25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0463
ANALYSIS OF THE TEMPERATURE FIELD FOR CHARACTERIZATION OF THE CONCENTRATION OF THE WATER-ALCOHOL MIXTURE

Pedro Granville Gonçalves
Dhiego Luiz de Andrade Veloso
Universidade Federal da Paraíba, Cidade Universitária - João Pessoa - PB - Brasil - CEP: 58051-900
Instituto Federal da Paraíba - IFPB, Jaguaribe - João Pessoa - PB - Brasil - CEP: 58015-430
pedrogranville@gmail.com
dhiego_vel@hotmail.com

Márcio Andrade Rocha
Carlos Antônio Cabral dos Santos
Universidade Federal da Paraíba, Cidade Universitária - João Pessoa - PB - Brasil - CEP: 58051-900
rochandrademarcio@hotmail.com
carloscabralsantos@yahoo.com.br

Jobson Francisco da Silva
Instituto Federal da Paraíba - IFPB, Jaguaribe - João Pessoa - PB - Brasil - CEP: 58015-430
jobsonfsilva@ig.com.br

Abstract. *This paper investigates heat transfer by conduction inside a circular tube filled with a fluid composed of different fractions of the water-ethyl alcohol mixture. The energy equation, which governs the problem, was solved by the generalized integral transform technique (GITT), which presents itself as a well-established method for solving problems of heat and mass diffusion. With the aid of the engineering equation solver (EES) software, we obtained the thermodynamic properties of the studied fluid through pre-defined mathematical functions. The results presented in the form of graphs and tables allow us to analyze the influence of different concentrations of the studied fluid on the development of the temperature field.*

Keywords: *Mixture water-alcohol, temperature field, GITT.*

1. INTRODUCTION

Mixtures containing water and an amphiphilic and / or hydrophobic solute have been extensively studied in recent years. A brief bibliographic review can be found in (Akpa et al., 2012; Hilser, 2011; Ball, 2008 and Palo et al., 2007). The applications of this study play an important role in many biological, chemical and engineering applications, examples include protein folding, membrane self-assembly, electron transfer reactions, heterogeneous catalysis and fuel cell technology (Li et al., 2014).

In the present work, we use GITT to study heat transfer – radial diffusion and periodic boundary conditions formulation - describing the behavior of temperature dynamics inside a cylindrical tube filled with volumetric fractions of 0, 4, 8, 12, 16 and 20 percent of ethyl alcohol mixed with water. The theoretical values of thermal properties, adopted as parameters for computational simulation, such as: thermal conductivity, specific mass, specific heat and thermal diffusivity, were extracted from the engineering equation solver (EES) software, since the alcohol content also exerts a great interference on the thermophysical properties of alcohol-water mixtures (Perez, 2013; Wakisaka, 2011).

2. PHYSICAL SYSTEM AND MATHEMATICAL MODELING

2.1 Model assumptions

In order to simplify the hydrodynamic model, the following considerations were adopted:

- Heat conduction equation in cylindrical coordinates;
- System is insulated, analysis neglects losses effects to environment;
- Initially in thermal equilibrium;

- Temperature gradients in longitudinal and angular directions weren´t considered;
- Constant thermal properties;
- Cylinder’s length is considered much longer than its radio.

2.2 Mathematical modeling

Energy equation:

$$\rho c_p \frac{\partial T(r,t)}{\partial t} = k \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T(r,t)}{\partial r}\right) \qquad (1)$$

Boundary conditions:

$$r = 0 \rightarrow \frac{\partial T(r,t)}{\partial r} = 0 \qquad (2)$$

$$r = r_0 \rightarrow T(r,t) = T_p \sin(\omega t) + T_w \qquad (3)$$

Initial condition:

$$t = 0 \rightarrow T(r,0) = T_0 \qquad (4)$$

2.2.1 Dimensionless form

The dimensionless groups adopted for the model are:

$$R = \frac{r}{r_0} \quad ; \quad \tau = \frac{\alpha t}{r_0^2} \quad ; \quad \theta(R,\tau) = \frac{T(r,t) - T_w}{T_0 - T_w} \qquad (5\text{-}7)$$

