PERFECTIONING OF AN EXPERIMENTAL CHAMBER FOR DETERMINATION OF THERMAL CONDUCTIVITIES

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Abstract. *The thermal project of artificial satellites has a relevant uncertainty generator factor associated with thermal conductivities in solid materials. To determinine of this thermal propertiy is essential for computing the heat transfer that takes place in the system. The improvement of the measuring instrument of thermal condutvitvity in the LIT (Integration and Testing Laboratory of INPE) has been made. Experiments for its calibration are presented in this article. Finally, experiments related to four different metals have been made and the uncertainties have been determined.*

Keywords*: Thermal conductivity, thermal property, experimental method, measuring instruments.*

1. Introduction

The heat transfer in solids, known as conduction, occurs with two main mechanisms: due to the molecular interactions, known as lattice waves, and due to the free motion of electrons, in metals and semiconductors. These two mechanisms are affected by other components as molecular forces or crystal imperfections. In a thermal system, the heat transfer rate, by conduction, follows the Fourier's Law (McAdams, 1958):

$$q_x = -k\,.\,A.\frac{\partial T}{\partial x} \tag{1}$$

q_x = heat transfer rate [W]; A = transversal section area [m^2]; k = thermal conductivity of the material [$W/m.°C$]; $\partial T / \partial x$ = temperature gradient [$°C/m$].

The thermal conductivity defined in Eq. (1) is usually based on experiments. Its values, for solids, vary a great deal, depending on the material. It can be a good heat conductor, like metals, or thermal isolations, like the asbest.

Thermal conductivity measuring has been made by several different experimental techniques. The book Thermophysical Properties Research Center Data Books (1963) lists around 800 references about thermal conductivity values in solids, and 600 of them apply essentially linear heat flux. In spite of the large number of papers that explores this field, the discrepancy of results, for this specific property, is very high. Continuous effort has to be made to develop and improve experimental apparatus for measuring the thermal conductivity of materials, particularly of new materials and metals with different alloys, whose values still lack in the literature.

This work aims to improve an experimental apparatus developed (Garcia and Carjilescov, 1987) at Technological Institute of Aeronautics (ITA). Many experiments of conductivity were made. This article presents the implementation, calibration and testing of the apparatus. These implementations are being held by the Aeronautic Mechanical Engineering of ITA in cooperation with Integration and Testing Laboratory (LIT) of National Institute of Space Research (INPE).

2. Objective

This work consists on the improvement of an experimental apparatus for determining the thermal conductivity of solid materials. The materials are placed in vacuum, between a heat source and a cold serpentine. The surface of the solid material (specimen) is protected with a thermal shield to avoid heat radiation losses. The measuring are made in high vacuum (below than $5x10^{-2}$ Pa), so, in this pressure level, the heat convection is negligible (Roth, 1982). Due to this process, the one-dimensional heat flux is obtained.

The experiments are being held in stead state, so, the Fourier´s Law, as presented in Eq. (1), can be applied in this situation. The temperature measures are given throughout the axial axis of the specimen. Figure 1 presents the thermocouples installed in the specimen, in the longitudinal direction, to measure this temperature profile.

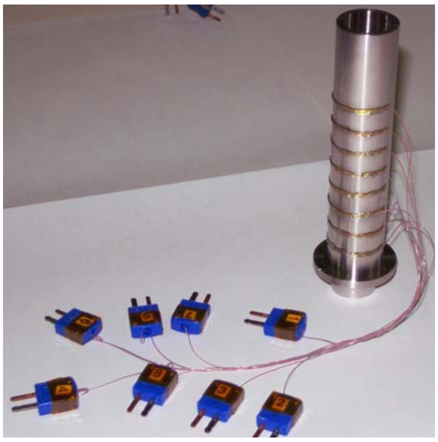

Figure 1. Thermocouples installed in the stainless steel specimen to obtain the temperature distribution.

The heat transfer rate *"q"* that crosses through the specimen is given by dissipation of electrical power in a skin-heater. The electrical power was measured by HP 34401A Multimeter. The skin-heater was adhered on the top of that specimen. Figures 2 and 3 presents some thermocouples, the brass specimen and the skin-heater, before and after their installations.

