DESIGN, CONSTRUCTION AND EVALUATION OF A THERMAL CONDUCTIVITY METER BASED ON ASTM E1225 STANDARD

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ABSTRACT

The focus of this work is the design, construction and evaluation of a thermal conductivity meter apparatus based on ASTM E-1225 standard. The thermal conductivity is a heat-transport propriety and with the development of new materials the determination of thermophysical properties for its correct use becomes necessary. The apparatus was projected in CAD software and the material selection was done following the standard recommendations. For the meter bars were used 304 stainless steel, since its thermal conductivity is known. The heater was made with an aluminum cylinder block and a cartridge electric resistance. The cooling system was assembled using a Peltier thermoelectric plate and a fin heat sink equipped with a fan. Lastly, a steel pipe was used for building the guard cylinder. In order to evaluate the apparatus, the first specimen tested was the 304 stainless steel, the same material as the meter bars. The result of thermal conductivity showed an error of 6% relative to the value found in literature. However, in this test the temperature of isothermal guard cylinder was lower than the temperature required by the standard. Thus, the future goals will be the development of a temperature control for the guard cylinder and realization of more tests with different materials.

NOMENCLATURE

k   thermal conductivity, W/mK
L   distance between a temperature difference, m
q_c conduction heat flux, W/m^2
r_A meter bars and specimen radius, m
r_B guard cylinder inner radius, m
T   temperature, K
T_i temperature at Z_i, K
$\overline{T}$ average temperature, K
Z_i position as measured from the right end of the column, m

Subscripts

C   cooler
g   guard cylinder
H   heater
I   insulator
M   meter bars
S   specimen

INTRODUCTION

The heat transfer is defined as the energetic interaction caused only by temperature differences. However, the heat flux is not just a function of temperature difference, but also a function of thermophysical properties, dimensions and geometries, time and fluids flow (Bejan, 2004). The heat transfer processes are classified in conduction, convection and radiation.

The conduction is the energy transfer from the more energetic particles to less energetic particles in a substance (solid, liquid or gas). In presence of a temperature gradient, the heat flux flows from a high temperature region to a low temperature region (Incropera et al., 2008). The heat flux transferred by conduction (q_c) is given by the Fourier's law:

$$q_c = k\nabla T \tag{1}$$

For homogeneous isotropic solids in steady conditions and one-dimensional analysis, the Eq. (1) becomes:

$$q_c = k\frac{T_2 - T_1}{L} \tag{2}$$

where temperatures T_2 and T_1 are a distance L apart.

The parameter k is a constant and a property of heat transport known as thermal conductivity

(Arpaci, 1966). The thermal conductivity is a characteristic of the material and indicates its heat conduction capacity. A high thermal conductivity value indicates that the material is a good heat conductor while a low thermal conductivity value indicates that the material is a thermal insulator, i.e., a bad heat conductor (Çengel et al., 2012).

With the development of new materials, mainly insulations and composites, it becomes necessary the determination of its thermophysical properties such as thermal conductivity.

Methods of measuring thermal conductivity

According to Simioni (2005), the methods of measuring thermal properties are divided in two groups: steady methods and dynamic methods. The dynamic methods do not need to reach the steady state, being faster than the steady methods. However, they are harder to carry out.

Among the steady methods, the Guarded-Hot-Plate principle and the Heat-Flow-Meter principle are the most common. The Heat-Flow-Meter principle is faster and more practical comparing with de Guarded-Hot-Plate principle (Müller, 2007).

The Heat-Flow-Meter is divided in two methods: absolute and comparative. The absolute method uses electronic means for determining the heat flux in the specimen. On the other hand, the comparative method uses referenced materials, i.e., materials with known thermal conductivity, to determine the heat flux in the specimen (Müller, 2007).

The ASTM E1225 standard (2013) describes a technique for the determination of the thermal conductivity of homogeneous isotropic solids, using a Comparative-Heat-Flow-Meter method. This technique can determine the thermal conductivity in the approximate range of 0.2 to 200 W/mK over temperature range between 90 and 1300 K. It can be used outside these ranges with decreased accuracy.

