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A SYSTEM FOR MEASUREMENT OF THERMAL CONTACT RESISTANCE UNDER VACUUM CONDITIONS

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ABSTRACT

The microscopic peaks and valleys at the interface of two contacting bodies result in a “Thermal Contact Resistance” (TCR), which reduces the transfer of heat between the bodies. To make reliable temperature predictions in a satellite, the thermal designer must consider the TCR in all structural elements and electronic components. Using TCR data obtained from analytical formulations is associated with large uncertainties, making it necessary to determine TCR under realistic working conditions. In this paper, a system has been proposed, along with its design features, for measurement of thermal contact resistance between contacting surfaces under vacuum conditions. The system, with little modifications, can also be used for measurement of thermal conductivity of materials.

Keywords: Thermal contact resistance, Measurement system, ASTM5470 standard.

1. INTRODUCTION

A “Thermal Contact Resistance” (TCR) exists between any two contacting bodies. The TCR, which is due to microscopic peaks and valleys at the interface of the two bodies, reduces the transfer of heat at the contact surfaces. For the two contacting bodies, TCR depends on factors such as roughness of the contacting surfaces, contact pressure, thermal conductivity of the bodies, and the interfacial fluid at the interface of the two bodies. Figure 1 shows the heat flow and temperature distribution at a contact surface.

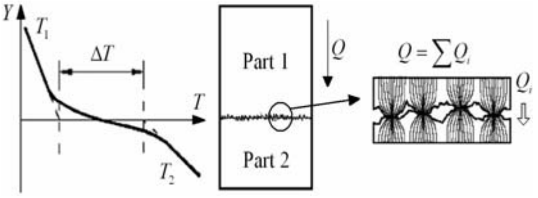

Fig 1: Temperature distribution around the interface of two contacting bodies (a) and the heat flux around the microscopic asperities (b)

The satellite thermal designer must consider TCR in the design process, wherever it is detrimental to the satellite thermal control, for example at satellite bolted joints and interfaces between satellite electronic boxes and the structure. Many researchers [1-4] have investigated the TCR phenomenon, and some formulas and empirical relations have been proposed for prediction of the TCR under rather idealistic conditions. But, applying these formulations in the design of satellite thermal control systems may be associated with large uncertainties. Therefore, to reduce the design uncertainty, it is necessary to determine the TCR under realistic working conditions [5,7].

Many studies have been performed on the actual measurement of TCR. Different methods have been followed, and various apparatus have been developed for this purpose. Most of the work has been carried out in the microelectronic industry, for evaluation of the filler materials used in various applications in this industry.

There are two main difficulties in the measurement of thermal impedance of joints. The first difficulty is due to absence of a standard method, which is agreed upon by all workers in the field [8]. As a result, the experimental data on the thermal fillers produced by various manufacturers can not be used for comparison of the thermal performance of these products.

The second difficulty concerns the problem of nonconformance of standard test conditions and parameters with real world conditions. This is mainly due to differences in the important parameters and conditions, which affect the thermal impedance in the joints in actual samples, and the test samples used in the standard tests. Therefore, the standard test results can not be applied to joints directly, and it becomes necessary to define a rather large safety margin for design of satellite joints. Also, in order to validate the design predictions, it is necessary to perform tests on the actual constructed joints, and improve the design of joints using the test data. This design-test cycle is time consuming, and costly. Therefore, to stay in the competition, many electronic manufacturers use other less accurate methods and procedures for obtaining the required data on their thermal fillers and other interface materials, such as [8]:

- Relying on past experiences (which may not be up-to-date)
- Using data from thermal filler manufacturers' catalogs in their thermal designs, without performing actual tests under actual working conditions
- Considering only the bulk thermal conduction of the thermal filler, and paying no attention to the thermal contact resistance between the thermal filler and the surfaces

In this paper, a system for use in space applications has been proposed, along with its design features, for measurement of TCR between contacting surfaces, with and without thermal fillers, under vacuum conditions. The system, with some modifications, can also be used for measurement of thermal conductivity of materials in accordance with ASTM D5470-06 standard

2. MEASUREMENT METHODS

There are two categories of methods for measurement of TCR of joints and thermal conductivity of thermal fillers:

- Steady-state
- Transient (dynamic)

In steady-state methods, usually the Fourier's law ($Q = kA\Delta T / \Delta x$) is used for the modeling process. In these methods, prior to each measurement, enough time is provided for the thermal stabilization of the system.

