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Heat transfer monitoring by means of the hot wire technique and finite element analysis software

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A B S T R A C T

It is reported the study of the radial heat transfer in a homogeneous and isotropic substance with a heat linear source in its axial axis. For this purpose, the hot wire characterization technique has been used, in order to obtain the temperature distribution as a function of radial distance from the axial axis and time exposure. Also, the solution of the transient heat transport equation for this problem was obtained under appropriate boundary conditions, by means of finite element technique. A comparison between experimental, conventional theoretical model and numerical simulated results is done to demonstrate the utility of the finite element analysis simulation methodology in the investigation of the thermal response of substances.

1. Introduction

Heat transfer is the area which describes the energy transport between material bodies due to a difference in temperature, and its development and applications are of fundamental importance in many branches of engineering since provides economical and efficient solutions for critical problems encountered in many advanced equipment. Among the parameters that determine the thermal behavior of a material, the thermal conductivity is especially important because it represents the ability of a material to transfer heat, and it is one of the physical quantities whose measurement is in general difficult, and it requires high precision in the determination of the parameters involved in its calculations (Tritt, 2004; Lewis et al., 2004).

The hot wire technique (HWT) is an absolute, non-steady state and direct method which is considered an effective and accurate procedure to determining the thermal conductivity of a variety of materials, including ceramics, fluids, food and polymers (Lewis et al., 2004; dos Santos, 2003; Khayet and Zarate, 2005; Nahor et al., 2003). However, this technique is based on an approximation to the physical reality in the experimental setup, because complexity of the mathematical model, which results in an obstacle to obtain a more realistic theoretical model (dos Santos, 2007; Carslaw and Jaeger, 1954). Fortunately, nowadays the development of the advanced numerical methods and computing systems allow the application of high level software to obtain numerical solution to complex mathematical problems, constrained by boundary conditions congruent with the physical reality.

In particular, the finite element analysis (FEA) is a powerful mathematical tool for numerical solving of partial differential equations (PDE), involved in heat transfer problems.

This method was first developed in 1943 by Courant (1943), however, until the early 70s; FEA was limited to expensive mainframe computers generally owned by the aeronautics, automotive, defense, and nuclear industries. Since the rapid decline in the cost of computers and the phenomenal increase in computing power, FEA has been developed to an incredible precision. Nowadays, supercomputers and powerful computer programs based in FEA, like Comsol Multiphysics software (Pryor W., 2012), are able to produce accurate results for all kinds of parameters.

In this work, the Comsol Multiphysics software is used to determinate the numerical solution of the transient temperature distribution for the situation of a substance measured by means of the hot wire technique. For this, it is solved the heat conduction equation, in a finite medium, constrained by boundary conditions congruent with the physical reality, namely Neumann condition in the axial axis and Dirichlet condition at the interface with the outside. It is demonstrates the greater accuracy of the numerical simulation compared to conventional theoretical model in the correspondence with the experimental data.

2. Conventional theoretical model

In the conventional theoretical model the hot wire is assumed to be an ideal infinitely thin and long heat source which is

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immersed in an infinite surrounding material. By means of the solution of the heat conduction equation, in cylindrical coordinates, it can be obtained the temperature distribution divided in two stages (Carslaw and Jaeger, 1954):

Heating stage: $t \in (0, t_h]$

$$T_{hs}(t,r) = -\frac{Q_0}{4\pi k} Ei\left(-\frac{r^2}{4\alpha t}\right) \tag{1}$$

Cooling stage: $t \in (t_h, \infty)$

$$T_{cs}(t,r) = -\frac{Q_0}{4\pi k}\left[-Ei\left(-\frac{r^2}{4\alpha t}\right) + Ei\left(-\frac{r^2}{4\alpha(t-t_h)}\right)\right] \tag{2}$$

here, r is the radial distance from the lineal source, k is the thermal conductivity, α is the thermal diffusivity, Q_0 is the linear heat source (W/m), t_h is the heating time, and Ei is the exponential integral (Pryor W., 2012). By means of fitting the expression of T_{hs} (heating stage) or T_{cs} (cooling stage) to the experimental data, the thermal parameters of the sample can be obtained . The thick solid curve in Fig. 1 shows the graph of T_{hs} ($0<t<t_h$), and the thin solid curve represents the graph of T_{cs} ($t_h<t$), Eqs. (1) and (2), respectively in function of t for $r=a$ (fixed). Here, the thermal properties of the glycerol, given in Table 1, are considered. The values of 0.8 W/m for the linear heat source Q_0, and $a=0.6$ mm, the radius of the needle probe in the hot wire technique, were also considered.