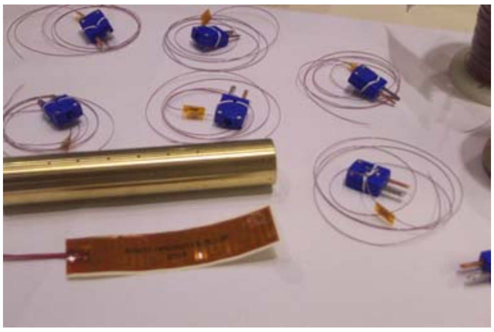

Figure 2. Thermocouples, the brass specimen and the skin-heater.

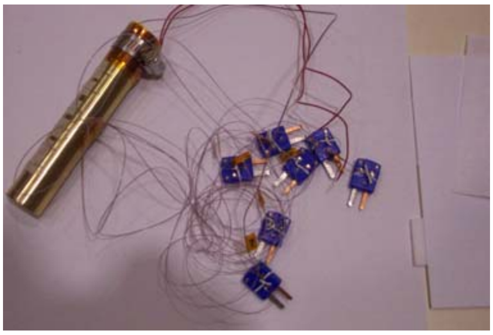

Figure 3. Thermocouples and the skin-heater installed in the brass specimen.

A formulation for this treatment was described by Ozisik (1980). In the phase of the project, this paper shows the implementations of the Thermo-Vacuum Chamber, its calibration and the tests of four materials: copper, stainless steel, aluminum and brass. The validation of the developed apparatus was done comparing of the results with the literature.

3. Experimental Apparatus

The testing specimens are put between a heat source and a cold serpentine, inside of a high vacuum chamber, and protected against thermal radiation losses. Therefore, heat radial losses of the testing specimens are negligible and the heat flux can be considered one-dimensional. The temperature distribution is gotten through the axial axes of the testing specimen, which results in the temperature gradients. The heat transfer rate q is given by dissipation of electrical power in a skin-heater. The testing specimens have a diameter of 25.4mm and a length of 140mm. Figure 4 presents the experimental apparatus, showing this high vacuum chamber with the specimen and the cold serpentine.

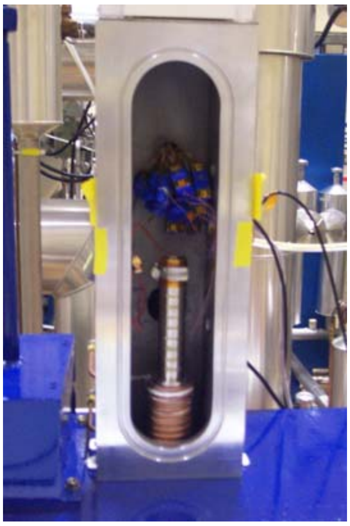

Figure 4. High Vacuum Chamber, the specimen with heat source (skin-heater) installed in a cold serpentine, and thermocouples.

Many leak detections have been fulfilled. In the leaks detected, repairs with welding and resins application were implemented. After these improvements, the leaks kept below than of the leak detector resolution of the $2x10^{-12}$ $Pa.m^3/s$ (Edwards High Vacuum International, 1984). The pumping system is made in two steps: the first is given by a mechanical pump; the second step is given by a diffusing pump to obtain the high vacuum (pressure less than $1x10^{-2}$ Pa). In this pressure level, the thermal convection can be totally negligible. That assures the hypothesis of one-dimensional heat flux. Figure 5 shows this vacuum pumping system.

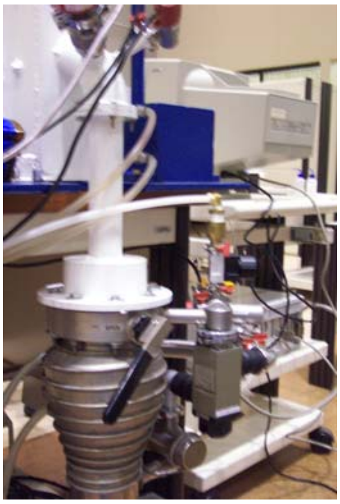

Figure 5. Vacuum Pumping System coupled in vacuum chamber: Edwards Diffstak MK2-100/30 Diffusion Pump plus E2M8 Mechanical Pump.