Energy equation dimensionless:

$$\frac{\partial \theta(R,\tau)}{\partial \tau} = \frac{1}{R}\frac{\partial}{\partial R}\left[R \frac{\partial \theta(R,\tau)}{\partial R}\right] \qquad (8)$$

Boundary conditions dimensionless:

$$R = 0 \rightarrow \frac{\partial \theta(R,\tau)}{\partial R} = 0 \qquad (9)$$

$$R = 1 \rightarrow \theta(1,\tau) = \theta_p(\tau) = \frac{T_p \sin\left(\frac{\omega r_0^2 \tau}{\alpha}\right)}{T_0 - T_w} \qquad (10)$$

Initial condition dimensionless:

$$\tau = 0 \rightarrow \theta(R,0) = 1 \qquad (11)$$

2.2.2 Auxiliay eigenvalue problem in the radial direction

The auxiliary problem for the temperature field can be described by a system of second order differential equations, representing a classic Sturm-Liouville problem. The auxiliary problem chosen for the determination of the temperature field is written as follows:

$$\frac{1}{R}\frac{\partial}{\partial R}\left(\frac{R d\psi_i R}{dR}\right) + \mu_i^2 \psi_i(R) = 0 \qquad (12)$$

$$R = 0 \rightarrow \frac{d\psi_i(R)}{d(R)} = 0 \qquad (13)$$

$$R = 1 \rightarrow \psi_i(R) = 0 \qquad (14)$$

The signal count method developed by (Mikhailov and Vulchanov, 1983) was used for determining the eigenvalues (μ_i), the eigenfunctions, $\psi_i(R)$, and the norms ($N_i = \int_0^1 R\psi_i^2(R)dR$).

2.2.3 Integral transformation of the temperature field

GITT is based on the fact that a function can be written as an expansion in terms of eigenfunctions (Cotta, 1993). Thus, the transformed-inverse pair is given by:

$$\bar{\theta}_i(\tau) = \frac{1}{N_i^{1/2}} \int_0^1 R\psi_i(R)\theta(R,\tau)dR \tag{15}$$

$$\theta(R,\tau) = \sum_{i=1}^{\infty} \frac{\psi_i(R)\bar{\theta}_i(\tau)}{N_i^{1/2}} \tag{16}$$

After analytical treatment of Eq. (8) by integral operators, using the definition of the integral transform given by Eq. (15), as well as using the auxiliary problem defined by Eq. (12), (13) and (14), we can transform problem in the following ODE system:

$$\frac{d\bar{\theta}_i(\tau)}{d\tau} + \mu_i^2\bar{\theta}_i(\tau) = -\frac{1}{N_i^{1/2}}\frac{d\psi_i(1)}{dR}\theta(1,\tau) \tag{17}$$

This ODE has classic solution given by:

$$\bar{\theta}_i(\tau) = \bar{\theta}_i(0)e^{-\mu_i^2\tau} - \frac{1}{N_i^{1/2}}\frac{d\psi_i(1)}{dR}\left(\frac{T_p}{T_0 - T_w}\right)\left[\frac{-\frac{\omega r_0^2}{\alpha}\cos\left(\frac{\omega r_0^2\tau}{\alpha}\right) + \mu_i^2\sin\left(\frac{\omega r_0^2\tau}{\alpha}\right) + \frac{\omega r_0^2}{\alpha}e^{-\mu_i^2\tau}}{\frac{\omega^2 r_0^4}{\alpha^2} + \mu_i^4}\right] \tag{18}$$

Such that:

$$\bar{\theta}_i(0) = \bar{f}_i = \int_0^1 \frac{R\psi_i(R)}{N_i^{1/2}}dR \tag{19}$$

3. RESULTS

Theoretical results were obtained through computational code written in FORTRAN programming language using Fortran PowerStation 4.0 software.

