type thermocouples.

Table.1: Geometric and thermal properties of test body 1

	Body 1	**Body 2**	**Body 3**
Geometry	Cylindrical	Spherical	Cylindrical
Diameter [m]	0,0254	0,0502	0,0254
Height [m]	0,1524	-	0,1524
Material	Electrolytic Copper	Electrolytic Copper	Brass
Density [kg/m³]	8.890,0	8.890,0	8.530,0
Cp [J/kg.°C]	385,0	385,0	380,0
k [W/m.°C]	395,0	395,0	127,0
T_∞ [°C]	255,0	255,0	255,0
Volume [m³]	$7,7232.10^{-5}$	$6,6238.10^{-5}$	$7,7232.10^{-5}$
Surface Area [m²]	0,0132	0,0079	0,0132

Thermal properties were obtained in [5]. The test bodies and experimental apparatus are shown in **Fig.2**: *Test bodies and experimental apparatus*

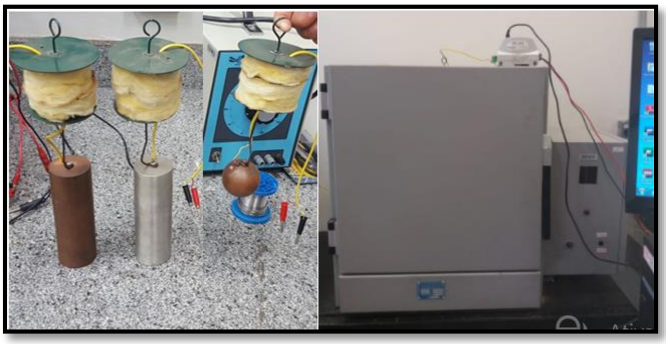

Fig.2: Test bodies and experimental apparatus

The experimental procedure consisted of heating the tests bodies individually inside the stove until a temperature of 200 °C, while the data logger recorded the temperature and time. Subsequently, the heat transfer coefficient was determined using the global capacitance method presented in item II.

IV. RESULTS AND DISCUSSION

In order to calculate the convective coefficient, the obtained data were treated, and the curve -Ln (θ/θi) x was lifted, and by means of the angular coefficient (m), it was possible to obtain the convective coefficient using equation 7. The heating profile and the curve -Ln (θ/θi) x time for each test body are shown in Fig.3*: Heating profile and -Ln (θ/θi) x time for test body 1* Fig.*4: Heating profile and -Ln (θ/θi) x time for test body 2* and Fig.*5: Heating profile and -Ln (θ/θi) x time for test body 3.*

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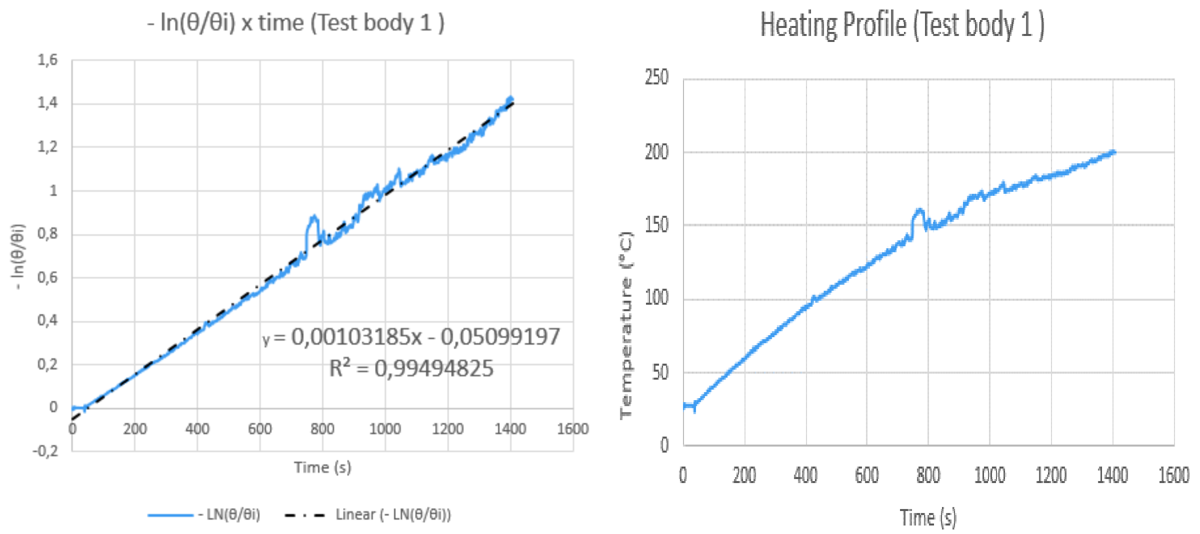

