NEW EXPERIMENTAL CHAMBER FOR DETERMINATION OF THERMAL CONDUCTIVITY AND THERMAL CONTACT RESISTANCE

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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 property and thermal contact resistance are essential for computing the heat transfer that takes place in the system. The improvement of the measuring instrument of thermal conductivity and thermal contact resistance in the LIT (Integration and Testing Laboratory of INPE) has been made. Experiments for its calibration are presented in this article. Experiments related to four different metals have been made and the uncertainties have been determined for measuring of thermal conductivities. Also, measuring of thermal contact resistances as function of contact pressure was performed.

1. INTRODUCTION

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.

Thermal Contact Resistance, "R_c", occurs when two solids surfaces are in contact and submitted by a heat transfer rate, "q_x". "R_c" is strongly influenced by imposed pressure of contact. The formulation and results of "R_c" is part also of this paper.

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. The apparatus here described was modified to perform, also, measuring of "R_c", for steel specimen. 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.

The heat transfer rate “q_x” 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.

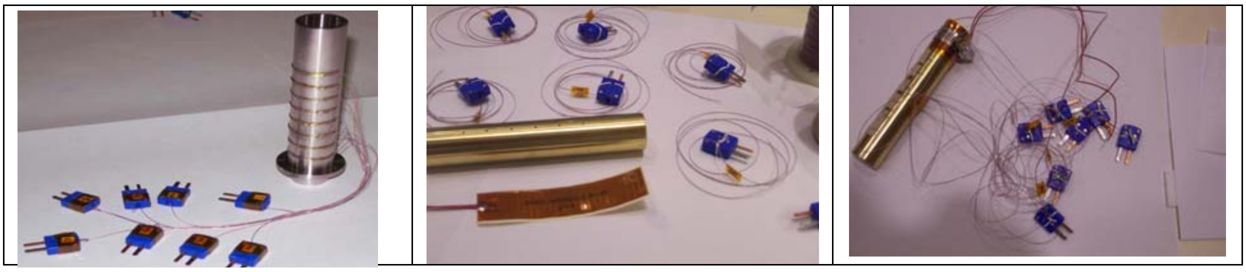

Figure 1. Thermocouples installed in the stainless steal to obtain the temperature distribution (left); thermocouples and the skin-heater installed in the brass (center and right side).

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 steal, 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 2 presents the experimental apparatus, showing this high vacuum chamber with the specimen and the cold serpentine.

Figure 2. High Vacuum Chamber: the specimen with heat source (skin-heater) installed in a cold serpentine, and thermocouples (left side); General View of the test setup (center); Vacuum Pumping System (right side).

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 $2\text{x}10^{-12}$ $\text{Pa.m}^3\text{/s}$ (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 $1\text{x}10^{-2}$ Pa). In this pressure level, the thermal convection can be totally negligible. That assures the hypothesis of one-dimensional heat flux. 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.

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

Thermal Contact Conductance is defined as (Garcia and Carajilescov, 1987):

$$hc = \frac{q_x}{A.\Delta T_c} \tag{3}$$

Where "ΔT_c" is the drop of temperature in the contact of two surfaces. In this way, the Thermal Contact Resistance is defined as the inverse of "h_c":

$$R_c = {}^{1}\!/_{h_c} \tag{4}$$

5. RESULTS OF THERMAL CONDUCTIVITY PROPERTIES

The six thermocouples were placed on the copper, brass and aluminum testing specimens with a distance of 15mm from each other. Figure 3 presents, for the stainless steal and copper specimens, the thermal gradients developed after the convergences to stead states, for fdifferent inputs of heat transfer rates “*q*”. The good linearities of these gradients confirm the one-direction assumptions in this work. Figure 4 presents the thermal gradients brass and aluminum.

