CAPÍTULO 5

VALIDATION OF EXPERIMENTAL RESULTS IN THE DETERMINATION OF THERMAL CONDUCTIVITY

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ABSTRACT: A non-destructive experimental technique, by electrical measurements, was used to determine the thermal conductivity of volumetric samples and will be presented here. This technique involves applying heat pulses using electrical current to a resistive element and monitoring the temperature rise over time. For technique validation, experimental results of reference samples, such as water and ice, for liquids and solids, respectively, are presented. Experimental results of dielectric liquids used in electric power transformers are also presented, as well as a sample of sand used by the Electric Sector in the thermal dissipation of underground electric cables.

KEYWORDS: Thermal conductivity; measurement; validation; reference material.

1 I INTRODUCTION

Brazil has experienced a sudden and growing development in solar and wind power generation parks. Due to the origin of abundant wind resources and the abundant availability of flat sunny areas, such parks have been established, mainly, in the Northeast Region. For practicality and financial convenience, many of these installations have medium voltage insulated electrical cables of up to 34.5 kV laid directly on the sandy soil. On the other hand, these areas are still little explored and studied for such purposes, presenting themselves with materials of little-known thermal characteristics. Time and resources are not always found to check the environment where the electrical cables will be laid and, in fact, there have been premature failures due to overheating, either due to the low thermal conductivity of the surrounding environment, or due to the considerable accumulation of circuits, or density of cables in the same narrow trench.

This work will describe the experimental techniques used for soil thermal conductivity surveys, without sophisticated or specific equipment for this purpose. To validate the experimental technique, well-studied reference samples are used, such as water and ice, with the use of linear regression and student statistical distribution, for the evaluation of dispersion in the quality of the result of the determined magnitude. It also presents the results found for the thermal conductivity of a set of solid and liquid samples used by the Electric Sector, including magnetic nanofluids.

It is noteworthy that this technique broke a myth that insulating mineral oil with magnetic nanoparticles could exhibit greater dissipation capacity in electrical transformers[1].

This publication will deal with an experimental technique to validate the experimental determinations of the physical quantity called thermal conductivity. The technique is fast and non-destructive. Samples can be reassessed several times to perform averages and display results.

2 I PURPOSE AND APPLICATION OF THERMAL CONDUCTIVITY IN THE ELECTRICAL SECTOR

Electrical cables for transmission and distribution of electrical energy, with the exception of superconductors, heat up with the passage of electric current through metals, such as copper and aluminum. Such cables made up of several layers of electrical insulation and shielding, form barriers for the transfer of heat to the environment which, in the case of underground installations, are made up of sand and gravel, or rolled pebbles, in the North region. Knowledge of the thermal dissipation characteristics of the medium that surrounds such electrical cables is a fundamental basis for sizing them. The lack of such specific knowledge and the use of typical values have led to occurrences of collapses in important underground installations for the transmission and distribution of electrical energy. Thus, efforts are justified in the previous knowledge of the thermal conductivity of the materials to be involved in the thermal dissipation and, mainly, in the reliability of such parameters.

3 I ABOUT THE REASONS THAT MOTIVATED THE RESEARCH

Studies and efforts to improve the reliability of the evaluation of the thermal conductivity of the materials that involve the electrical cables of underground installations are highly justifiable, considering their costs and generation losses, for example, from wind and/or solar parks caused for faults. Repairs or replacement of a buried cable or set of cables laid directly into the ground takes a long time. Often, other cables are installed and the damaged ones are abandoned to speed up the plant's return to normal operating conditions. The present study constitutes a warning to electrical cable designers and installers that the initial cost of analyzing the materials is fully justifiable, considering the costs and possibilities of future losses.

4 I FUNDAMENTAL CONCEPTS

The transient hot-wire method is also known as the THW method. The THW method is a transient dynamic technique that measures the temperature rise of a linear heat source (hot wire) embedded in the tested material[2],[3] and[4]. For an infinitely long metallic wire (length/radius ratio 200 or more) heated at time t > 0 with a constant heat flux per unit length Q and immersed in an infinite homogeneous medium (thermal conductivity and diffusivity: λ and α, respectively.) with uniform initial temperature, the temperature rise ΔT(t) of the wire is given by Equation (1)[5]:

$$\Delta T(t) = \left[\frac{Q}{4 \cdot \pi \cdot \lambda}\right] \cdot \ell n\left(\frac{4 \cdot Fo}{C}\right) \qquad \text{Equation (1)}$$

where $C = e^{\gamma} = 1.781$; γ is Euler's constant ($\gamma = 0.5772$) and Fo is the Fourier number defined by

$$Fo = \frac{\alpha \cdot t}{r_o^2}. \qquad \text{Equation (2)}$$

Equation (1) is the analytical solution of an ideal thermal conductor model valid for Fo >>1 and without convective transfers[6],[7],[8],[2] and[9].