The aim of this work is to present the design and construction of a thermal conductivity meter apparatus based on ASTM E1225 standard and the preliminary test carried out for the apparatus evaluation.

THEORY

The technique described in ASTM E1225 standard (2013) consists in inserting a material of unknown thermal conductivity (k_S), called specimen, between two similar specimens of a material with known thermal conductivity (k_M), called meter bar. A temperature gradient is established in the column, keeping the heater in a temperature T_H, and the cooler in a temperature T_C. The heat losses are minimized by the thermal insulator (k_I) and by a longitudinal cylinder guard that are around all test stack. The Fig. 1 presents the main parts of the meter

apparatus.
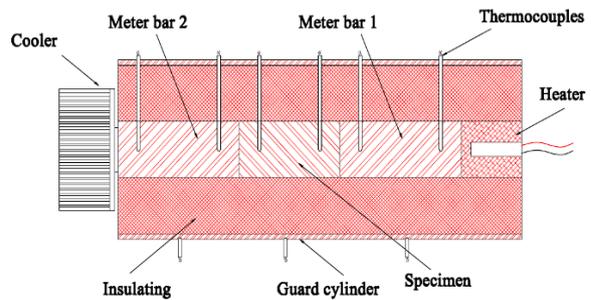
Figure 1. Main parts of thermal conductivity meter.

When the meter bars and the specimen are right-circular cylinders of equal radius, r_A, the technique is described as comparative-cut-bar method.

The apparatus is closed by a longitudinal guard cylinder with an inner radius r_B, maintained in a temperature $T_g(z)$ that can be either a linear gradient of temperature with temperatures next to temperature gradient inside the test stack or an isothermal longitudinal guard cylinder, i.e., constant temperature in all points of the guard cylinder. In case of isothermal guard, the constant temperature is equal to the average temperature of the specimen, with a maximum variance in z equal to $\pm$ 5 °C. The guard can be either metal or a ceramic, and its internal radius must be that the ratio r_B/r_A between 2.0 and 3.5.

In steady state, the specimen thermal conductivity is calculated by the inside temperature gradient, measured in the specimen and meter bars and by thermals conductivity of meter bars, as follows:

$$k_S = \frac{Z_4 - Z_3}{T_4 - T_3}\left[\frac{k_{M_1}}{2}\frac{T_2 - T_1}{Z_2 - Z_1} + \frac{k_{M_2}}{2}\frac{T_6 - T_5}{Z_6 - Z_5}\right] \quad (3)$$

where T_i and Z_i are temperatures and positions of thermocouples, respectively, according Fig. 2.
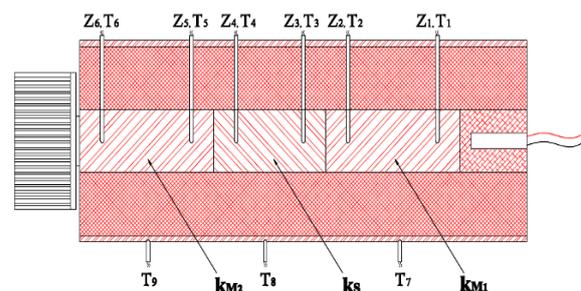
Figure 2. Thermocouples location.

There must be a minimum of two thermocouples in each meter bar and two in the specimen, situated within a distance equal to r_A from an interface. In the longitudinal guard cylinder there

must be a minimum of three thermocouples equally spaced one of the others. The use of thermocouples is recommended due its small size and easy fixation.

APPARATUS DESIGN

The apparatus was designed in CAD software, checking the possible dimensions for each material. The Fig. 3 presents the apparatus design.
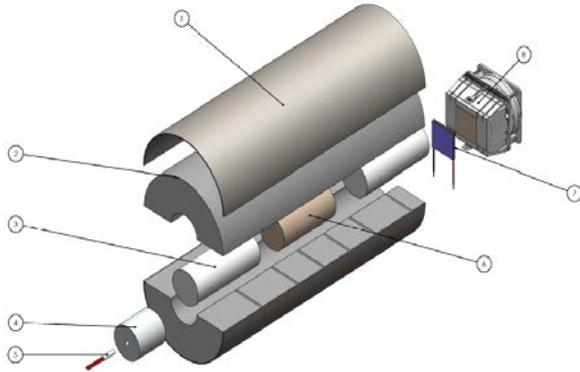
Figure 3. Apparatus design in explod view.

