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HOT WIRE METHOD FOR DETERMINATION OF THE THERMAL CONDUCTIVITY OF SUGAR CANE FIBERS

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Abstract. Natural fibers have an important role in research aimed at renewable resources, because its natural characteristics reduce the impact on the ecosystem when discarded. In this context, this article aims to determine the thermal properties of sugar cane fiber as it is a fiber abundantly found in the country, for its ecological characteristics and for easy handling. For that, measurements were made using the hot wire method with dry fiber and wet fiber. The method is relatively simple, being a transient heating process with well-defined boundary and initial conditions. The result of the thermal conductivity of the sugar cane fiber was approximately 0.116 W/(m·K) for wet sample and 0.0996 W/(m·K) for dry sample. The process uncertainty generated a value below 0.5% relative error, proving that the fiber has a good performance for heat treatment.

Keywords: thermal conductivity, cane fiber, hot wire method, thermal insulation.

1. INTRODUCTION

In recent years there has been an increase in the demand for renewable resources, low cost, reusable and especially organic materials, that are abundant in nature These resources have technological applications in the most different industrial sectors, such as: sound insulation, thermal comfort and improvement of mechanical properties. Therefore, the present work aims to determine the thermal property of the conductivity of the sugar cane fiber, because besides being an economically viable and sustainable material, it can be easily found throughout the national territory. The determination of the thermal properties of cane in this work was determined using the hot wire method.

The hot wire technique is basically a thin wire of negligible diameter traveled by a current, which promotes heating due to the joule effect. The wire is immersed in a cylindrical support filled with sugar cane fibers. The technique is a transient heating process, with well-defined boundary and initial conditions. (Santos, 2002)

The hot wire method is well established and has been widely used to determine the thermal properties of various materials. (Santos *et al.*, 2004) used the method to determine the conductivity in polymers; (Richard, R. G. and Shankland,., 1989) used the method for determining conductivity in gases and liquids. A more recent application for treatment of geomaterials for the purpose of use in civil construction, was carried out by the researches (Merckx *et al.*, 2012).

2. MATHEMATICAL FORMULATION

As already mentioned, the hot wire method was used to determine the thermal conductivity of cane fibers. The method can also be used for other physical configurations, such as porous material, granular and liquids in general. According to the ISO 8894-2 the hot wire method is a measurement procedure based on the evolution of temperature as a function of time, whereas that a heat source operates on a permanent basis. That is the electrical power converted into heat it is given by the product of source of tension continues and current also continues.

The heat diffusivity equation applied in a material free of molecular motion is expressed as (Incropera and Witt, 1990):

$$\partial T(r,t)/\partial t = \alpha \nabla^2 T \qquad (1)$$

Being:

T- temperature [°C]
t- time [s]
α- material heat diffusivity [m^2/s]
r- distance from the heated wire [m]

The Eq. (2), (3) and (4) indicate the boundary and initial conditions applied on the solution of the differential equation represented by Eq. (1).

$$\Delta T(r,t)=0 \qquad (t \leq 0, \quad 0 \leq r \leq R) \tag{2}$$

$$\lim_{r \to 0}\left(r\frac{\partial T}{\partial r}\right) = -\frac{q}{2\pi k} \qquad (r = 0, \ t \geq 0) \tag{3}$$

$$\lim_{r \to 0}\Delta T(r \to \infty, t) = 0 \quad (r \to \infty, \ t \geq 0) \tag{4}$$

Being:

ΔT – increased temperature in the conductive wire [°C]
k – thermal conductivity [W/(m·K)]
q – constant heat flow released by the hot wire [W]

Physically explaining the conditions imposed, the Eq. (2) to Eq. (4) respectively states that: the first boundary condition establishes that both the wire and the sample at the beginning of the experiment are in thermal equilibrium with the external environment. The second condition establishes that the heat flow generated by the wire is fully absorbed by the sample. The third and last condition states that the external surface of the sample is in thermal equilibrium with the external environment, besides that the temperature does not vary throughout the experiment (Incropera and Witt, 1990):

From the boundary and initial condition, Eq. (5) represents the solution of the transient problem regarding the hot wire method. This equation will be used to determine the thermal conductivity of the material. (Bejan, 1993)

$$T(t) - T(0)|_{(r=0,t)} = T(t) - T(0) = \frac{q}{4\pi k}\ln(t) \tag{5}$$

3. DESCRIPTION OF THE EXPERIMENT

The experiment consists of a hollow cylinder approximately 15 cm in diameter and 25cm long, filled with sugar cane fiber. In the center placed a nickel-chrome resistance wire, connected to a source of continuous voltage. Two fiber samples are previously prepared. One of them is preheated to a constant temperature of 50°C in order to remove humidity. Then the sample is cooled to room temperature in a closed humidity-controlled chamber. The second sample does not go through any previous drying process.