Fig.3: Heating profile and -Ln (θ/θi) x time for test body 1

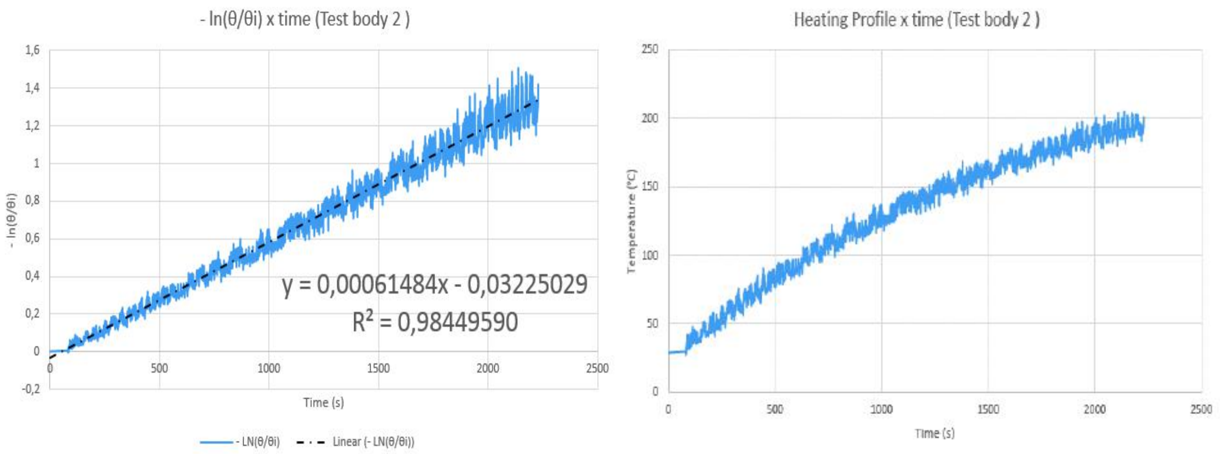

Fig.4: Heating profile and -Ln (θ/θi) x time for test body 2

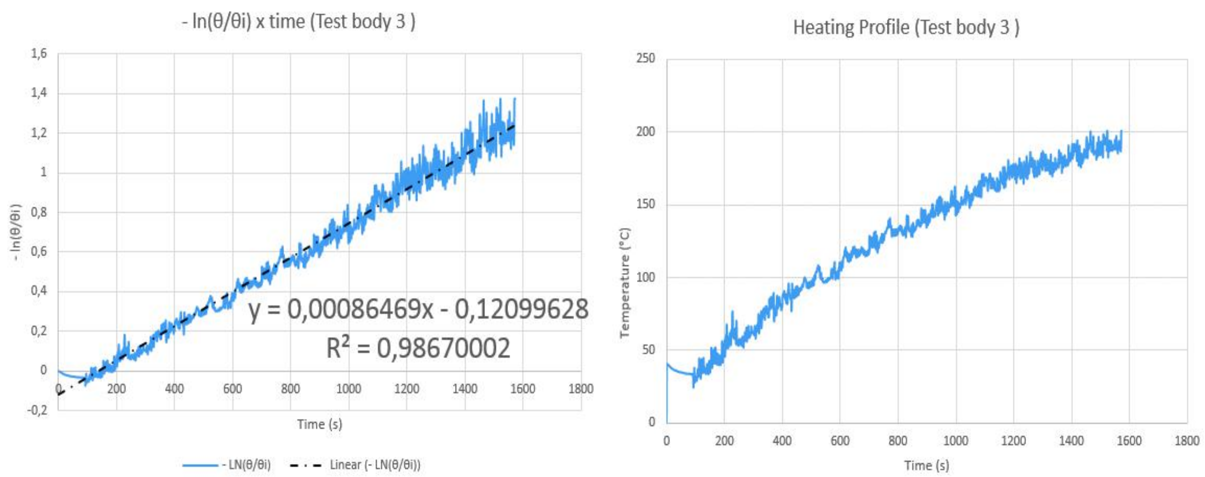

Fig.5: Heating profile and -Ln (θ/θi) x time for test body 3

Table.2: *Main results* presents the convective coefficients obtained during the thermal exchange of each of the test bodies and also the respective values for the Biot number.

Table.2: Main results

	Body 1	Body 2	Body 3
m	$1{,}032.10^{-3}$	$0{,}615.10^{-3}$	$0{,}865.10^{-3}$
h [W/m².K]	20,70	17,61	16,43

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lc	0,0059	0,0084	0,0059
Bi	0,0003	0,0004	0,0008

It is important to note that the use of the global capacitance method for determining the heat transfer coefficient is valid because the Biot number values are much less than 0,1 for all test specimens, these values were calculated using equation 8 and are set forth in Table.*2: Main results* 2.

According to Incropera et al. [5], typical values for the convection heat transfer coefficient for natural convection gases are between 2 to 25 W/m².K, so the values found were satisfactory, since they are within this range. The value of this coefficient for the copper cylinder (*test body 1*) was 20,70W/m².K, while that of the sphere (*test body 2*) of the same material was equal to 17,61W / m².K, which demonstrates the influence of the surface form. The heat transfer coefficient for the brass cylinder (*test body 3*) evaluated was equal to 16,43W/m².K, demonstrating the influence of the material on the convective coefficient. The linear coefficient of the curves -Ln (θ / θi) x time did not result in zero as expected. This deviation is due to the errors built into the experiment and the model, ie the temperature inside the greenhouse is not really constant over time and the temperature distribution inside the solid is not uniform.

V. CONCLUSION

The heat transfer coefficient, h, was obtained experimentally from the global capacitance method, since its validity was proved for the situations analyzed. The obtained values indicate a good agreement with the typical values indicated in the literature for the natural convention range between gases and solid bodies. With the experimental results, it is possible to observe the sensitivity of the convective coefficient of heat transfer to the superficial form and also to the material. In addition, the simplicity of the use of the global capacitance method in simplified transient conduction situations and their applicability was verified.

VI. ACKNOWLEDGEMENTS

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