From this ideal model and with known Q values, the thermal conductivity can be calculated by:

$$\lambda = \left(\frac{Q}{4 \cdot \pi}\right) \cdot \left[\frac{dT}{d(\ell n\, t)}\right]^{-1}, \qquad \text{Equation (3)}$$

where dT/d(ln t) is a numerical constant deduced from experimental data for values of t satisfying the condition Fo >>1.

For practical applications of the THW method, the dimensions of the sample of wire and material, among other hypotheses of the ideal model, are finite and the deviations from the ideal model must then be evaluated. Depending on the metallic material used for the construction of the resistive heating element, the variation of its resistance with temperature can be disregarded, since in these tests the temperature variation must not exceed 3 K. Metallic materials, such as constantan, have a coefficient of change in electrical resistance with temperature low enough for these purposes.

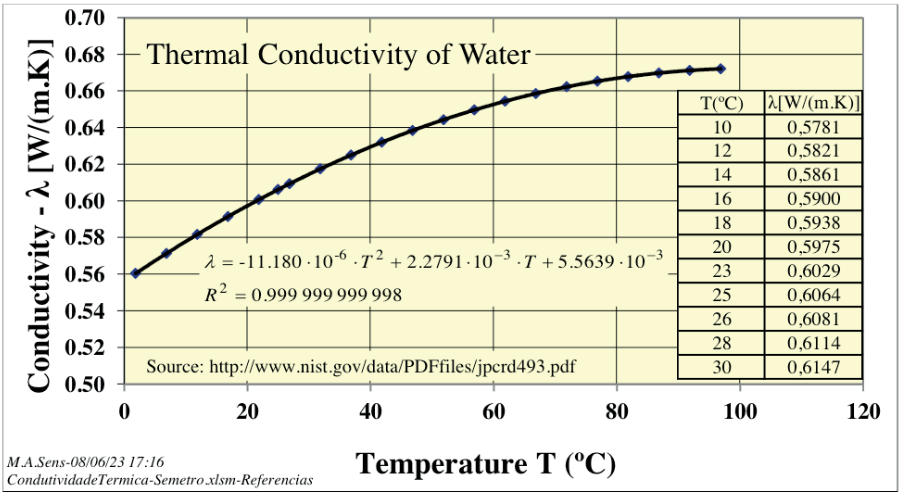
In fact, the response to heating the wire ΔT(t) resulting from the Joule effect due to an electric current I, where the power dissipated per unit length will be $Q = I^2$. R, where I is in amps and R is in ohms/meter, as per standard recommendation[11]:

$$\lambda = \frac{Q}{4 \cdot \pi \cdot \left\{\dfrac{(\Delta T_2 - \Delta T_1)}{\ell n(t_2 / t_1)}\right\}} = \frac{Q}{4 \cdot \pi \cdot \tau} \qquad \text{Equation (4)}$$

where λ is the thermal conductivity {W/(m.K)}, Q = Heating element power (W/m) and τ is a numerical parameter deduced from the experimental data of the logarithmic regression of the temperature rise ΔT(t) curve.

5 I LITERATURE SURVEY

Regarding the technique for determining the volumetric thermal conductivity of reference materials, such as liquids and sand, or soil, there are technical standards and abundant literature presenting automatic instrumentation. As reference materials, properly speaking, there is also abundant literature on the thermal conductivity of water[12], as graphically shown in Figure 1.



