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Technical Notes

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Experimental Determination of Overall Thermal Resistances of Satellite Bolted Joints

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Introduction

ONE of the main objectives of a satellite thermal design is to maintain all electronic equipment in their function temperature ranges. In orbit, the satellite environment is a vacuum and heat is transferred by radiation and conduction. Large temperature differences are not present at inside compartments for most satellites and, therefore, conduction is the principal heat transfer means. Therefore, the thermal conductances (or resistances) of bolted joints are important for the calculation of the satellite temperature distribution. The First Data Collection Brazilian Satellite (SCD1) can be taken as an example. Since only passive methods of thermal control were used, the heat conducted by the satellite panels and/or their electronic boxes depends on the thermal resistances of the joints.

The theoretical calculation of these resistances is difficult because it depends on many factors such as shape and physical properties of the materials, type and material of bolts, material and number of washers, applied torque, thermal contact resistance between washer and washer, bolt and washer, bolt and panel, washer and panel, etc. The use of bolted joints as thermal control devices has been considered by thermal engineers. If the overall thermal resistance of bolted joints can be controlled by some parameters such as the number of washers, the material of the washers and the applied torque, then bolted joints can be designed to provide the required overall thermal resistance.

Simplified joints, with no washers between the plates, have been studied in the literature.[1–4] As the bolted joints used for the SCD1 Satellite have washers between plates, the available results cannot be used. The present work has the following objectives: to measure experimentally the overall thermal resistance of bolted joints assembled using the satellite procedures and materials, to verify whether bolted joints can be used as a thermal control device, and to estimate the range of variation of the thermal resistance found for actual satellite bolted joints.

Experimental Simulation

An experimental parameter variation study was made. The parameters: temperature level, number of washers, applied torque, washer material, washer surface finish, and bolt material were changed. Several similar joints (4, 5, or 10 samples) were mounted and tested simultaneously. All tests were conducted under steady-state conditions, which were considered achieved when all of the measured temperatures varied less than 1°C in 1 h.

The tests were conducted in the experimental facilities of the Thermal Control Laboratory of the Brazilian Institute for Space Research (INPE). A cylindrical vacuum chamber, of inside volume 1 by 1 m, with nitrogen-cooled walls that reach temperatures of around −180°C, was used. The chamber operates in high vacuum (10^{-7} torr) and, at these space environment simulation conditions, convection heat transfer is assumed to be negligible.

The experimental apparatus (see Fig. 1), consisted of a round heater and cooler, which were joined by a bolt. The heater was made of two circular aluminum 6130 sheets (roughness of 5.194×10^{-6} m, standard deviation of 3.960×10^{-6} m and 0.232 of slope, standard deviation of 0.088), with an electrical resistive wire sandwiched between them. (The measurement of the surface parameters was made at the University of Waterloo, Canada. The parameters roughness and slope

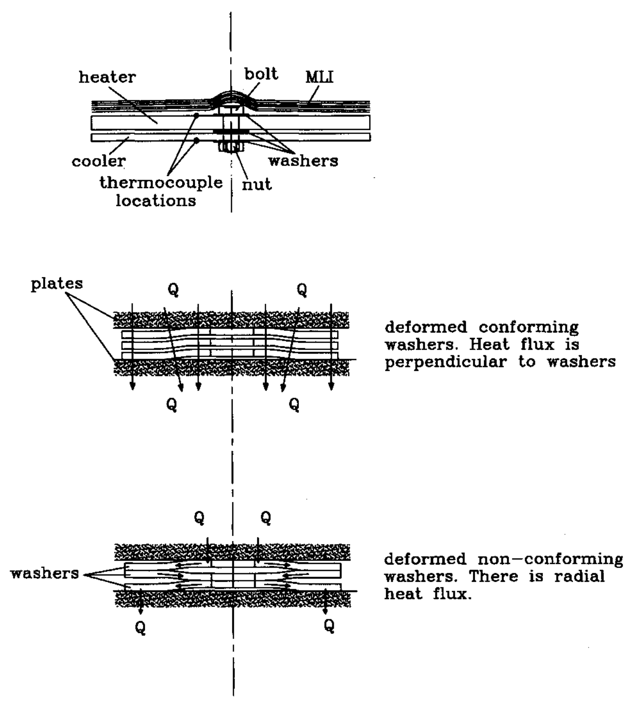

Fig. 1 Experimental mounting.