Although the cost and time for achieving good measurement accuracy are high, steady-state methods are still the most favored measurement methods, and measurement apparatus are mostly designed and constructed on the basis of these methods. Transient methods have also been used in recent years. In these methods, no temperature stabilization is required; therefore, they are less time consuming. Transient methods also enjoy an inherent higher accuracy compared to the steady-state methods. However, these methods usually involve complex modeling and analysis processes.

Many standards (all based on steady-state methods) such as ASTM E1530, ASTM D5470, TM F433, ASTM E1225, ASTM C518 and ASTM C177 have been prepared for measurement of the thermal conductivity in materials, providing different measurement procedures. However, in all these procedures, measurement of interface temperatures and thickness of filler materials, can prove difficult, mainly due to small thickness and flexible nature of the materials. This may complicate the issue further, and induce certain measurement errors[12] Some important parameters, which influence the measurement accuracy:[12]

- Type and location of temperature sensors,
- Measurement of heat flux,
- Measurement of sample thickness, and
- Quality and placement of test fixtures

Heat flux through the test samples is a critical quantity, as it appears in the equation representing Fourier's law. Hence, accurate measurement of this parameter has determinative effect on the test results. One important factor which influences measurement of heat flux is the mechanical and thermal uniformity of the flux meters.

In-situ measurement of thicknesses of the samples can be difficult, and measurement of sample thickness after the completion of test is associated with errors, which is mainly due to the flexible nature of filler materials. Therefore, usually the sample thickness is measured before conducting the test, which induces an obvious inherent error.

Heat transfer between the test section and its surroundings can influence the test results. The high vacuum in the vacuum jar is enough to eliminate heat convection effects. Radiation shields, which completely cover the test section, greatly reduce the heat radiation to and from the test section

3. THE PROPOSED SYSTEM

In order to provide real data to the satellite thermal engineers, we have designed a system, shown in Figs. 2 and 3, for measuring thermal resistance between contacting bodies under vacuum conditions.

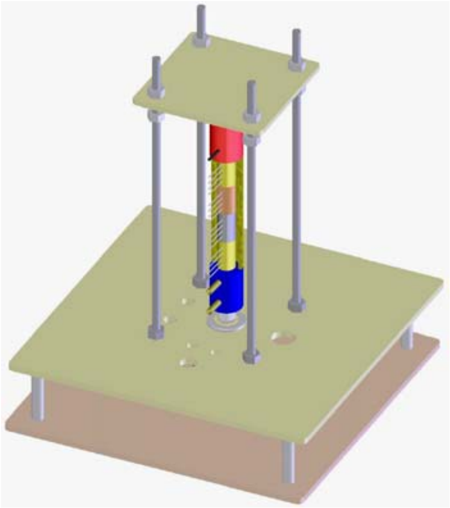

Fig 2: Perspective view of the proposed measurement system (vacuum bell jar removed)

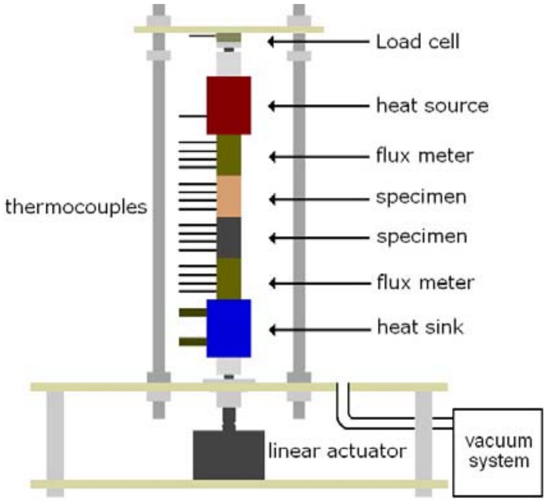

Fig 3: Section view of the proposed measurement system (vacuum bell jar removed).