T(°C)	λ[W/(m.K)]
10	0,5781
12	0,5821
14	0,5861
16	0,5900
18	0,5938
20	0,5975
23	0,6029
25	0,6064
26	0,6081
28	0,6114
30	0,6147

$$\lambda = -11.180 \cdot 10^{-6} \cdot T^2 + 2.2791 \cdot 10^{-3} \cdot T + 5.5639 \cdot 10^{-3}$$

$$R^2 = 0.999\,999\,999\,998$$

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Figure 1 - Thermal Conductivity of Water[12]

6 I OBJECT UNDER TEST

A stable solid-liquid suspension is called nanofluid in which the continuous phase is liquid and the dispersed phase consists of nanoparticles with characteristic dimensions smaller than 100 nm[10]. Ferrofluids are nanofluids whose nanoparticles are ferromagnetic or ferrimagnetic. Its main difference in relation to non-magnetic nanofluids is that ferrofluids can be magnetized by an external magnetic field and generally lose magnetization after removal of the external magnetic field, which is why they can be classified as superparamagnetic materials. The emergence of these materials constitutes an apparently promising technology for the liquid dielectric of power transformers, as it consists of the addition of ferrofluids to the traditional insulating mineral oil (IMO) of transformers, aiming at improving dielectric and/or thermal properties.

Such materials, candidates for replacing traditional fluids for power transformers, were evaluated here to verify the hypotheses raised by retailers, manufacturers and users, that they would have advantages in transferring heat from the windings of electrical transformation equipment.

Distilled water and ice samples were taken as references to validate the experimental technique, since such materials have properties that have been very well studied and evaluated, with plenty of easy access to them.

7 | METHODOLOGY PROPOSED IN THIS WORK

The proposed experimental technique for determining the thermal conductivity of liquid or pasty materials, including sand, consists of applying a heat pulse to a metallic needle, introduced in the center of a sample, whose radius is greater than twenty times the radius of the needle, and in monitoring the rise in temperature over time. One cannot, of course, apply heat pulses of magnitudes that could cause changes in the sample, in the test time, or marked convection. In the present work, samples with a volume of one liter were used, placed in glass containers, with the metallic thermal needle centered on them.

The thermal needle is shown in Figure 2, and the test circuit, with the equipment used, in Figure 3.