The Fig. (1) shows the cylindrical apparatus filled with fibers, used in the experiment to determine thermal conductivity.
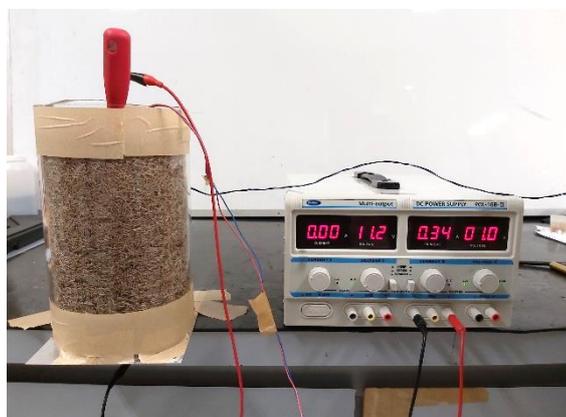

Figure 1 – Simplified scheme of the hot wire method.

Through the Fig. (1) it is possible to observe that wire is in direct contact with the samples and in thermal equilibrium with the fibers. The evolution of the wire temperature over time is obtained through a data acquisition board, where a thermocouple is connected in contact with the resistance wire. The Fig. (2) presents in a simplified way the test bench used to obtain the data regarding the thermal conductivity of the fibers, which is the aim of analysis if the present research.
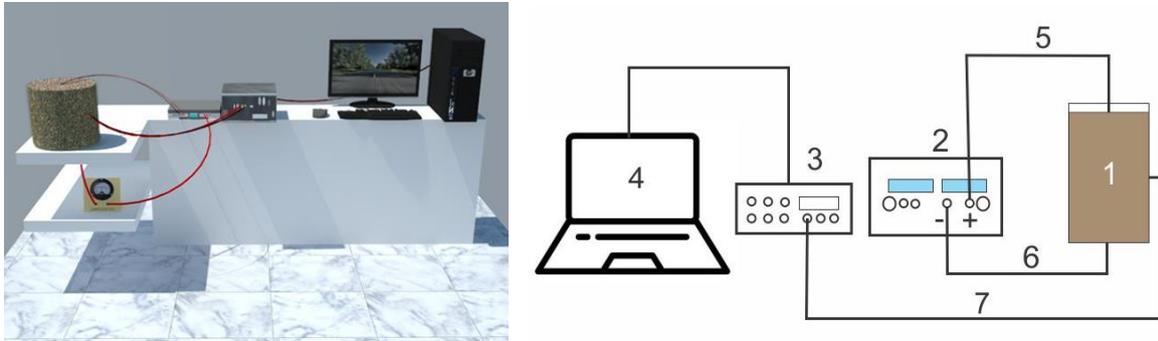

Figure 2 – (2.a) Simplified test bench layout. (2.b) 1- Apparatus with sugar cane fiber; 2- Power supply; 3- Data acquisition card; 4- Central process unit; 5 e 6- Nickel-chrome resistance wire; 7- Thermocouple.

As already mentioned, the heat dissipation for the material occurs through the Joule effect, the electrical energy being converted into heat due to the current that runs through the wire. The values of voltages and current throughout the experiment are shown in Table 1, respectively the values of 0.016% and 0.018% for the measurement uncertainty. In should be noted that in addition to the measurement uncertainty, the numbers for current and voltage oscillate around a mean value due to internal oscillation voltage source.

Table 1 – Technical data regarding voltage and current for wet and dry samples.

	Supply voltage (V)	Electric current (A)
Wet Sample	1.042±0.005	0.432±0.004
Dry Sample	1.010±0.016	0.420±0.002

The power dissipated by the wire was 0.445±0.006W and 0.424±0.016W for wet and dry samples, respectively.