The thermocouples are T-type, 36 AWG, from Omega (2005). The temperature measure system is a HP3497 system, with multiplexed channels and data acquisition rate of 30 s. Figure 6 presents a general view of the setup.

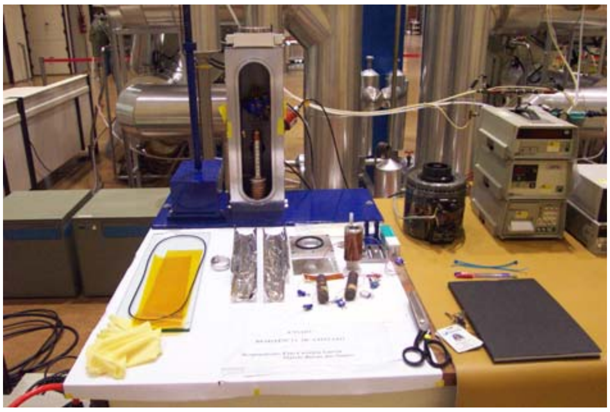

Figure 6. General View of the test setup.

4. Mathematic Formulation

As discussed previously, for the one-dimensional flux, in stead state, the thermal conductivity k can be determined by applying the Fourier's Law, according to Eq. (2):

$$k = \frac{q}{A\,(\Delta T/\Delta x)} \tag{2}$$

For the acquired values obtained for "k", Chauvenet's Criteria (Coleman and Steele, 1999) of rejection was applied.

5. Results

The six thermocouples were placed on the copper, brass and aluminum testing specimens with a distance about 15 mm from each other. The stainless steel specimen was differently prepared as described in Table 1.

Table 1. Thermocouples' spots on the Stainless Steel testing specimen

Thermocouple	1	2	3	4	5	6	7	8
Position "x" (mm)	42.6	55.1	67.9	80.0	93.2	106.8	119.7	132.5

Figure 7 presents, for the stainless steel specimen, the thermal gradients developed after the convergences to steady states, for five different inputs of heat transfer rates "q". The good linearities of these gradients confirm the one-direction assumptions in this work. Figures 8, 9 and 10 present the thermal gradients for cooper, brass and aluminum, respectively.

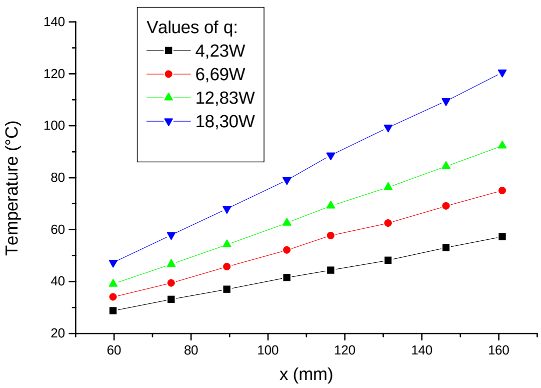

Figure 7. Thermal Gradients in the stainless steel for different heat transfer rate "q".

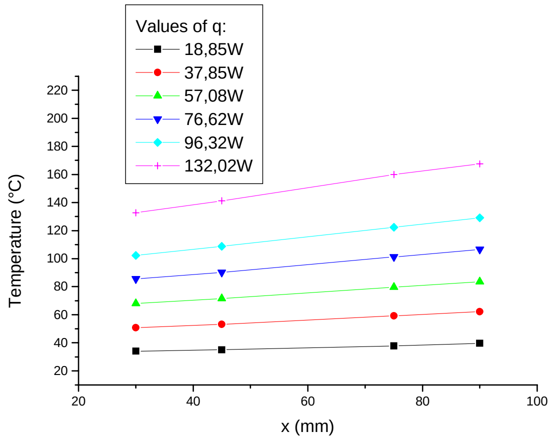

Figure 8. Thermal Gradients in the copper for different heat transfer rate *"q"*.