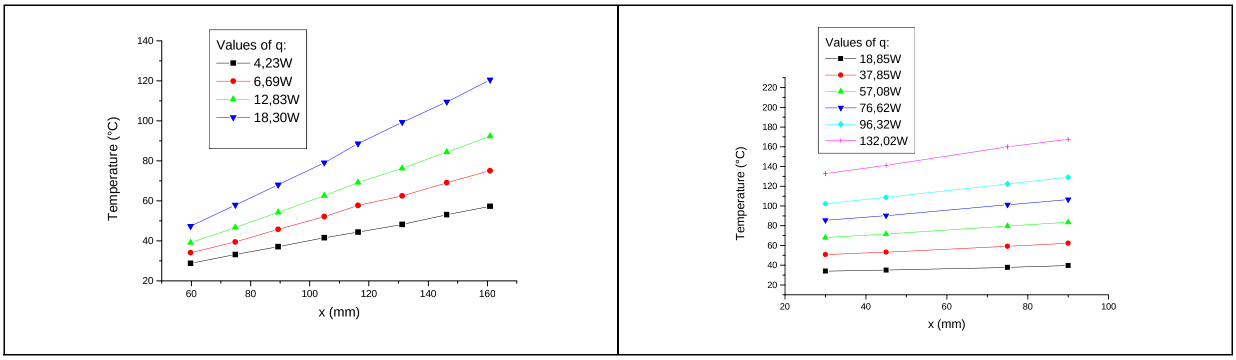

Figure 3. Thermal Gradients in the stainless steal (left) and copper (right)for different heat transfer rate “*q*”.

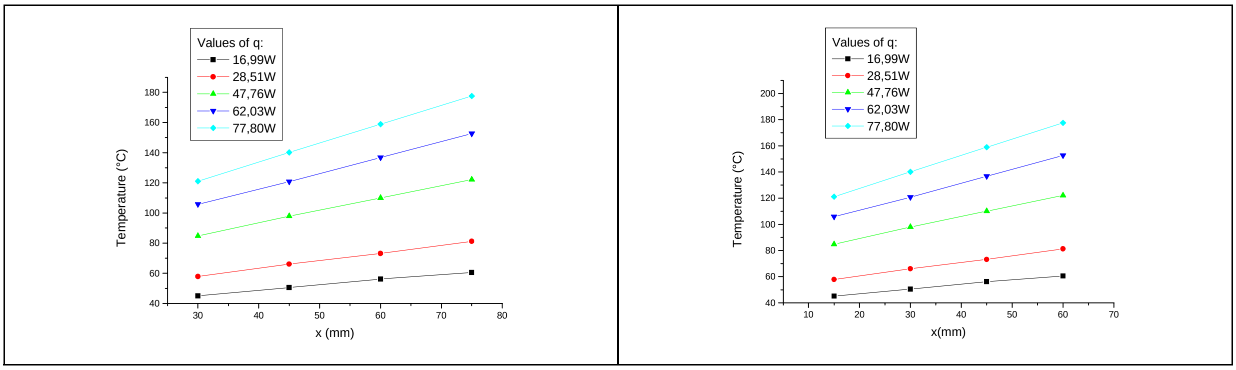

Figure 4. Thermal Gradients in the brass (left side) and aluminum (right side) for different heat transfer rate “*q*”.

Tables 1 and 2 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 1. Thermal Conductivities and respective Total Uncertainties computed for the Stainless Steel and Cooper.

Specimen: Steel		
Temperatures (°C)	$k_{average}$ (W/°Cm)	Uk
20 to 40	13.54	0.28
40 to 60	17.40	0.27
60 to 80	18.95	0.25
80 to 120	19.20	0.22
120 to 160	20.51	0.22
$k_{average}$ = 17.9875 w/m.°C		

Specimen: Cooper		
Temperatures (°C)	$k_{average}$ (W/°Cm)	Uk
103.51	290.09	29.74
134.03	351.41	35.80
164.97	372.98	38.10
164.17	454.49	46.15
$k_{average}$ = 362.49 w/m.°C		

Table 2. Thermal Conductivities and respective Total Uncertainties computed for the Brass and Aluminum

Specimen: Brass		
Temperatures (°C)	k $_{average}$ (W/°Cm)	Uk
83.55	88.13	8.99
57.26	106.25	10.81
154.4	112.60	11.47
167.43	140.68	14.28
131.39	245.70	24.77
$k_{average}$ = 138.67 w/m.°C		

Specimen: Aluminum		
Temperatures (°C)	k $_{average}$ (W/°Cm)	Uk
92.08	114.06	12.00
123	145.18	14.81
159.32	163.25	16.62
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. Than, different values of the thermal conductivity could be got as function of the temperature levels. Figure 5 presents these variations for the four specimens.