4. RESULTS

The Fig. (3) shows the evolution of temperature as a function of time for two different situations: for the first case the fibers were previously dried for a approximately 1 hour, with constant temperature of approximately 50°C, and then the sample was cooled in a controlled humidity environment to an ambient temperature of more or less 24°C. In the second case, the fibers did not undergo the drying treatment, although the experiment it was performed in a controlled humidity environment as in the first case. This differentiation of pre-treatment was necessary to verify whether the thermal conductivity changes substantially from one situation to the next.
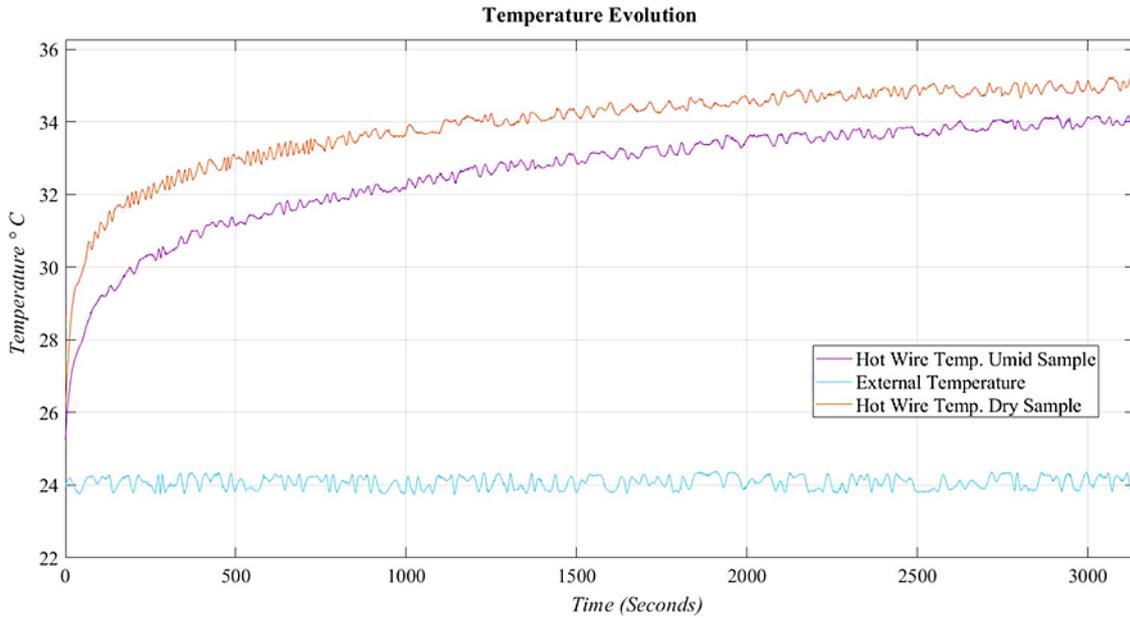
Figure 3- Temperature evolution over time for both samples- dry and wet ones, respectively.

Before applying the hot wire method, as described in Eq. (5), it is necessary to perform the logarithmic transformation of the temperature evolution with the time to get the linear region, therefore, the Fig (4.a), and (4.b), presents an evolution of the temperature of the wire, on a logarithmic scale, for the case (1), and (2), respectively.

The Fig. (4.a), and (4.b) show too, an instability temperature measurement, after the linear region, this is due to the limitations of the boundary conditions at the border of separation between the media. Over time the outermost layer of the sample heats up and the boundary condition is no longer applicable.
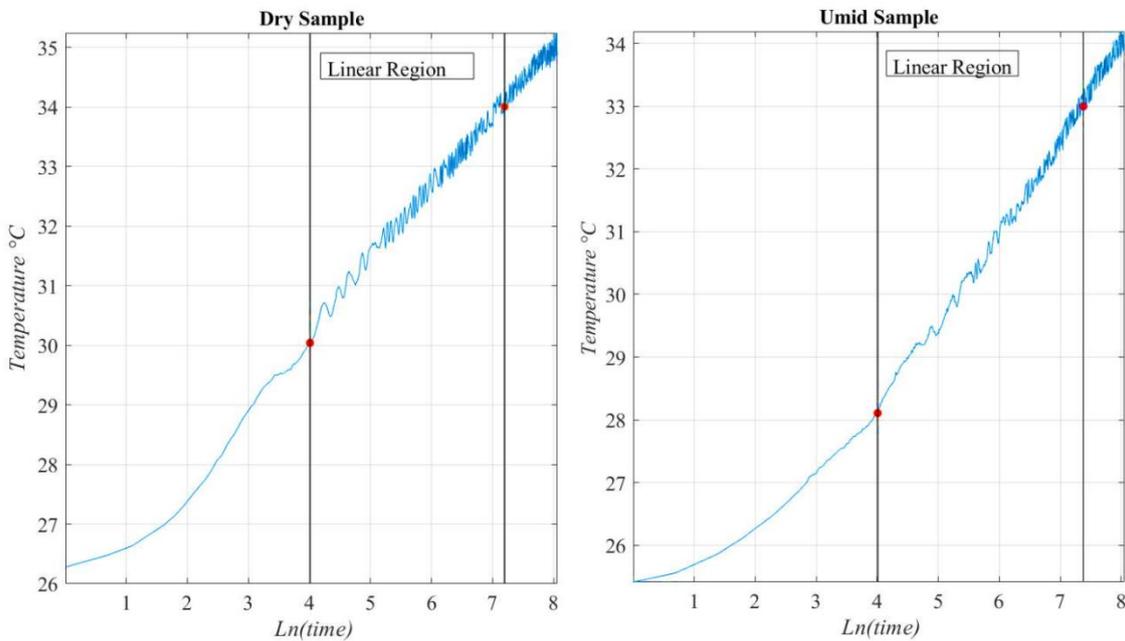