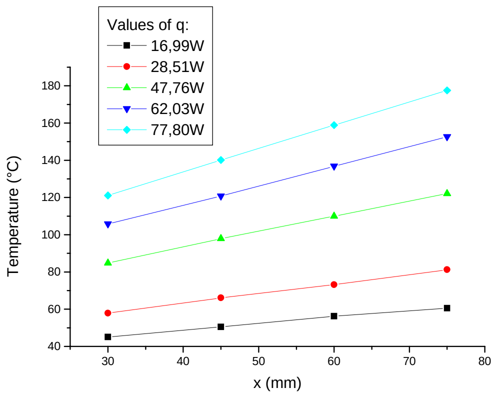

Figure 9. Thermal Gradients in the brass for different heat transfer rate *"q"*.

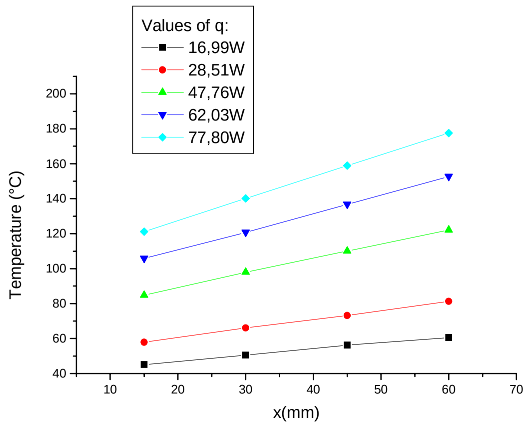

Figure 10. Thermal Gradients in the aluminum for different heat transfer rate *"q"*.

Tables 2, 3, 4 and 5 show the values of the thermal conductivities for each material and their respective uncertainties "*Uk*" for a level of confidence of 95% (as described in item 6, ahead). Also, these tables present the variation of "*k*" with the average temperatures, and average thermal conductivities obtained.

Table 2. Thermal Conductivities and respective Total Uncertainties computed for the Stainless Steel Specimen

Power (W)	*Specimen Temperatures (°C)*	$k_{average}$ *(W/°C.m)*	*Uk*
4.23 W	20 to 40	13.54	0.28
6.36 W	40 to 60	17.40	0.27
8.92 W	60 to 80	18.95	0.25
12.83 W	80 to 120	19.20	0.22
18.29 W-	120 to 160	20.51	0.22
$k_{average}$ = 17.9875 *W/m.°C*			

Table 3. Thermal Conductivities and respective Total Uncertainties computed for the Cooper Specimen

Power (W)	*Heater temperatures (°C)*	$k_{average}$ *(W/m.°C)*	*Uk*
37.85	103.51	290.09	29.74
57.08	134.03	351.41	35.80
76.62	164.97	372.98	38.10
96.34	164.17	454.49	46.15
$k_{average}$ = 362.49 *W/m.°C*			

Table 4. Thermal Conductivities and respective Total Uncertainties computed for the Brass Specimen

Power (W)	*Heater temperatures (°C)*	$k_{average}$ *(W/m.°C)*	*Uk*
16.99	83.55	88.13	8.99
28.51	57.26	106.25	10.81
47.75	154.4	112.60	11.47
62.03	167.43	140.68	14.28
77.80	131.39	245.70	24.77
$k_{average}$ = 138.67 *W/m.°C*			

Table 5. Thermal Conductivities and respective Total Uncertainties computed for the Aluminum Specimen

Power (W)	*Heater temperatures (°C)*	$k_{average}$ *(W/m.°C)*	*Uk*
18.87	92.08	114.06	12.00
37.72	123	145.18	14.81
57.26	159.32	163.25	16.62
77.08	164.45	213.07	21.71
$k_{average}$ = 158.89 *W/m.°C*			

For each heat transfer rate imposed to specimen, a value of thermal conductivity, based on Eq. (2), was obtained. Each heat transfer rate also imposed different temperature levels. Then, different values of the thermal conductivity could be got as function of the temperature levels. Figure 11 presents these variations for the four specimens. Figure 12 presents closer view for the stainless steel.