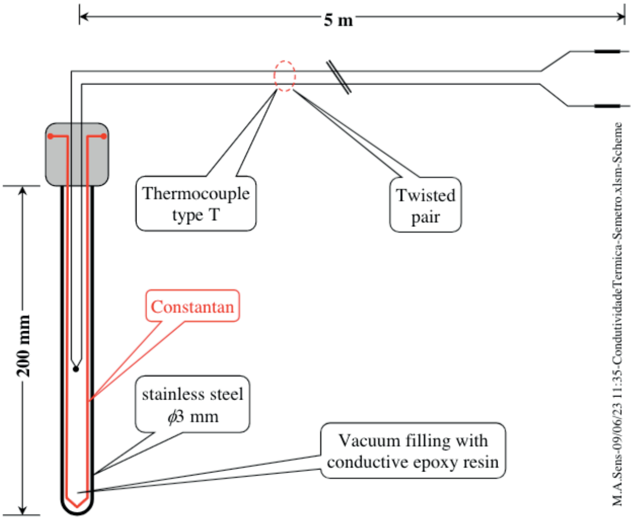

Figure 2 - Thermal Needle Design

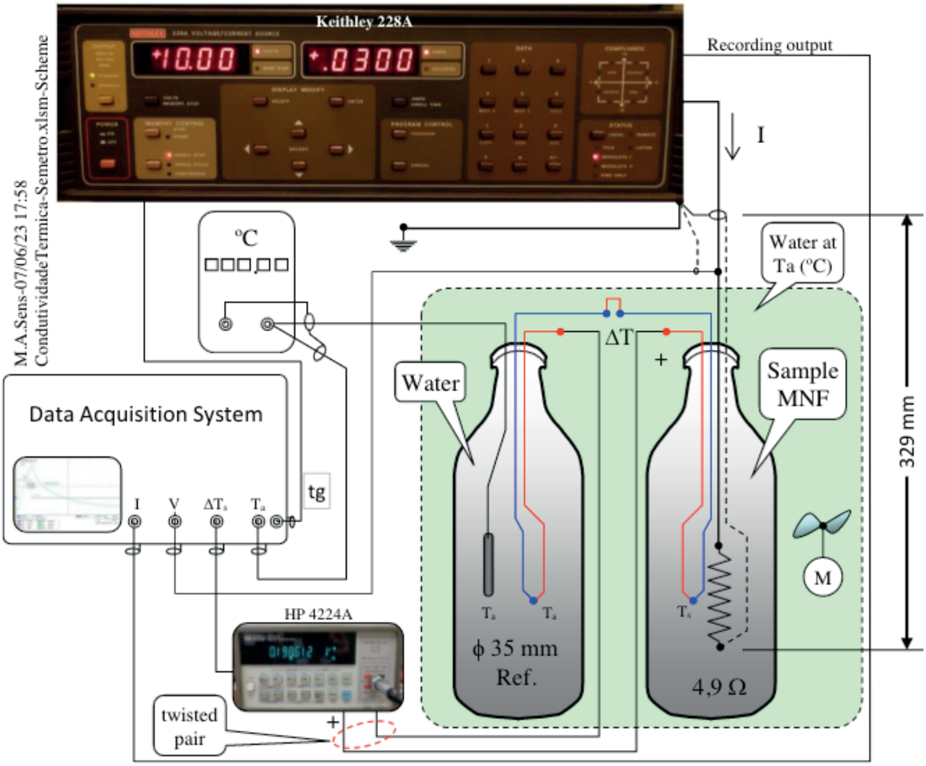

Figure 3 - Experimental Setup to Determine the Thermal Conductivity of Liquids and Sand

8 I EXPERIMENTAL TEST RESULTS

Initially, as a reference material, ice was tested, resulting in Figure 4, or 2.2 W/(m.K) ± 2.4 %, which was very close to the values in the literature[13].

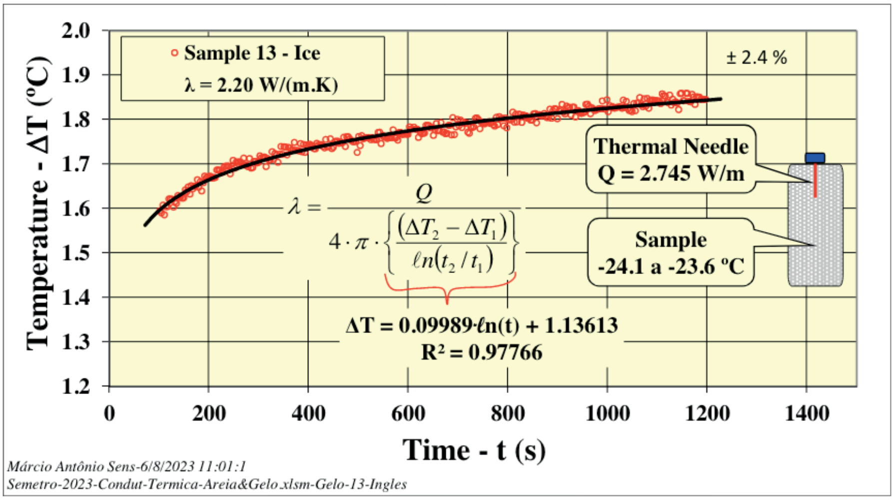

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Figure 4 - Experimental Result of the Thermal Conductivity of Ice.

In the previous case, the sample was solid and validates measurements on rocks, bricks, and refractories by the present experimental technique. For liquid, distilled water was tested at different temperatures, between 10 and 40 °C. The results for a temperature of 20 °C are shown in Figure 5.

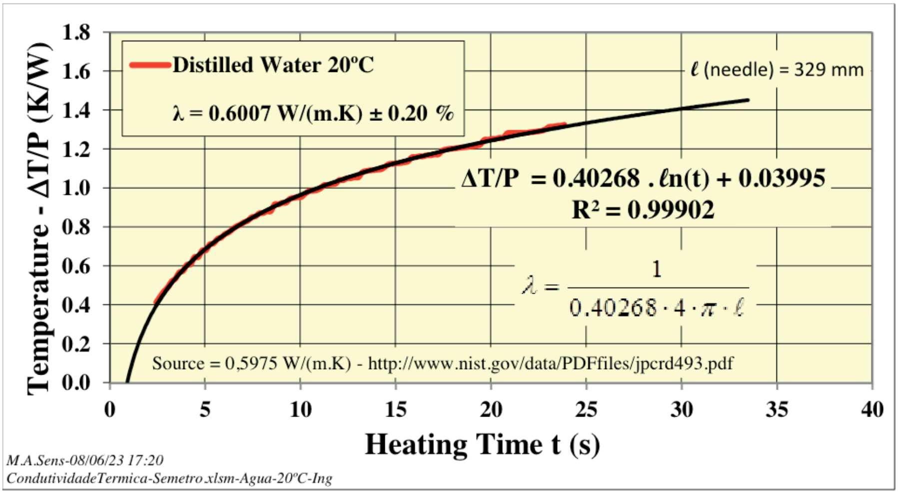

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Figure 5 - Determination of Thermal Conductivity of Water 20 °C

The results were also quite consistent with the literature[12], as shown in Figure 1, page 2, thus validating the technique for liquids, as well as for solids.