Figure 4. Delimitation of the linear region of temperature evolution on a logarithmic scale for dry sample (4.a) and wet samples (4.b).

The Fig. (5) show the line that most closely matches the theoretical values, obtained using the least squares method for both dry and wet samples. It is necessary to observe that the experimental data show a fluctuation around the average linear value due to the uncertainty that occurs in the temperature measurement. According to the manufacturer´s manual, this value is ± 0.03 K. There is also a fluctuation in electrical power due to uncertainty in the voltage source that fluctuates around an average value. As previously mentioned, there is also a fluctuation in electrical power due to uncertainty also

in the voltage source that fluctuates, around an average value, as seen in the previous item. In the next section, the efficiency of the linear method for determining thermal conductivity.
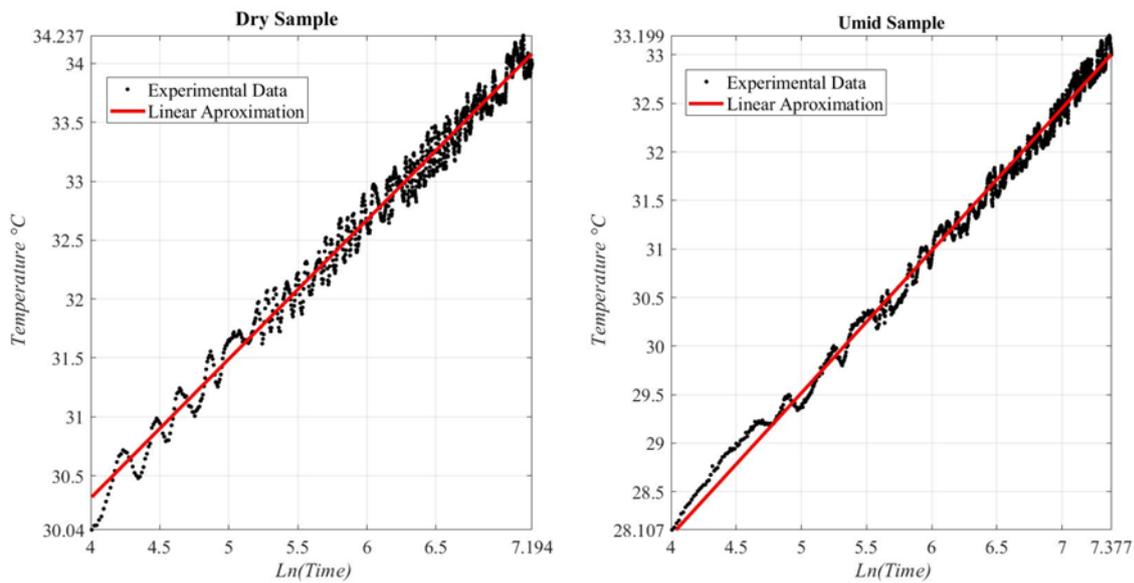

Figure 5 - Linear numerical approximation of experimental values, for dry sample (5.a) and wet samples (5.b).

From the slope of the line, it is possible to determine the thermal conductivity of the samples. For this case the value was approximately 0.116 W/(m·K) for wet sample and 0.099 W/(m·K) for dry sample.

