THERMAL SCALE MODELING OF SMALL SATELLITES

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ABSTRACT

The application of thermal similarity to small satellites, in connection with the necessity of thermal environmental verification tests and the existence of small test facilities is investigated. A survey of principal scaling techniques is given for a radiation-conduction system. Special scaling techniques for multilayer insulation, bolted joints and thermal control coatings are given and techniques to correct errors, caused by the use of imperfect scale models, are discussed. Results of an experimental investigation on a simple space vehicle element are presented for measurements on a full-scale prototype and half-scale thermal models. Difficulties in achieving accurate simulation are pointed out.

Keywords: Thermal scaling, thermal similarity, temperature preservation, material preservation, surface emissivity control, space environment simulation

References: 84

1. INTRODUCTION

The Verification of the thermal behavior of spacecraft (S/C) is still not possible without tests in a simulated space environment despite the capability of numerical evaluation. This paper shall present techniques to apply thermal similarity to small satellites, to use the relatively small space simulation facilities of the Space Technology Department (WS-WT) of the Institute of Space Sensor Technology of the German Aerospace Establishment in Berlin-Adlershof for the tests of small satellites or satellite device. From the three possible ways of heat transfer by conduction, radiation and convection only radiation-conduction-systems shall be considered here, because unmanned satellites do not have an internal atmosphere.

The use of mathematical approaches to predict temperature distribution of S/C in a space environment is not always sufficient, and thermal testing is required. In general a full-scale thermal engineering model (TEM) would be built and tested. But the low budget of small satellite programs will limit the scope of test and model philosophy. Some kind of protoflight philosophy will be necessary for small satellite projects. Therefore, the use of thermal scaling techniques, as applied to reduced scale models, combined with the use of cheaper, existing small test facilities offer an alternative solution. The test of a scaled model during the development phase when hardware yet not exists, makes it possible to use valid experimental data about the thermal behavior of the satellite at a very early moment. The data can be used to upgrade thermal mathematical models (TMM). For small satellites the scaling factor is not very low and lies above the lower limit of 1/5. Thus the desired prediction accuracy can be achieved. Thermal scaling techniques for S/C application were developed during the 1960s and the early 1970s. The purpose of this paper is to give a survey of important reference literature and scaling techniques and to discuss experimental results performed on simple space vehicle elements.

2. LITERATURE REVIEW

Most scientific reports on thermal similitude were published in 1966. A review on this early publications is given in [39]. The following review of literature is intended to point out some special topics on applying thermal similitude to S/C.

Experimental results of tests performed on S/C hardware are described in the following references: Mariner IV probe in [24], [27], [28], [29], [30], [33], [57], [76], Apollo hardware or applications in [63], [64], [79] and Chinese satellites in [53], [70], [71]. Tests and scaling techniques applied to special S/C components are described in the following references: optical systems in [26], [58], [59], heat pipes in [35], [50], [51] and radiators in [14], [15], [19].

Further scaling techniques concerning physical effects not considered in this paper can be found in the following references: internal convection in [6], [15], [37], [42], [43], [54], [63], [64], [65] and scaling of thermo-structural distortions in [26], [56], [58], [59].

A more complete literature review is given in [48].

3. THERMAL SIMILARITY

In this paper "model" always means a reduced scale model of a 1:1 original. The original is always denoted as "prototype". The scaling factor is defined as the ratio of a characteristic length of the model to a characteristic length of the prototype. The value of the scaling ratio is determined by the costs , size of the test facilities or arbitrarily by the model designer. The next step is to answer the question if and how besides the scale the other physical quantities have to be modified and to express these modifications as scaling laws.

By the use of dimensional analysis a set of nondimensional groups can be derived that must be identical in model and prototype [39]. From these similarity criteria scaling laws for the physical quantities of temperature, time, absorbed radiation, contact conductance, thermal conductivity, thermal storage, emissivity and internally generated power can be deduced for three principal scaling techniques: temperature preservation technique, material preservation technique and surface emissivity control technique [67].

4. TEMPERATURE PRESERVATION TECHNIQUE

The application of the temperature preservation technique to a reduced scale model makes it possible to preserve temperature, intensity of absorbed radiation, contact conductance and IR-emissivity. It requires reduction of time, thermal conductivity and power.

The temperature preservation technique has the following advantages: By temperature preservation the temperature dependence of thermo-physical properties need not to be considered. No increased intensity of the simulated solar illumination is required during the test of a reduced scale model. When preserving the intensity of simulated solar illumination the scaling factor is not restricted. The intensity is independent of the scaling factor.

The temperature preservation technique has the following disadvantages: It has to be selected material with a reduced thermal conductivity which is proportional to the scaling ratio. This is difficult because the conductivity of different materials has to be well known. If the prototype is designed of low conducting materials it is difficult to find materials with further reduced conductivity for the model.

The temperature preservation technique was often used to verify the thermal design of S/C. Complicated S/C, like Mariner IV and several Chinese satellites, had been successfully modeled with scaling factors between 1/2 to 1/4 at steady state conditions. The major problem of this technique is the selection of material with the required conductivity.

5. MATERIAL PRESERVATION TECHNIQUE

The application of the material preservation technique to a reduced scale model makes it possible to preserve thermal conductivity, thermal storage and IR-emissivity. It requires reduction of time and power and an increase of temperature, intensity of absorbed radiation and contact conductance.

The material preservation technique has the following advantage: No material selection problems appear.

The material preservation technique has the following disadvantages: There exists an influence of temperature dependence of the thermo-physical properties, caused by elevated temperatures in a reduced scale model. The increasing intensity of the simulated solar illumination causes a restriction for the scaling factor. Because most solar simulators can simulate at the most two solar constants, the scaling factor is restricted to a minimum of 0.6.