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Table 1 Bias limits

Error	Value
Radiative black surface emissivity	0.1
Radiative heat transfer area	6.28×10^{-5} m^2
Radiation (heat)	0.00073 W
Chamber temperature (overall)	1°C
Chamber temperature–instrumentation	1.33°C (for $T \geq -59$°C) and 0.99°C (for $T < -59$°C)
Temperatures–disturbance	1×10^{-5}°C
Temperatures–instrumentation	1.20°C (for $T \geq -59$°C) and 0.80°C (for $T \geq -59$°C)
Temperatures–computational	0.5°C
Temperature–data acquisition	0.3°C

of the contacting surfaces were measured four times and their rms values were obtained. The parameters presented in this article are the average for all the similar surfaces.) That wire was rolled in a plan spiral and electrically insulated by polyester films. Another circular aluminum 6130 plate (same surface characteristics), with the same heater diameter, and with one face painted black, was used as a radiative cooler. The heater external face was insulated radiatively by a multi-layer insulator (MLI, designed for radiative insulation in vacuum environment) as shown in Fig. 1.

Some (1, 3, 5, 7, and 9) stainless steel (SS) 304 no. 8 washers (0.0004 m thick, roughness of 0.2×10^{-6} m, standard deviation of 0.073×10^{-6} m and 0.0046 of slope, standard deviation of 0.003) were placed between the heater and cooler, in 105 mountings. For all of the mountings there was one SS washer between the heater and bolt head and another one between the nut and the cooler. Ten mountings were assembled using 2024 aluminum washers (0.0015 m thick, roughness 6.7×10^{-6} m) and 10 using fiberglass and epoxy washers (0.0015 m thick). Following a procedure adopted for satellites, the washers were taken from a large lot and positioned in the mounting at random. The SS washers presented variable surface deformation, due to their fabrication process. The measurement of the spring constant of the washers is beyond the objectives of this article.

Torque (0.82, 1.65, and 2.47 N · m) was applied to the washers by means of a torque wrench, which consisted of a dynamometer connected perpendicularly to an aluminum stick of known length. Following a satellite-mounting procedure, the mounting was assembled and disassembled several times (at least seven), before it was tested.

The heater and cooler temperatures were monitored through type T 36 gauge thermocouples located at two points, as shown in Fig. 1. Previous tests showed that the variation of the cooler and the heater temperatures can be considered uniform in the radial direction (variation within 1°C). Therefore, the temperatures of one point of the cooler and another one of the heater were measured and used in the determination of the overall thermal resistance.

The overall thermal resistance of the bolted joint, determined for each mounting, is defined as the ratio between temperature difference of the heater and the cooler and the heat transferred through the joint: $R = (T_h - T_c)/Q$, where R is the overall thermal resistance, T_h is the heater temperature, T_c is the cooler temperature, and Q is the heat transferred through the joint. The heat conducted through the mounting was transferred by radiation to the chamber walls, through the cooler black surface. The value of Q is estimated as $Q = \varepsilon A \sigma (T_c^4 - T_{ch}^4)$, where ε is the emissivity of the painted black surface of the cooler, A is the cooler surface area (radiative heat exchange area), σ is the Stefan–Boltzmann constant, and T_{ch} is the chamber temperature. The view factor between the black painted cooler face and the chamber is considered equal to 1.

Uncertainty Analysis

The uncertainty analysis developed in this work is mainly based on Moffat's[5] work. According to him, the sources of

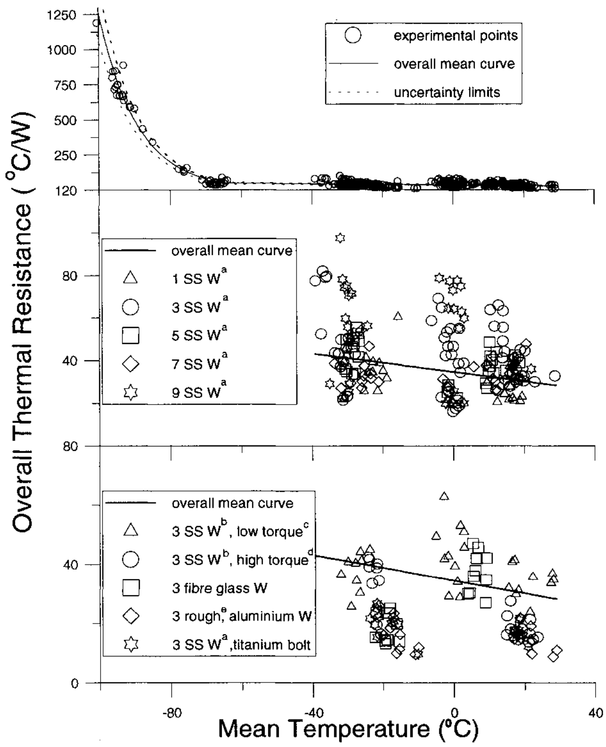

Fig. 2 Overall thermal resistance as a function of the mean temperature; a = torque: 1.65 N · m, surface roughness: 0.2×10^{-6} m; b = surface roughness: 0.2×10^{-6} m; c = 0.82 N · m; d = 2.47 N · m; and e = roughness: 6.7×10^{-6} m.

errors are categorized as fixed (bias errors) and random, depending on whether the error they introduce is steady or changes during the time of one complete experiment. The bias errors found are presented in Table 1. As the temperatures could present random errors, they were measured several times (at least 30), after the steady-state condition was achieved. The Kline and McClintock[6] theory was used to estimate the influence of these errors in the determination of the thermal resistances and of the heat transferred through the joints. Figure 2 shows the thermal resistance of the samples tested as a function of the mean temperature, which is defined as the average between the cooler and the heater temperatures. The average uncertainty limit curves are presented in Fig. 2 because the plot of error bars over each experimental point would cause an excessively cluttered appearance to the graph.