The Table 1 presents the list of components and materials used in the apparatus construction.

Table 1. List of components and materials used in the apparatus construction.

Item number	Description	Material
1	Guard cylinder	Steel
2	Thermal insulator	Polyurethane
3	Meter Bars	304 Stainless Steel
4	Heater	Aluminum
5	Electric resistance	Cartridge
6	Specimen	Test material*
7	Thermoelectric plate	Semiconductors/Ceramic
8	Heat sink	Aluminum and fan

*The test material can be metal, ceramic, polymer or composite.

Specimen and meter bars

The design of the apparatus started from specimen and meter bars sizing. Cylinder bars were selected with 50.8 mm (2 inches) in diameter due it be a commercial available dimension. The specimen length (Fig. 4a) was designed with 100 mm and the meter bars (Fig. 4b) with 120 mm.

(a)

(b)
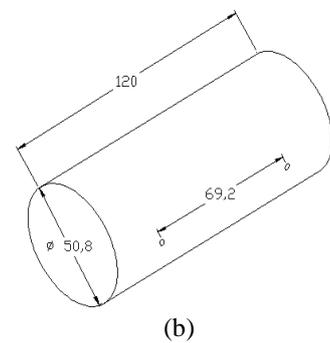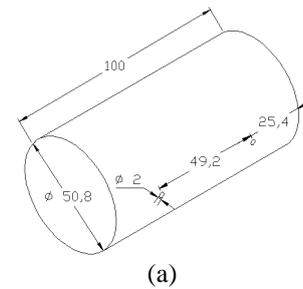
Figure 4. Dimension in milimeters of the parts. (a) specimen. (b) meter bars.

The specimen can be metal, ceramic, polymer or composite. For the meter bars, it was selected the 304 austenitic stainless steel because it has a known thermal conductivity (Ho and Chu, 1977):

$$k_M = 0.0178\overline{T}_M + 9.4805 \qquad (4)$$

where $\overline{T}_M$ is the average temperature (in Kelvin) of the meter bar. The Equation (4) must be used between 200 K to 500 K with an uncertainty of $\pm 5\%$.

Guard cylinder

For the longitudinal guard cylinder, a steel pipe was selected with 152.4 mm (6 inches) in diameter, which is thrice the diameter of the specimen. The pipe was cut with 380 mm in length, and after it was cut in the middle (Fig. 5). Thus, the apparatus can be opened for changing the specimen and thermocouples fixations.
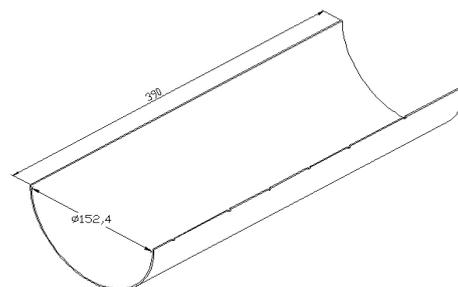
Figure 5. Guard cylinder dimension in milimeters.

Thermal insulation

The expansive polyurethane foam was the insulator selected because it is easily applicable and malleable in format of the guard cylinder (pipe) while it expands. The polyurethane is a good thermal insulator; its thermal conductivity is approximately 0.035 W/mK (Wu et al., 1999). The foam was applied between the guard cylinder (steel pipe) and the test stack. After 24 hours, the foam was removed and cut (Fig. 6).

Figure 6. Thermal insulator constructed using polyurethane foam.

Heater

In order to provide heat in one of the apparatus extremities, an cartridge electric resistance (Fig. 7a) was coupled to an aluminum cylinder block and connected to a DC power. The cylinder has a concentric hole for the cartridge (Fig. 7b).
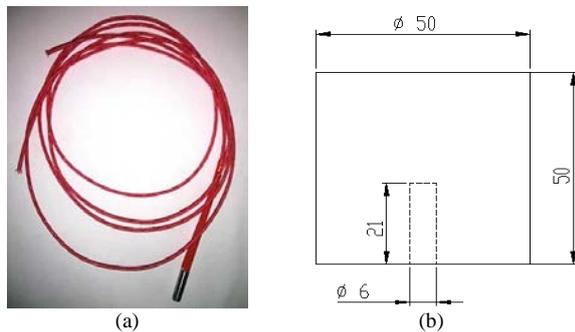
Figure 7. Heater assembly. (a) Heater cartridge.(b) Aluminum cylinder block dimension in milimeters.