Once the experimental and mathematical analysis procedures were validated, a series of liquids were tested that are candidates for replacing the traditional liquid dielectrics used in power transformers, insulating mineral oil with the addition of magnetic nanoparticles, magnetite, Fe_3O_4. The distribution of samples in the thermal bath is shown in Figure 6 and the monitoring results are shown in Figure 7, together with a test of one of the sand samples, sand from Guamaré, from Rio Grande do Norte – Brazil, also evaluated in the field[14].

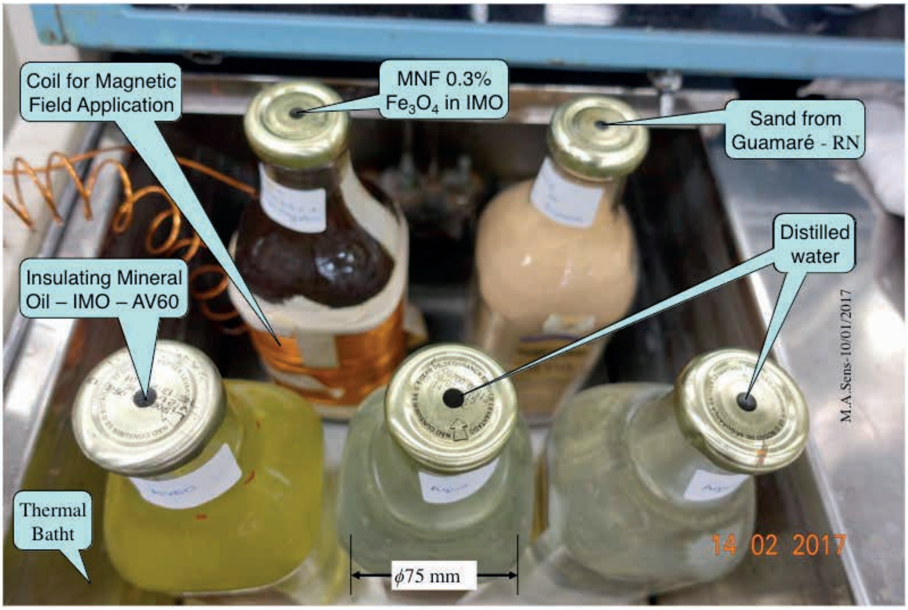


Figure 6 – Distribution of Samples in the Thermal Bath

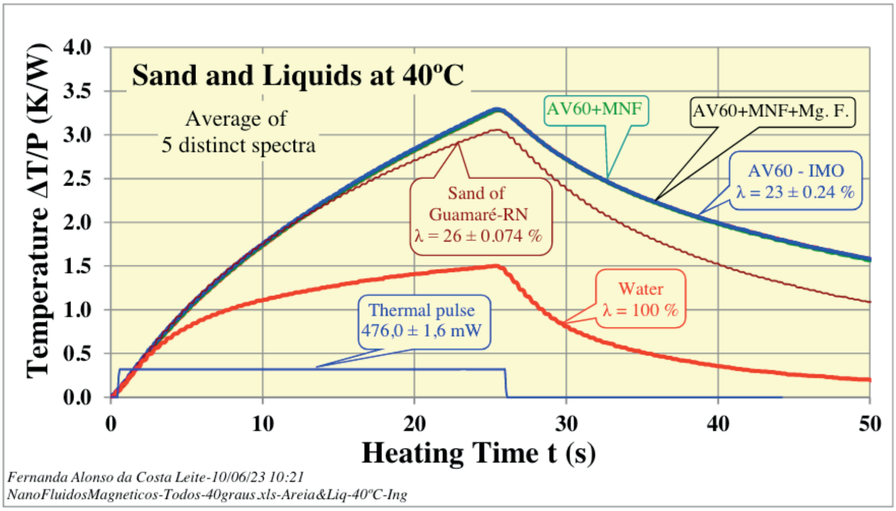
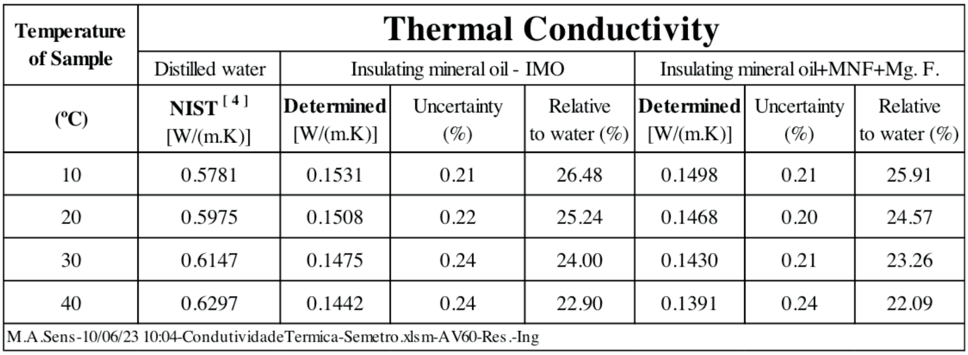