Discussion

All of the thermal resistances obtained are plotted as a function of the mean temperature in the first plot of Fig. 2. The mean thermal resistance curves and the lower and upper mean uncertainty limits are plotted in this same figure.

The effect of the temperature is evident for low temperature levels. The value of the coefficient of thermal expansion of the bolt material is lower than that of the washer and plate materials, and at low temperatures, the bolt shaft shrinks less than the washers and plates together. The contact pressure applied at room temperature is released and the thermal contact resistance between joint components increases significantly. For higher temperature levels, this effect is inverse. The fact that only one curve fits the experimental points obtained from different mounting configurations, shows that the parameter temperature, for low temperature levels, affects the overall thermal resistance more than any other parameter.

On the other side, from mean to high temperature levels (temperatures between -70 and $+40°C$), the overall thermal resistances present a large range of variation for similar joints (see second plot of Fig. 2). The thermal resistances are expected to increase with the increase in the number of washers since, for each washer inserted in the junction, two new thermal contact resistances (between washers) appear. Even if this trend can be observed, this effect is not clear. Actually, the experimental points are spread around the mean curve. This happens because most of the stainless steel washers are not perfectly flat and some contacts between washers may not occur over the entire area. Therefore, a constriction resistance in the radial direction of the washer may appear (see Fig. 1). Since the washer is thin and its material has a low thermal conductivity, this constriction resistance may be large.

In the third plot of Fig. 2, a comparison among the thermal resistance of mountings made of aluminum washers, mountings made of fiberglass and epoxy washers, and the overall mean thermal resistance curve is presented. Considering the thermal conductivity of the aluminum, which is the largest among other washers tested, the thermal resistance points for the aluminum washer mountings are expected to be under the overall thermal resistance curve. In addition, the fabrication process, special for the aluminum washers (they could not be found in the market), resulted in washers with low surface deformation. In opposition, the surfaces of the aluminum washer surfaces are rougher than those of SS washers, increasing the overall thermal resistance. The position of the experimental points under the mean curve demonstrates that, for these mountings, the material resistance decreases in a higher rate than the contact resistance increases.

The fiberglass and epoxy washers have the lowest thermal conductivity of all the washers used. Therefore, the overall thermal resistance is expected to be above the mean curve. This effect is observed only for high-temperature levels. The physical properties of this material change very much with the temperature, vacuum, and torque conditions, and the combination of these effects leads to an unpredictable behavior. Therefore, fiberglass and epoxy washers are not recommended for use in space applications.

All of the points for mountings assembled with titanium bolts are located under the mean curve. Also, for these mountings, the overall thermal resistance presents a small variation with the temperature level. This effect is expected, since the coefficient of thermal expansion of the titanium is lower than that of the SS, and therefore, the temperature has a lower effect in the overall thermal resistance. Finally, the overall thermal resistance, as well as its range of variation, decrease with the increase in the applied torque, as expected (see Fig. 2).

Conclusions

The temperature level is the controlling factor for temperatures less than $-70°C$. The combination of the coefficients of thermal expansion of the materials of the bolted joint components leads to this effect.

For mean to high-temperature levels (-70 to $+40°C$), the number of washers is not a controlling parameter if the washers present deformation resultant from the fabrication process. The material of the washers has a great influence in the overall thermal resistance. The fiberglass and epoxy washers are not recommended for satellite applications.

The range of variation of the thermal resistance is large, sometimes of the same order of magnitude of the values as the overall thermal resistances. The satellite-mounting procedures adopted resulted in bolted joints whose thermal resistances are difficult to estimate with precision. Therefore, the uncertainty in the estimation of the thermal resistance of bolted joints is high and large coefficients of safety must be used for the thermal design of satellites. Finally, the use of these bolted joints as satellite thermal control devices is not recommended.

Acknowledgments

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Optimization Analysis of a Disk-Shaped Heat Pipe

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Nomenclature

h = thickness, m
K = permeability of wicks, m^2
p = pressure, Pa
u, v, w = radial, vertical, angular velocity components, m/s
ε = porosity of wicks
μ = dynamic viscosity, $N \cdot s/m^2$
ρ = density, kg/m^3
Φ = angle of each internal flow channel of the disk-shaped heat pipe

Subscripts
l = liquid phase
v = vapor phase

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