The most relevant parameters involved in this analysis are: the thermal diffusivity of the mixture, the tube radius, period and amplitude of the thermal oscillation. The results shown show that small changes in each of these parameters correspond to noticeable differences observed in the peak temperature and phase angle of the temperature signals measured at the center of the tube.

The theoretical values of the thermal diffusivity of the mixtures, adopted as parameter for computational simulation, were obtained from the engineering equation solver (EES) software. The table below contains the thermal diffusivity values for each concentration analyzed. In the temperature ranges evaluated in the present work, from 293.15K to 303.15K, from 288.15K to 308.15K and from 283.15K to 303.15K, a small variation in the thermal diffusivity values was observed, we consider them constant from an average value.

Table 1. Thermal diffusivity values for different fractions of the water-alcohol mixture obtained with the software (EES).

Concentration (%)	Average diffusivity (293.15 K to 303.15 K)	Average diffusivity (288.15 K to 308.15 K)	Average diffusivity (283.15 K to 313.15 K)
0	1.460×10^{-7}	1.459×10^{-7}	1.456×10^{-7}
4	1.383×10^{-7}	1.382×10^{-7}	1.380×10^{-7}
8	1.308×10^{-7}	1.307×10^{-7}	1.305×10^{-7}
12	1.239×10^{-7}	1.238×10^{-7}	1.237×10^{-7}
16	1.179×10^{-7}	1.178×10^{-7}	1.177×10^{-7}
20	1.127×10^{-7}	1.126×10^{-7}	1.126×10^{-7}

With the aid of the engineering equation solver (EES) software, which has its own library of predefined thermophysical functions, we have obtained the thermodynamic properties of the studied fluid. The thermal diffusivity values, for different concentrations of the water-alcohol mixtures as a function of the concentrations and temperatures, are presented in the graph below.

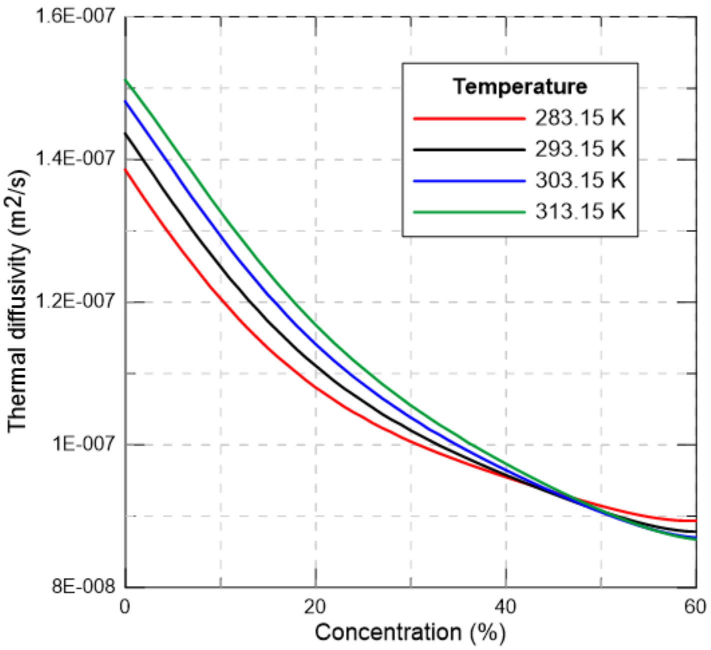

Figure 1. Thermal diffusivity curves by concentration for different temperatures.

Observing the thermal diffusivity curves by the concentration, it is possible to perceive that their behavior is similar to an asymptotic function, that is to say, as the alcoholic concentration increases the values of thermal diffusivity tend to get closer and closer, from 20% of alcohol. In order to obtain a higher sensibility of measuring the concentration of the water-alcohol mixture, we chose the region of the curve, between 0% and 20%, where its behavior is approximately linear.