Cooler

The cooler was put in the opposite extremity of the heater, for the purpose of to remove heat from the apparatus; then creating a temperature gradient. The cooler was formed by a Peltier thermoelectric plate TEC12706 (15.4 V and 6 A) with square dimensions 40×40 mm^2 (Fig. 8a) and a fin heat sink with fan (Fig. 8b).
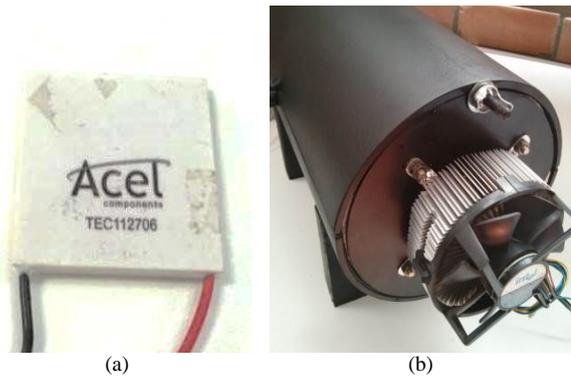
Figure 8. Cooler assembly. (a) Pelter thermoelectric plate.(b) fin heat sink with fan.

Instrumentation

Thermocouples were used for the temperatures measuring. In test stack (specimen and meter bars), it was used the type J thermocouples, being two in each meter bar and two in specimen. Others three type K thermocouples were used in the longitudinal guard cylinder.

It was used a Data Acquisition (DAQ) Agilent 34970A (Fig. 9) for thermocouples reading. The thermocouples were connected to 34901A module (20-Channel Armature Multiplexer). The DAQ carried out the measurement and registered it in a microcomputer through a serial port.

Figure 9. Data Acquisition Agilent 34970A.

EXPERIMENTS

After the construction of all parts, the apparatus was assembled (Fig. 10a and 10b). As can be seen in Fig. 10b, it was necessary the inclusion of a side lock to close the longitudinal guard cylinder and axial lock for axial force application. The axial force was constant in the transversal section of test stack in order to reduce the contact thermal resistance between the meter bars and specimen (thermal grease was also used).

(a)

(b)

Figure 10. Thermal conducitivity meter apparatus.
(a) opened apparatus. (b) closed apparatus.

The experimental layout used for the test is showed in Fig. 11. The first test carried out was the measurement of 304 austenitic stainless steel thermal conductivity, the same material used in meter bars, however with 100 mm in length. The data were acquired every 300 seconds. The thermocouples position order was the same as presented in Fig. 2.
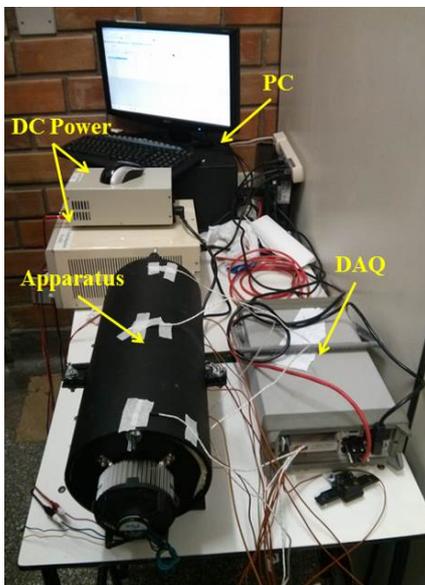
Figure 11. Experimental layout.