During the first seconds of the heating stage there is a fast increase of temperature with time. This rate of change of T with t gradually decreases until the end of the heating time ($t_h=30$ s, in this case), for which the temperature difference reaches its maximum value. Then, at the beginning of the cooling stage there is a fast decrease of temperature with time, so that the rate of change gradually slows until the temperature difference tends to zero for large values of t.

3. Experimental procedure

The measurement was realized by means of the HWT at room temperature, using the commercial device KD2-Pro (Decagon devices Inc.). Fig. 2 shows the configuration of the probe in this technique, which is based in a needle with a heater and temperature sensor inside. A rectangular power density is passed through the heater and the temperature of the probe is monitored over a specific period of time. An analysis of the transient temperature response is used to investigate the thermal response of the sample.

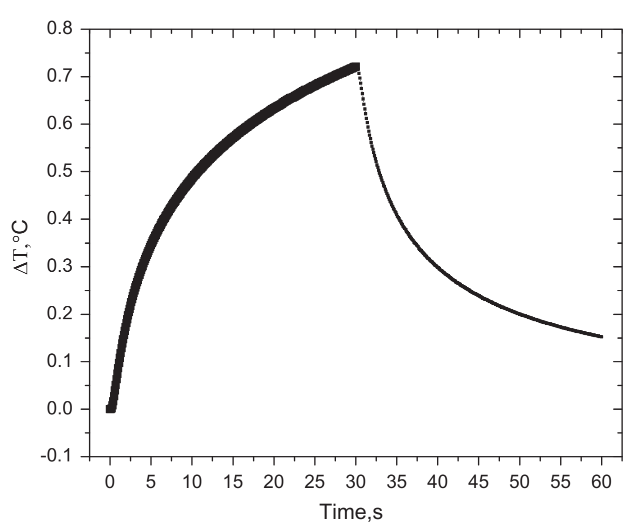

Fig. 1. Temperature difference versus time according to the conventional theoretical model of the hot wire configuration.

Table 1
Thermophysical properties of glycerol (CAS 56-81-5).

Property	Magnitude	Unit
ρ	1261	kg/m^3
k	0.285	W/mK
c	2470	J/kg K

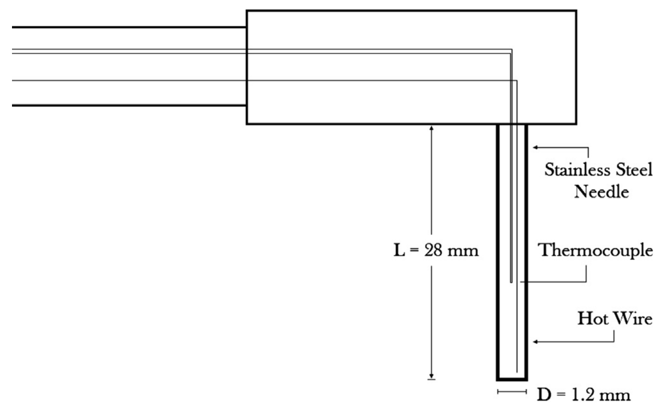

Fig. 2. Probe configuration in the hot wire technique.

The experimental measurements were realized on samples of glycerol (CAS 56-81-5) whose thermal properties at room temperature are shown in Table 1.

4. Simulation process

The Numerical Simulation was done by using the COMSOL Multiphysics software to solve the heat transport equations, in the configuration of hot wire technique with appropiate boundary conditions.

In the software graphic user interface (GUI), it was built a 2D hollow cylinder of inner radius a and outer radius b, which represent the sample-probe arrangement. The hollow cylinder gives certain advantages in the numerical calculation process. One of these advantages is to reduce complexity in the model and the other is to simplify the boundary regions (see Fig. 3).

Once the geometry is defined, the physical process that takes place in the experiment is defined in the heat transfer module. This module use the heat diffusion equation (HDE), given by:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u_{\mathrm{trans}} \nabla T = \nabla \times (k \nabla T) + Q + W_p \tag{3}$$

Where ρ, C_p are the density and the heat capacity respectively. In Eq. (3), only the Laplacian term and the time dependent contribution are needed, therefore the HDE is reduced to the homogeneous form:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \times (k \nabla T) = 0 \tag{4}$$

The boundary conditions and initial values were chosen as follow:

For $r=a$, a Neumann boundary condition was used, given as:

$$Q(r=a,t) = Q_0 \times \Pi_{0,30}(t) \tag{5}$$

where $\Pi_{0,30}(t)=\mathrm{H}(t)-\mathrm{H}(t-30)$ is the boxcar function which is equal to 1 for $0 \le t \le 30$ s and 0 otherwise, and $\mathrm{H}(t)$ is the Heaviside step function (Weisstein).