The influence of the amplitude of the thermal oscillation in the tube wall on the temperature dynamics in the center of the tube was evaluated. Simulations were performed with three distinct values - 278.15, 283.15 and 288.15K - amplitude, the results are presented in the graphs and tables below.

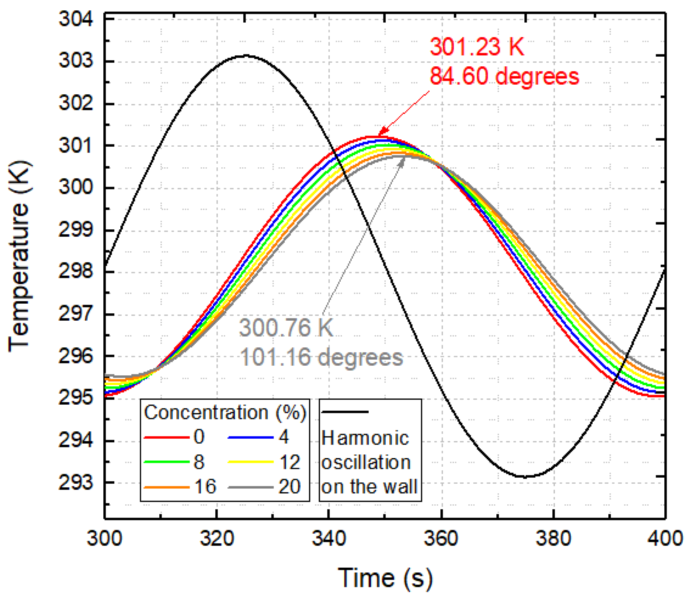

Figure 2. Temperature measurements as a function of time for a tube with radius of 4mm, frequency of 0.01Hz and amplitude of 278.15K.

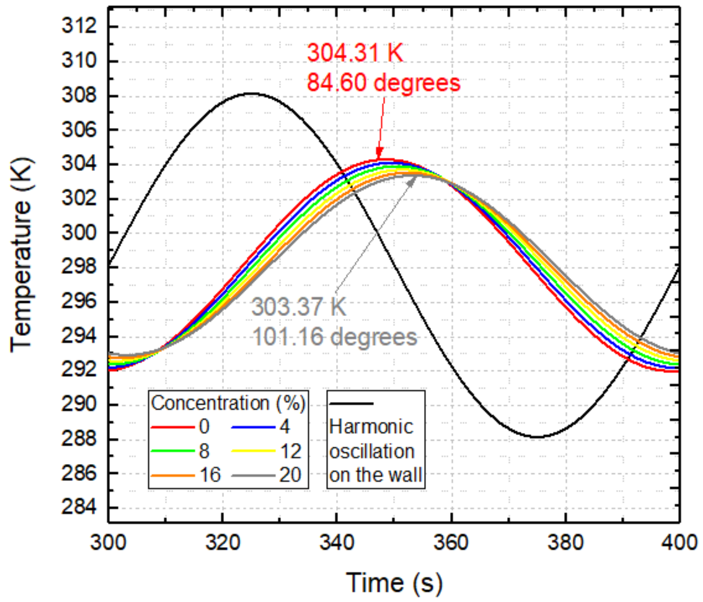

Figure 3. Temperature measurements as a function of time for a tube with radius of 4mm, frequency of 0.01Hz and amplitude of 283.15K.