RESULTS AND DISCUSSION

The Fig. 12 presents the temperature curves of the first test (the data were plotted every 10 minutes). The steady state occurred approximately before 500 minutes. Additionally, 100 minutes were left in order to verify the steady state. Lastly, the last five measures were picked on each thermocouple to calculate the specimen thermal conductivity.
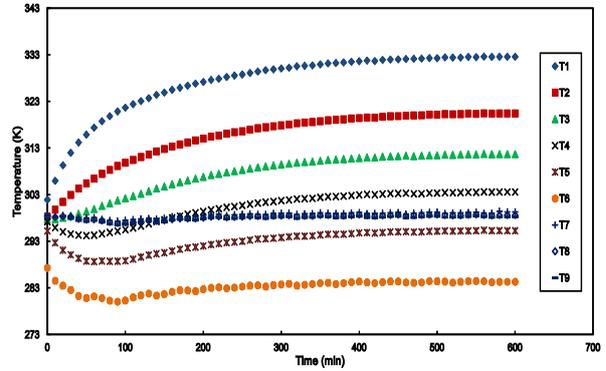
Figure 12. Steady state verification for the test with the specimen of 304 austenitic stainless steel.

The Table 2 presents the main data used to calculate the thermal conductivity and the experimental result of the thermal conductivity of the specimen.

Using the ASTM E1225 method, $k_S = 15.81 \pm 2.60$ W/mK was obtained. On the other hand, using the equation of thermal conductivity of 304 austenitic stainless steel, Eq. (4), where the specimen average temperature is 307.8 K, $k_S = 14.96 \pm 0.75$ W/mK was obtained. The value obtained for the experimental method (ASTM standard) gives an error of 6% on the value obtained by Eq. (4)

On the first test, it was not applied a thermal load in the guard cylinder. It was preferred to use an isothermal guard, such that guard temperature was equal to environment temperature. The Fig. 13 presents thermographic images taken during the test.
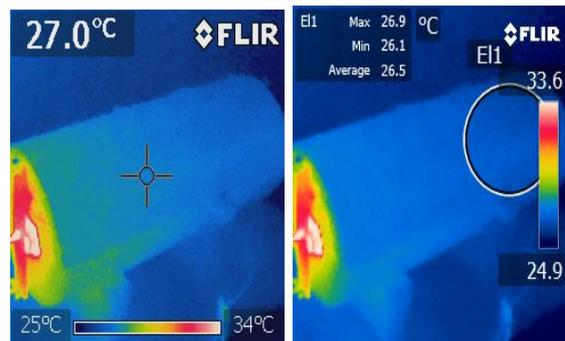
Figure 13. Thermograph images of guard cylinder taken during the first test.

Table 2. Main data of test with specimen of 304 austenitic stainless steel.

Object	Average Temperature (K)	ΔT (K)	Thermal conductivity (W/mK)	Heat flux (W/m²)	Distance between thermocouples (mm)
Meter bar 1	326.66 ± 0.41	12.15 ± 0.82	15.30 ± 0.76	2765.55 ± 239.77	67.20 ± 1.50
Meter bar 2	289.96 ± 0.41	11.02 ± 0.82	14.64 ± 0.73	2394.18 ± 220.76	67.40 ± 1.50
Specimen	307.80 ± 0.41	8.11 ± 0.82	**15.81 ± 2.60**	2579.86 ± 326.52	49.70 ± 1.50

Based on the images and thermocouples data (T_7, T_8, T_9) put on the guard cylinder, it is possible to see that the guard was really isothermal, with temperature between 299 and 300 K. However, the temperature was under approximately 8 K of the specimen average temperature, distancing from standard limits, which require that the maximum variance can be ± 5 K.

Therefore, although the specimen thermal conductivity error between the experimental method and equation had been considered low, some improvements in the guard cylinder, such as a thermal load with temperature control, may decrease the heat losses, thereby making the experimental result of thermal conductivity more accurate.

CONCLUSIONS

The ASTM E1225 standard presents an effective test technique for measuring thermal conductivity. The apparatus was designed and constructed. Its evaluation showed that the method could obtain results next to values showed in the literature. The test also showed that the use of isothermal guard can be done since a temperature control is carried out.

Future works will be the installation of a thermal load and a temperature control in the guard. Furthermore, more tests will be carried out with different materials to verify the apparatus operation.

ACKNOWLEDGEMENTS

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