The system is based on ASTM D5470-06 standard, and consists of the following parts and components:

- heating source (a single heater),
- two flux meters,
- heat sink (water cooled)
- radiation shield for cutting off the radiation effects
- mechanism for cutting off heat conduction paths other than the main flow direction
- two test samples
- mechanism for application of the required pressure
- linear actuator and a load cell
- mechanism for adjusting the distance between the two flux meters
- vacuum chamber and the associated instruments, capable of achieving and holding the required vacuum level (10^{-5} Torr)
- temperature sensors (thermocouples)
  PC, with suitable data acquisition system.

3.1 Design Features of the System

It is important to ensure one-dimensional heat flow from the heat source to the heat sink through the contact surface. For this purpose, the entire apparatus is contained within a vacuum chamber capable of maintaining high vacuum, using a combination of mechanical and diffusion vacuum pumps. The contact pressure, which greatly influences thermal contact resistance, can be applied using a linear actuator. The interface temperature can be controlled through control of the heater block and the constant temperature bath supplying the heat sink. Data acquisition and control over the experiment are performed through data acquisition boards and a computer.

The heater can be placed on top or bottom of the test column. In vacuum conditions, convective heat transfer is absent and heater can be placed either way. The heater comprises electric heating elements imbedded in a copper box. This choice is preferable to liquid-circulation heaters, as its power and temperature can be controlled more easily.

As the heater is placed at the top, the cooler is placed at the bottom of the column plate. Ethylene Glycol is circulated in the cooling circuit to absorb heat from the test column. The cooler body is made of copper, as it has a high thermal conductivity.

Measurement of heat flux is done by two flux meter bars above and below the specimens. Heat flux bars are made of homogenous materials and are fabricated with great care to ensure structural and physical uniformity. Thermal conductivity of these bars is accurately measured in precision laboratories. By knowing the temperature gradient in the flux meters and using Fourier's law ($Q = kA\Delta T / \Delta x$), the thermal flux passing through can be measured. Several thermocouples are mounted in the flux meters at different points, and using the data collected from these thermocouples, temperature gradient is found as illustrated in Fig. 4. For this purpose, two thermocouples are theoretically sufficient in each bar, but in order to improve measurement precision, four thermocouples are used. Mean root square regression is done to find the best line covering the temperature data, and the slope of this line is considered as the thermal gradient.