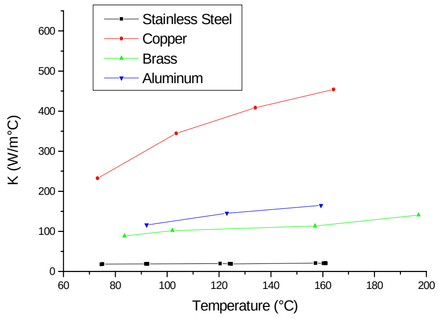

Figure 5. Thermal Conductivity of each Testing Specimen as a function of the Temperature Level.

6. RESULTS OF THERMAL CONTACT RESISTANCE

Figure 6, left side, presents the thermal gradients in two steel specimens, and the drop of temperature due the contact of the surfaces. Figure 6, right side, presents the influence of the contact pressure (between two steel surfaces), in the thermal contact resistance.

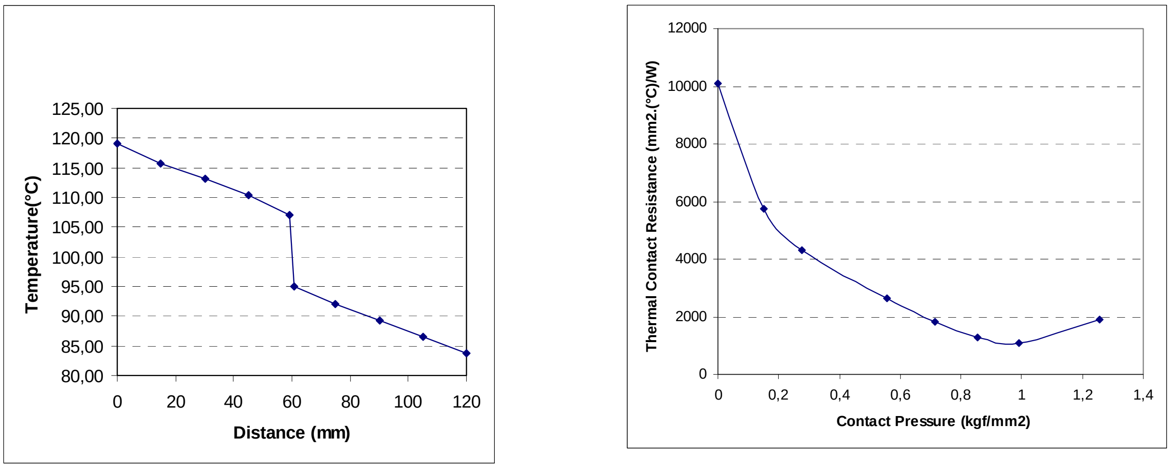

Figure 6. Left side: Thermal gradients in two steel specimens; drop of temperature due the contact of the surfaces. Right side: Thermal Contact Resistance as function of the Contact Pressure. Specimens: two steel bodies.

7. UNCERTAINTY ANALYSIS FOR RESULTS

The total uncertainty of each variable was composed by combination of random and bias uncertainties as describe by Coleman and Steele (1999). 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:

$$Uk = \sqrt[2]{\left(\frac{\partial k}{\partial q}\right)^2 .U_q{}^2 + \left(\frac{\partial k}{\partial x}\right)^2 .Ux^2 + \left(\frac{\partial k}{\partial T}\right)^2 .U_T{}^2 + \left(\frac{\partial k}{\partial A}\right)^2 .U_A{}^2} \tag{5}$$

Where:

$$\frac{\partial k}{\partial(\Delta T)} = +\frac{q.\Delta x}{A(\Delta T)^2}; \qquad \frac{\partial k}{\partial(A)} = +\frac{q.\Delta x}{A^2 \Delta T}; \qquad \frac{\partial k}{\partial(\Delta x)} = +\frac{q}{A\Delta T}; \qquad \frac{\partial k}{\partial(q)} = +\frac{\Delta x}{A\Delta T} \tag{6}$$

8. CONCLUSION

According to Holman (1983), for the same temperature bands of these experiments, 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. 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 values of "R_c" demonstrated a strong dependence of contact pressure, as it is, frequently, described in the literature, (Garcia and Carjlescov, 1987). The next phase of this project will consist on making more experiments to reduce the uncertainties of the final results of thermal conductivities, and analyze of the "R_c" for different materials.

9. REFERENCES

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