5. TREATMENT OF PROCESS UNCERTAINTY AND EFFICIENCY

Once the conductivity value is determined, it is necessary to analyze the efficiency of the linear model, through the error function. The error is nothing more than the Euclidean distance between experimental values and theoretical values.

In order to determine the uncertainty of the conductivity measurements, it is first necessary to analyze the error propagation, corresponding to the measurements of the variables to which is linked with the conductivity determination.

According to the Equation below directly derived from Eq. (5), it is important to realize that the measurement of conductivity uncertainty falls both on the power measurement uncertainty and on the temperature measurement uncertainty, performed by the data acquisition board.

$$k = \frac{q}{4\pi\Delta T} ln\,(t)$$

Being:

$$\Delta T = \mathrm{T}(t) - \mathrm{T}(0)$$

The Eq. (6) are used to determine the uncertainty of measuring the conductivity of the samples, as a function of the uncertainties, present both in the reading of the voltage source and in the temperature measurement, and from the uncertainty determination theory [1]:

$$\frac{I_K}{k} = \pm\sqrt{\left(p_q \frac{I_q}{q}\right)^2 + \left(p_{\Delta T} \frac{I_{\Delta T}}{\Delta T}\right)^2} \tag{6}$$

Being:

I_K - Uncertainty in the measurement of thermal conductivity
$\bar{k}$ - Medium thermal conductivity
p_q - Weight function of uncertainty due to the contribution of energy flow

I_q - Uncertainty in the measurement of energy flow due to electrical power
$p_{\Delta T}$ - Weight function of uncertainty due to the contribution of the temperature differential
$I_{\Delta T}$ - Temperature differential measurement uncertainty
$\overline{\Delta T}$ - Temperature differential
The weight functions are defined as:

$$p_q = \frac{\partial k}{\partial q}$$
$$p_{\Delta T} = \frac{\partial k}{\partial \Delta T}$$

Table 2 presents the results obtained for the calculation of the uncertainty.

Table 2 – Conductivity values corrected according to the uncertainties of the experiment

	Wet Sample [W/(m·K)]	Dry Sample [W/(m·K)]
Thermal Conductivity	0.116 ±0.002	0,099±0.004

From Fig. (6), and (7), it is possible to observe than more than 90% of the population that composes by sample of measures has a value below 0.5% relative error. The Fig. (6), and (7) show in a simplified way the efficiency of the linear approximation, at least squares method for determination of thermal conductivity, for dry and wet sample, respectively, and for both cases, only a small portion of the measurements has a significant error in relation to the theoretical value obtained through the method as mention before.
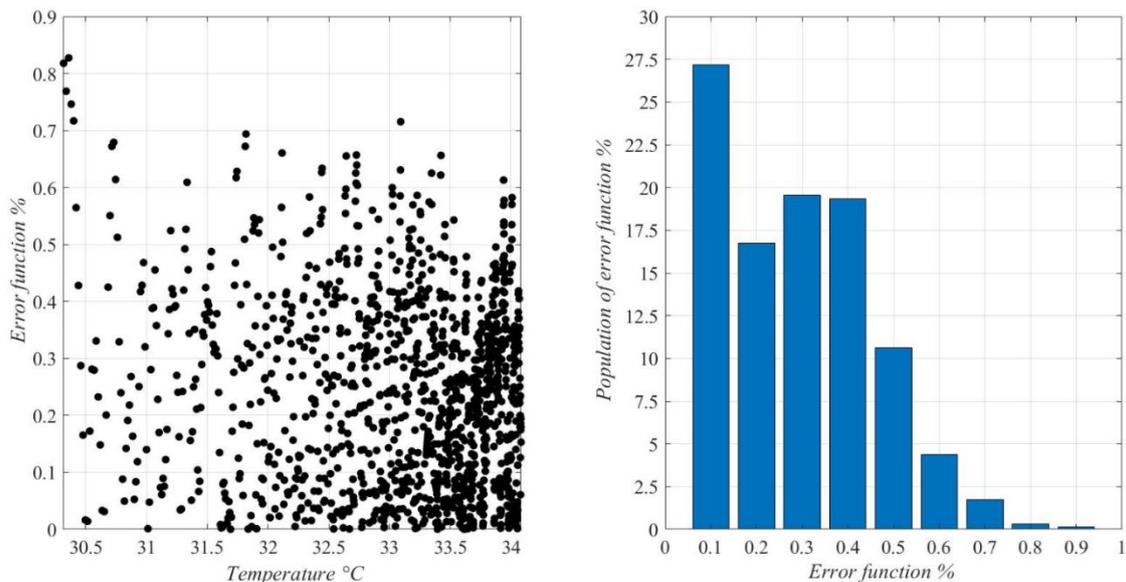