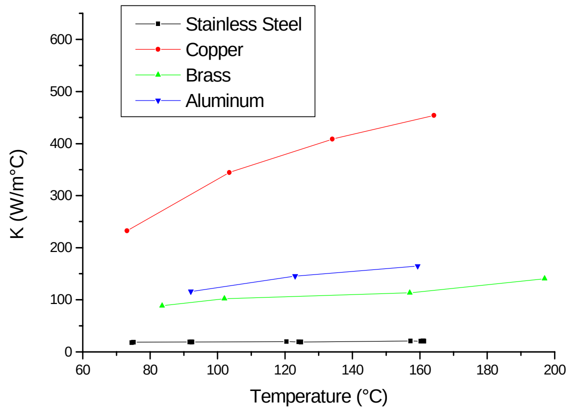

Figure 11. Thermal Conductivity of each Testing Specimen as a function of the Temperature Level.

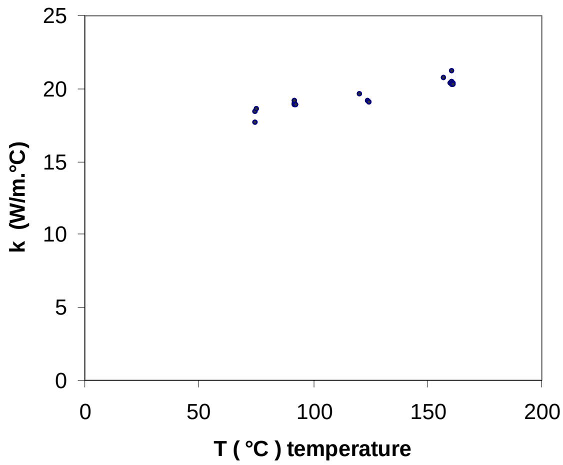

Figure 12. Closer view of the Thermal Conductivity of the Stainless Steel as function of the temperature level.

6. Uncertainty Analysis for Results of Thermal Conductivity

The total uncertainty of each variable was composed by combination of random and bias uncertainties as describe by Coleman and Steele (1999). Table 6 presents the bias uncertainties adopted for the variables. Method of Kline and McClintock (1953) was employed for propagation of primary variable uncertainties, for a level of confidence of 95% (or 20:1), as described ahead:

$$Uk = \sqrt[2]{\left(\frac{\partial k}{\partial q}\right)^2 .U_q{}^2 + \left(\frac{\partial k}{\partial x}\right)^2 .Ux^2 + \left(\frac{\partial k}{\partial T}\right)^2 .U_T{}^2 + \left(\frac{\partial k}{\partial A}\right)^2 .U_A{}^2} \tag{3}$$

Where:

$$\frac{\partial k}{\partial(\Delta T)} = + \frac{q.\Delta x}{A(\Delta T)^2}; \quad \frac{\partial k}{\partial(A)} = + \frac{q.\Delta x}{A^2 \Delta T}; \quad \frac{\partial k}{\partial(\Delta x)} = + \frac{q}{A\Delta T}; \quad \frac{\partial k}{\partial(q)} = + \frac{\Delta x}{A\Delta T} \tag{4}$$

Table 6. Bias Uncertainties of the primary variables

Variable	Temperature	Current	Tension	Length
Bias Uncertainty - U_B	0.001°C	0.001A	0.0001V	0.0001m

7. Conclusion

According to Incropera (2003), for the same temperature bands of these experiments, the thermal conductivity of Aluminum (pure and alloys) varies between 168 to 237 *W/m.°C,* for the Stainless Steel, it varies from 13.4 to 15.1 *W/m.°C*; for the Pure Copper is 401 *W/m.°C;* for Brass (70% of Cu, 30% of Zn) is 110 *W/m.°C.* Holman (1983) presents the thermal conductivity of Aluminum alloys varies between 144 to 215 *W/m.°C*; for the Stainless Steel, it varies from 17 to 19 *W/m.°C*; for the Copper, it varies between 374 to 386; and for the Brass it lays between 71 to 144 *W/m.°C.* Garcia and Carajilescov (1987) developed a similar work; they got close values of the obtained in this paper. Noting that the thermal conductivity bands are sufficiently similar to the ones computed in this work; the experimental chamber can be used for further analysis of different alloys of interest whose thermal conductivities are eventually unavailable. The next phase of this project will consist on making more experiments to reduce the uncertainties of the final results of thermal conductivities.

8. References

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