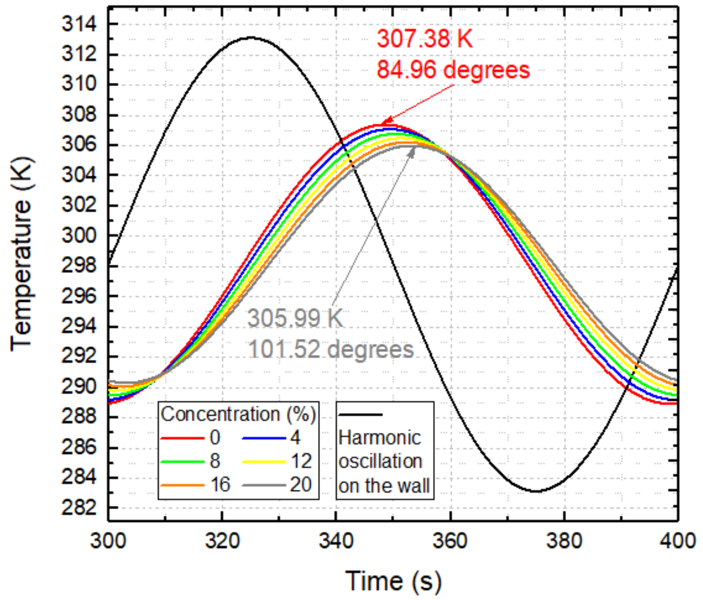

Figure 4. Temperature measurements as a function of time for a tube with radius of 4mm, frequency of 0.01Hz and amplitude of 288.15K.

Figures 3-5 show the relationship between the temperature curves measured in the sample and the periodic heat flow curve in the wall. From the figures above, a gradual increase in peak temperature values can be observed as we increase the amplitude of periodic excitation, in other words, the signals acquired in the sample tend to increase the difference between the temperature peaks for each concentration, whereas, the phase angle values remain constant.

In order to evaluate the diameter of the tube that was able to provide the best response to the system under study and to indicate the best mechanical design, simulations were performed with 4, 6 and 8mm long radii.

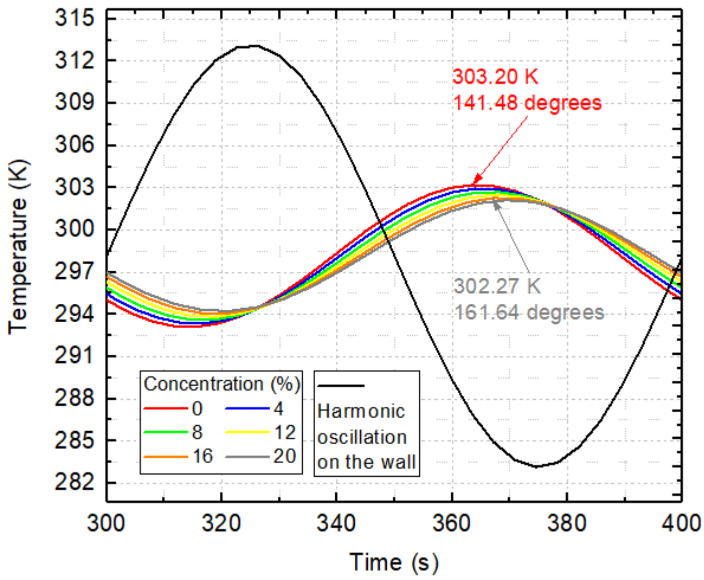

Figure 5. Temperature measurements as a function of time for a tube with radius of 6mm, frequency of 0.01Hz and amplitude of 288.15K.