Figure 7 - Heating of Samples by Thermal Pulse-Monitoring

It should be noted that one of the samples was tested under a magnetic field of 60

Hz, simulating the conditions found inside a power transformer. The glass container was such that the needle was less than 1/20 of the diameter of the circle that circumscribes the sample under evaluation.

Using the thermal conductivities of water at different temperatures as a reference, the thermal conductivity of different liquid samples was calculated in relation to that of water, as shown by Table 1 and also illustrated in Figure 8.



Temperature of Sample	**Thermal Conductivity**						
	Distilled water	Insulating mineral oil - IMO			Insulating mineral oil+MNF+Mg. F.		
(ºC)	**NIST** [4] [W/(m.K)]	**Determined** [W/(m.K)]	Uncertainty (%)	Relative to water (%)	**Determined** [W/(m.K)]	Uncertainty (%)	Relative to water (%)
10	0.5781	0.1531	0.21	26.48	0.1498	0.21	25.91
20	0.5975	0.1508	0.22	25.24	0.1468	0.20	24.57
30	0.6147	0.1475	0.24	24.00	0.1430	0.21	23.26
40	0.6297	0.1442	0.24	22.90	0.1391	0.24	22.09

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Table 1 - Thermal Conductivity of Samples in Relation to Water

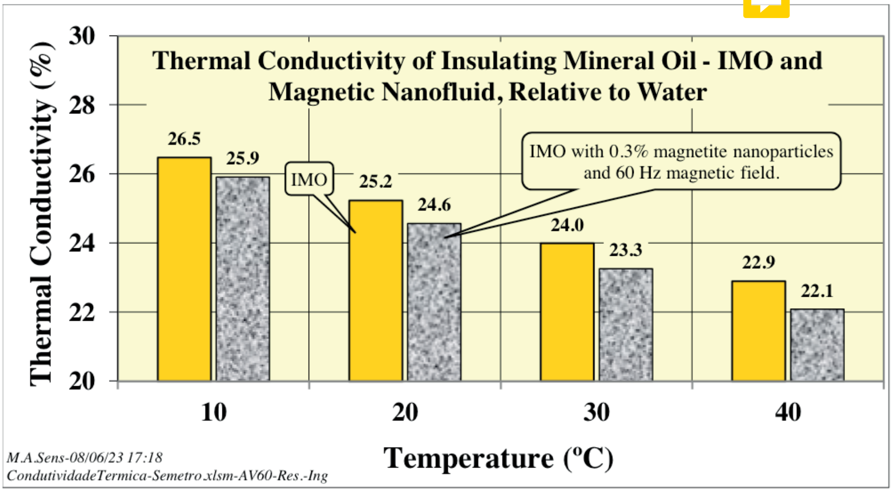

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Figure 8 - Thermal Conductivity of Samples in Relation to Water

9 I CONCLUSIONS

It was concluded that the experimental technique, by electrical measurements, was completely satisfactory in determining the thermal conductivity of liquid and sand samples, in comparison with the literature. That is the technique and the mathematical equation, by curve fitting, by the least squares technique, fully met expectations.