Figure 6 – (6.a) Graph showing the value of the relative error of samples of measurements, as a function of temperature, (6.b) Graph showing the percentage of samples measurements as a function of the relative errors.
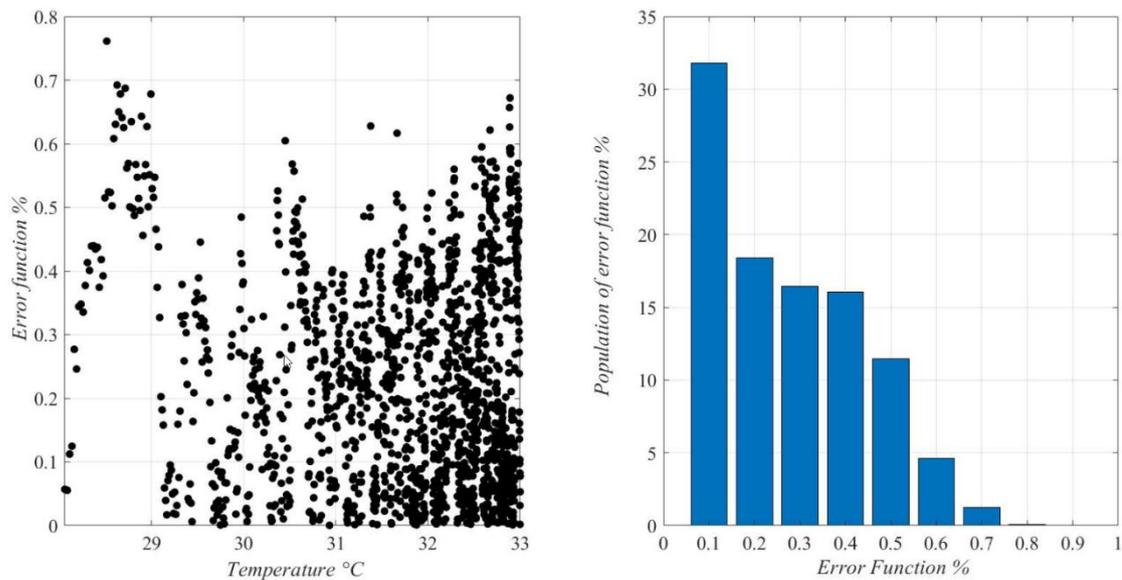
Figure 7 – (7.a) Graph showing the value of the relative error of samples of measurements, as a function of temperature, (7.b) Graph showing the percentage of samples measurements as a function of the relative errors.

6. CONCLUSION

The dry sample shows the thermal conductivity in the value of 0.099 ± 0.004 W/(m·K) with 0.116 ± 0.002 W/(m·K) for wet samples. Even in the worst-case sugar cane fiber can serve to increase insulation and thermal comfort. The present work also showed that the determination of the heat conductivity by the hot wire method presents satisfactory results in the characterization of the thermal properties of non-compacted fibers. For future works, it is necessary to determine the degree of occupation of both the cane fibers and the trapped air.

7. REFERENCES

Bejan A., 1993, *Heat Transfer*, John Wiley & Sons, New York.

Incropera, F. O. and Witt, D. P., 1990, *Fundamentos de transferência de calor e massa. Rio de Janeiro: LTC - Livros Técnicos e Científicos*.

Merckx, B., Dudoignon, P., Garnier, J. and Marchand, D., 2012, "Simplified Transient Hot-Wire Method for Effective Thermal Conductivity Measurement in Geo Materials: Microstructure and Saturation Effect", *Advances in Civil Engineering*.

Minakov, A.V, Rudyak, V. Y. , Guzei, D.V., Pryazhnikov, M.I.,A.S and Lobasov, A.S., 2015, "Measurement of Thermal-Conductive coefficient of nanofluids by hot-wire method". *Journal of Engineering and Thermophysics*, Vol 88.

Richard, R. G., Shankland, I. R., 1989, "A transient hot-wire method for measuring the thermal conductivity of gases and liquids", *International Journal of thermophysics*.

Santos, W.N., 2002, O método de fio quente: técnica em paralelo e técnica de superfície.

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