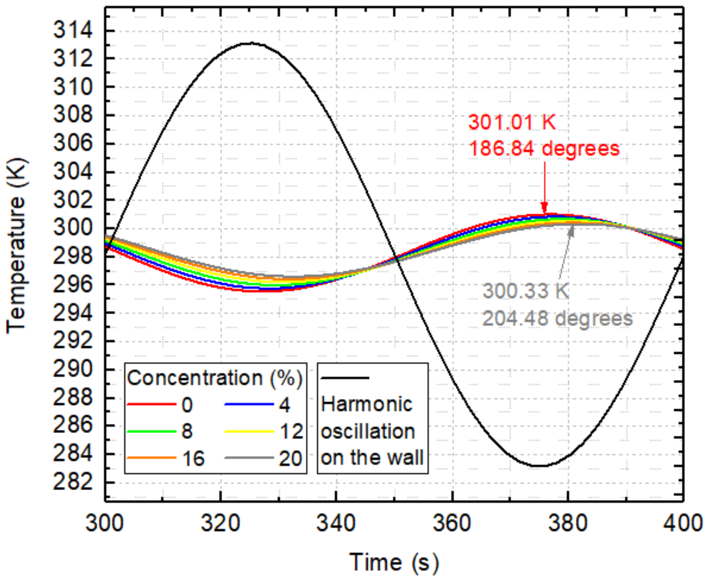

Figure 6. Temperature measurements as a function of time for a tube with radius of 8mm, frequency of 0.01Hz and amplitude of 288.15K.

From the curves shown in Fig. 5 and 6, the temperatures measured at the center of the tube show a considerable difference in both peak temperature and phase angle, for different concentrations, when compared with Thermal excitation signal on the tube wall. It can also be seen that the tube radius directly reflects the temperature dynamics at the center of the tube, these differences occur due to the delay of thermal propagation caused by the distance between the excitation source and the sample measurement sensor. The results indicate that as the pipe radius increases, the greater the attenuation of the measured signal will be.

In order to understand the influence that the frequency of thermal oscillation would have on the thermal signals measured by the thermocouple immersed in the sample, simulations were performed considering the following excitation frequencies: 0.02 and 0.005Hz. In the figures below, we can see the results of the temperature curves, caused by the thermal oscillation in the wall, for the simulations of the analyzed frequencies.

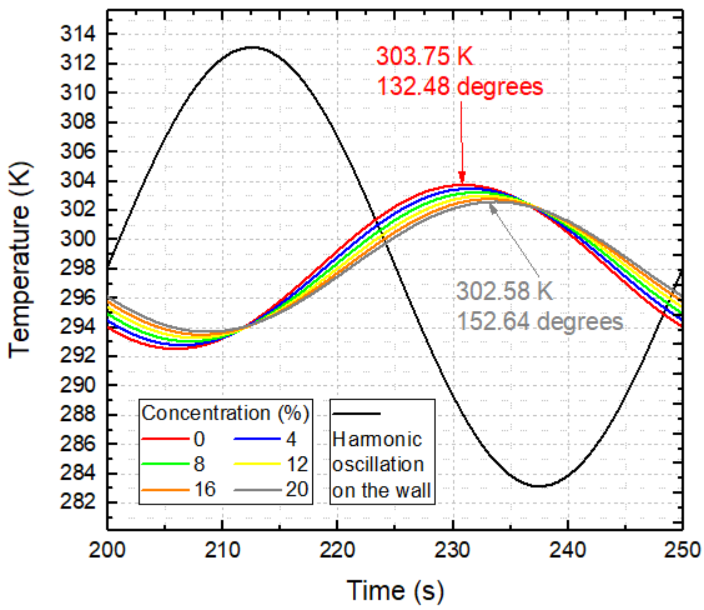

Figure 7. Temperature measurements as a function of time for a tube with radius of 4mm, frequency of 0.02Hz and amplitude of 288.15K.