Samples of insulating mineral oil, with or without additives of magnetic nanoparticles, and with or without applied alternating magnetic field, showed thermal conductivity around 23 ± 0.24% in relation to the conductivity of water, at the same temperature. And the sand sample from Guamaré showed a conductivity of 26 ± 0.074% in relation to water, as shown in Figure 7.

On the other hand, the results found identified that the hypothesis of the addition of magnetic nanoparticles in the mineral oil would promote the increase of the thermal conductivity of the insulating mixture, in amounts of up to 0.3%, capable of completely blackening the original sample, without or with a magnetic field - is a myth. At contents greater than this proportion, the dielectric strength of the compound drops drastically, making its application in electrical power transformers unfeasible[10].

REFERENCES

[1] Sens, Márcio Antônio " Condutividade Térmica Efetiva de Nanofluidos para Transformadores Elétricos" - Grupo de Estudo de Transformadores, Reatores, Materiais e Tecnologias Emergentes - XXIV SNPTEE - Seminário Nacional de Produção e Transmissão de Energia Elétrica, 22 a 25 de outubro de 2017 Curitiba – PR.

[2] J. J. Healy, J. J. de Groot, and J. Kestin, “The theory of the transient hot-wire method for measuring thermal conductivity,” Physica B+C, vol. 82, no. 2, pp. 392–408, 1976.

[3] J. R. Parsons Jr. and J. C. Mulligan, “Measurement of the properties of liquids and gases using a transient hot-wire technique,” Review of Scientific Instruments, vol. 49, no. 10, pp.1460–1463, 1978.

[4] A. Kadjo, J. P. Garnier, J. P. Maye, and S. Martemianov, “A new transient two-wire method for measuring the thermal diffusivity of electrically conducting and highly corrosive liquids using small samples,” International Journal of Thermophysics, vol. 29, no. 4, pp. 1267–1277, 2008.

[5] H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Oxford University Press, London, UK, 1959.

[6] “Measurement of the transport properties of fluids,” in Experimental Thermodynamics, W. A. Wakeham, A. Nagashima, and J. V. Sengers, Eds., vol. 3, Blackwell Scientific Publications, London, UK, 1991.

[7] Healy, J., de Groot, J., & Kestin, J. (1976). The theory of the transient hot-wire method for measuring thermal conductivity. Physica B+C, 82(2), 392-408. https://doi.org/10.1016/0378-4363(76)90203-5

[8] B. Merckx,1,2P. Dudoignon,1J. P. Garnier,3and D. Marchand2 "Simplified Transient Hot-Wire Method for Effective Thermal Conductivity Measurement in Geo Materials: Microstructure and Saturation Effect"; Hindawi Publishing Corporation Advances in Civil Engineering Volume 2012, Article ID 625395, 10 pages doi:10.1155/2012/625395, https://doi.org/10.1155/2012/625395.

[9] I. H. Tavman, “Effective thermal conductivity of granular porous materials,” International Communications in Heat and Mass Transfer, vol. 23, no. 2, pp. 169–176, 1996.

[10] Assis Filho, Francisco; Sens, M. A, Ueti, Edson e outros “Viabilidade de Utilização de Nanofluidos Magnéticos em Transformadores Elétricos”, XXIII SNPTEE Seminário Nacional de Produção e Transmissão de Energia Elétrica - GRUPO – GTM-Grupo de Estudo Transformadores, Reatores, Materiais e Tecnologias Emergentes, 18 a 21 de Outubro de 2015, Foz do Iguaçu – PR.

[11] ASTM D5334/05 - Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe.

[12] M. L. V. Ramires; C. A. Nieto de Castro;Y.Nagasaka;A. Nagashima; M. J. Assael; W. A. Wakeham, “Standard Reference Data for the Thermal Conductivity of water - TCHW - Transient coated hot wire technique” – NIST-USA, July 1994. Disponível em: http://www.nist.gov/data/PDFfiles/jpcrd493.pdf.

[13] Thermal properties of ice, https://material-properties.org/ice-density-strength-melting-point-thermal-conductivity/

[14] M. A. Sens, Relatório Técnico DVLF 41444/2009 - GDK S. A., "Condutividade Térmica de Solo Arenoso e Britas do Polo Industrial da Petrobras de Guamaré – RN, Avaliada no Local", 15 páginas, Rio de Janeiro, 24/11/2009.