A large aperture orbiting telescope covered with multilayer insulation (MLI) has been modeled with scaling factors of 1/2 and 1/6.43 by the use of material preservation technique, to preserve the MLI properties [58], [59]. The model was constructed using an insulation identical to that of the prototype. The major problem of material preservation is that this technique leads to elevated model temperatures. This results in a change of the material properties which degrades model accuracy.

6. SURFACE EMISSIVITY CONTROL TECHNIQUE

The application of the surface emissivity control technique to a reduced scale model makes it possible to preserve temperature, thermal conductivity and thermal storage. It requires reduction of time, thermal conductivity and power and an increase of IR-emissivity, intensity of absorbed radiation and contact conductance.

This technique makes it possible to preserve temperature and materials in the reduced scale model. But the preservation of temperature and materials requires an increased emissivity in the scale model. The application of this technique is normally limited by the small range (between 0 and 1) in which the emissivity can be varied.

For test bodies with high emissivity it is mostly impossible to design a reduced scale model because the emissivity of the model cannot be enlarged anymore. The application of this technique to MLI covered device is possible because MLI is a low emissivity insulation. The emissivity is controlled by the variation of the number of layers only. The MLI materials are preserved. No tests of this technique have been reported in the literature.

The technique may allow a combination of thermal scaling and structural modeling to consider stresses and distortions caused by temperature changes.

7. MULTILAYER INSULATION

The effective insulation properties of MLI with low discontinuity densities for cryogenic applications can be expressed as sum of conduction and radiation effects. By preserving the MLI properties the following scaling laws can be deduced: The temperature preservation technique requires an identical blanket thickness in model and prototype. The material preservation technique requires a consideration of the quantitative influence of heat transferred by conduction and radiation to predict the blanket thickness of the model. The surface emissivity control technique permits a reduction of the blanket thickness with the scaling factor. The blanket thickness is directly proportional to the number of layers.

Typical S/C MLI with medium discontinuity densities is described in [84] by an effective emissivity. Built-in discontinuities degrade the performance of MLI blankets. If these degradations are considered and applied to thermal scaling, temperature preservation and material preservation technique require an increased blanket thickness in a reduced scale model. The surface emissivity control technique allows a reduction only.

8. BOLTED JOINTS AND THERMAL CONTROL COATINGS

No practical scaling laws can be given for bolted joints and thermal control coatings (TCC). If a modeling of bolted joints is necessary, pretests of geometrically scaled joints should be performed [59]. The influence of TCC is mostly very low. It becomes important below a scaling factor of 1/4 [48].

9. LIMITATIONS AND MODEL ERRORS

A calculation of the probable model errors results in a realistic minimum scaling factor of 1/5 [46], [48]. One technique to reduce these errors is called imperfect modeling. This method is based on an investigation of the error path of three imperfect models [8], [9]. Therefore the expense of this technique is very high. The second approach is called upgrading of thermal mathematical models (TMM). Model tests are used to upgrade a prototype TMM which also corrects model errors caused by scaling compromises [63], [64].

10. EXPERIMENTS

Three test objects for transient and steady state tests with solar simulation have been produced and tested at the Department WS-WT [83]: a prototype with a diameter of 140mm, a model (No. 1) for the temperature preservation technique and a model

(No. 2) for the material preservation technique. The scaling factor is about 0.6 and results from the constraint of the material preservation technique to carry out the test at a maximum of two simulated solar constants. The test objects were produced as machined devices, because machining secures a high precision. The objects consist of two parallel circular plates, which are connected by a cylindrical conduction path to simulate heat transfer by radiation and conduction.

The test objects were completely machined each from one slug, to prevent contact conductance. The chosen materials are aluminum (Al 99.5) and an aluminum alloy (AlCuMgPb), because aluminum is often used in S/C design, is available as customary in the trade material, can be machined and published values of the material properties are available. The choice of AlCuMgPb results from the scaling law for the thermal conductivity that requires a material with a 0.6 reduced conductivity for the model.

The test objects have been designed in that way that the sun side of the body is bigger as the shadow side. The bigger plate is designed as truncated cone with a bigger diameter on the sun side. This design shall guarantee that the power generated by the lamp reaches the test object at one defined area. Two thermocouples were attached to each plate and one at the middle of the shadow plate.

The scaling laws require for temperature preservation and material preservation technique a preservation of the surface emissivity. So all test objects were painted with the same coating. A black paint with a high solar absorption was chosen, to ensure a good heating of the test objects. The coating is space qualified, to resists the coldness of the liquid nitrogen cooled wall and the simulated space environment.

The measured temperature errors between model and prototype were 5K for temperature preservation and 3.9K for material preservation technique. The experiments have shown that the solar simulation is mainly responsible for the resulting temperature errors between model and prototype [83]. The differences in the equilibrium temperatures are within the limits given in [48] and are about half as big as predicted.

The experiments have been carried out under simplified conditions. The leads of the thermocouples were not heated. The thermocouples were not scaled. Under these conditions the measured differences are acceptable.

11. CONCLUSIONS AND OUTLOOK

To reduce the temperature prediction error a combination of model tests with TMM is feasible. The evaluation of the experiments gives the following result: To achieve the required accuracy electrical heater elements instead of solar heating should be used.

Experiments on electrically heated, MLI covered test objects are planned at the Department of Space Technology (WS-WT) of the Institute of Space Sensor Technology to test the surface emissivity control technique. The tests shall be combined with investigations on MLI, because this technique can be applied on S/C elements with low IR-emissivity only. The enlarged emissivity of the model shall be controlled by reducing the number of layers.

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