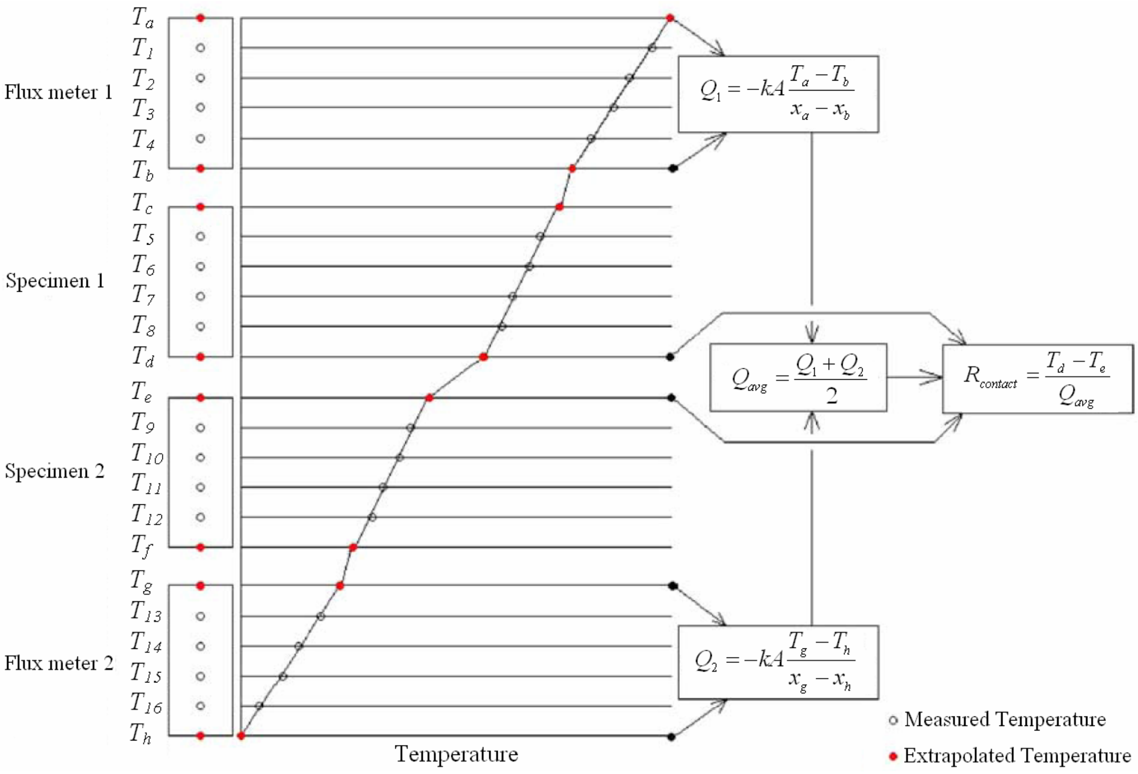

Fig 4: Estimation of temperature gradient in the flux meter, determination of the assumed temperature at the two contacting surfaces, and calculation of thermal contact resistance[14

To imbed the thermocouples in the flux meter bars, fine holes are made in them which reach the centerline of the bars. As the holes interfere with the heat flux in the bars, they must be as narrow as possible to minimize the effect. After drilling the holes, thermocouples are placed in them and proper glue is used to ensure good thermal contact between the bar and the thermocouple tip. The practice of drilling and thermocouple installation is one of the most critical parts of the job and should be done with great care and precision.

The only removable parts of the system are the two test specimens, which are prepared according to the requirements of the test. Specifically, the contact surfaces of the specimens must be prepared according to the need of the experiment. If a piece of thermal interface material is tested, the surface temperatures will be found by extrapolating the data of the two flux meters. In case two specimens are used, several thermocouples are placed in the two specimens (Fig. 3), as is done for the flux meter bars. Surfaces of the flux meters, as well as surfaces of the test specimens facing the flux meters, are leveled and polished to induce minimum thermal resistance. Also, cleaning the test contact surfaces is a very important issue which must receive special attention.

To minimize thermal radiation to/from flux meters and specimens, and obtain a one-dimensional heat flow in them, a radiation shield is used. This shield can be a flexible multilayer insulation wrapped around the flux meters and specimens. Another option is to use a solid shield consisting of two half cylinders [**Error! Reference source not found.**,14] with proper surface absorptance and emissivity (one of the half cylinders is shown in Fig. 3). To eliminate conductive heat transfer, a small gap must be kept between the inner surface of the shield, and the specimens and flux meters.

Air pressure has a great influence on thermal contact resistance. As many TCR models neglect the effect of air and assume vacuum conditions, experimental data to verify these models must be obtained in vacuum conditions. Also, in vacuum, convective heat transfer between different parts is eliminated, and unidirectional heat flow in the test column is ensured. Therefore, TCR experiments are usually conducted in vacuum. The proposed device can provide vacuum conditions in a glass jar. In case vacuum is not required, the glass jar is removed and the tests are conducted in ambient pressure.

4. CONCLUSIONS

A simple system has been proposed for measurement of thermal contact resistance under vacuum conditions. Use of vacuum eliminates the effects of convection heat transfer, bringing the test conditions closer to the actual conditions in space. When constructed, the system will provide the thermal design engineers with valuable experimental data on TCR, for use in development of satellite thermal control systems. The system, with little modifications, can also be used for measurement of thermal conductivity of materials under vacuum conditions.

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