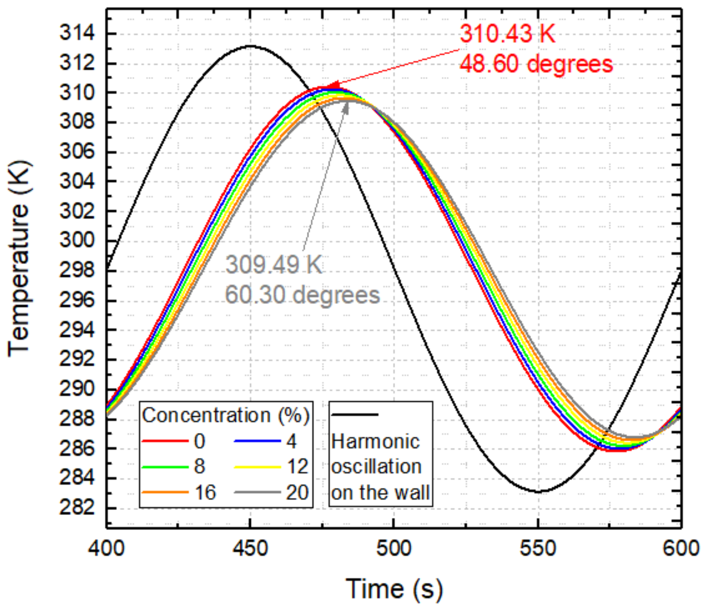

Figure 8. Temperature measurements as a function of time for a tube with radius of 4mm, frequency of 0.005Hz and amplitude of 288.15K.

According to Fig. 7 and 8, the temperature dynamics in the center of the tube can be verified for different frequencies of the thermal oscillation in the wall. Sample temperature curves show that certain frequency values cause different peak temperature and phase angle values. However, in practical terms, very high frequencies require intense heat exchange, in other words, removing and placing heat in a very short time span and heat exchange capacity of a thermal control system, as well as very low frequencies may require a very long time to perform the experimental measurements.

The graphs depicted in Fig. 2-8 analyze the development of the thermal field for the different concentrations of the water-ethyl alcohol mixture. It can be observed that small changes in each of these parameters correspond to notable differences observed in the peak temperature and in the phase angle of the temperature signals.

The results show that the harmonic perturbations in the tube wall tend to propagate through the fluid until reaching the center of the tube with different amplitudes and phases, according to the concentration analyzed.

4. CONCLUSIONS

In this work, it is concluded from the analysis of the results obtained that the application of GITT is effective in solving the proposed problem. In this way, the objectives were satisfactorily achieved, showing the influence of the alcohol on the temperature dynamics of the mixture. The results showed that it is possible to detect changes in the development of the thermal field when variations occur in the concentration values of the water-alcohol mixture. The data show the potentiality of the method used in the characterization of liquid mixtures.

5. ACKNOWLEDGEMENTS

The authors acknowledge the CNPq and UFPB for financial support.

6. REFERENCES

Akpa, B. S.; D ’ Agostino, C.; Gladden, L. F.; Hindle, K.; Manyar, H.; McGregor, J.; Li, R.; Neurock, M.; Sinha, N.; Stitt, E. H., 2012, “Solvent Effects in the Hydrogenation of 2-Butanone”. J. Catal., 289, 30−41.

Ball, P., 2008, “Water: Water an Enduring Mystery”. Nature, 452, 291 −292.

Cotta, R., 1993, Integral Transform in Computational Heat and Fluid Flows, 1ª Edição ed. Flórida: CRC Press, Inc.

Mikhailov, M. D.; and Vulchanov, N. L. 1983; “Computational procedure for Sturn-Liouville problems”, Journal of computational Physics, v. 5, 323-336.

Hilser, V. J., 2011, “Structural Biology: Finding the Wet Spots”. Nature, 469, 166−167.

Li, R.; D’Agostinho, C.; McGregor, J.; Mantle, D. M.; Zeitler, A.; Gladden, F., 2014, ”Mesoscopic Structuring and Dynamics of Alcohol/Water Solutions Probed by Terahertz Time-Domain Spectroscopy and Pulsed Field Gradient Nuclear Magnetic Resonance” J.Phys.Chem.B, 118, 10156−10166.

Palo, D. R.; Dagle, R. A.; Holladay, J. D., 2007, “Methanol Steam Reforming for Hydrogen Production”. Chem. Rev., 107, 3992−4021.

Parez, S. G. Guevara-Carrion, H. Hasse and J. Vrabec, 2013, “Phys. Chem.“ Chem. Phys., 15, 3985.

Wakisaka, A.; Matsuura, K.; Uranaga, M.; Sekimoto T.; Takahashi M., 2011, “J. Mol. Liq.”,160, 103.

7. RESPONSIBILITY NOTICE

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