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Comparison between Solar Simulation and Infrared Technique for Thermal Balance Test

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***Abstract*—**The precision of heat flux simulation influences the temperature field and test aberration for TB test and also reflects the test level for spacecraft development. This paper describes TB tests for a small satellite using solar simulator, electric heaters, calrod heaters to evaluate the difference of the three methods. Under the same boundary condition, calrod heaters cases were about 6°C higher than solar simulator cases and electric heaters cases for non-external-heat-flux cases (extreme low temperature cases). While calrod heaters cases and electric heaters cases were 5~7°C and 2~3°C lower than solar simulator cases respectively for high temperature cases. The results show that the solar simulator is better than calrod heaters for its better collimation, non-homogeneity and stability.

***Keywords*—**solar simulation, infrared simulation, TB test, TMM

I. INTRODUCTION

THERMAL balance (TB) test and thermal vacuum (TC) test are necessary tests for spacecraft design, manufacture and verification. In the TB test, the solar radiation, earth infrared (IR) radiation and earth albedo must be simulated with the vacuum and cryogenic-black background. The precision of heat flux simulation influences the temperature field and test aberration for TB test and also reflects the test level for spacecraft development.

Electrical heaters, infrared heaters and solar simulator are three major heat flux simulation equipments. Electrical heaters can be controlled very precisely for various shapes. But they can not be mounted on optical parts. So they are often used in prototype module (PM) spacecraft instead of flight module (FM) spacecraft, or used in external parts. Infrared heaters simulate the total heat flux for the surface of satellite. But they can not simulate the collimation and spectrum characteristics of real solar and also have the disadvantage of lower uniformity. On the other hand, solar simulation is an ideal method. It can simulate the collimation and spectrum characteristics of solar. The high uniformity and non-contact characteristics are also ideal for complicated spacecrafts and optical parts such as lens, optical surface mirrors, etc. The disadvantage for solar simulator is perhaps it can not simulate the earth IR radiation and earth albedo, which can be compensated by the other two methods.

The special characteristics of solar simulator make it play important role in spacecraft TB test. It is also basic equipment for space technology and was widely used since the beginning of space exploration.

There are many large solar simulators in NASA, IABG, INTERSPACE, ESTEC, JAXA and IRSO [1]-[6]. Apollo spacesuit (USA), SAX satellite (Italy), Artemis, Mars Path Finder, and may other spacecraft were all tested with solar simulator as heat source [6]-[11].

For some cases, if there is lack of solar simulator or solar simulator can not fulfill the test requirements (for example, for LEO satellite, earth radiation and earth albedo must be simulated simultaneously with solar simulator), the IR technique is a fair well alternative. The test effectiveness for solar simulation and IR technique is very important to evaluate the accuracy of satellite temperature field in TB tests.

The International Communication V satellite used solar simulator and IR heaters separately to compare the difference between each method. The temperatures of former were 10 to 15 °C higher than those of later for high temperature cases. The solar simulator results fit the In-Orbit data better, which showed that the heat flux of solar simulator was more accurate than that of IR heaters.

GE aerospace Inc. used IR technique for INMARSAT-3 Thermal Control Satellite (TCM) TB test [12]. Before the final test, the test effectiveness was compared with solar simulation through a thorough procedure for some cases. The comparison tests were performed in two different space simulators. Three cases for solar simulation and four cases for IR technique (three of which were same with former) were performed. The results showed solar simulation can result in a more severe thermal stress, that was to say the temperature field for high temperature cases was higher and lower for lower temperature cases.

BepiColombo project is planning to observe Mercury. The thermal environment of BepiColombo is more severe than any other satellites. The solar radiation reaches as high as 10.7 Solar Constant (SC) (14.5kW/m^2) along with high Mercury radiation of 13.6 kW/m^2. The strongest solar simulator – JPL solar simulator – can provide solar beam of 13 SC within diameter of 2.3m, or 7.8 SC within 3.35m, or 2.7 SC within 5.6m. It still can not fulfill the requirement of BepiColombo. IR technique can provide higher heat flux for BepiColombo. Thus a comparison between solar simulation and IR technique was carried out at lower heat flux to ensure IR technique accuracy enough for TB test [12]-[13].

IR technique for spacecraft heat flux simulation was a sophisticated method and had a history of 30 years for China space exploration. A large solar simulator is under construction in Beijing. The purpose of this paper is going to find whether the sophisticated IR technique has almost the same test effectiveness with solar simulation, and how to use the solar simulator for various satellites.

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II. TEST DESCRIPTION

A. Test Objective

Three heat flux simulation methods (solar simulation, electrical film heater and calrod heater) were performed on a small Thermal Control Satellite (TCS) TB tests separately.

The same TB cases was conducted for the above three methods. The test results were compared to evaluate the effectiveness of different methods.

B. Satellite Status

The size of the small TCS is designed according to the small solar simulator. It is of cuboid shape with the external configuration of 600mm(X) X 300mm(Y) X 340mm(Z). There are six structural plates, the +Y panel and -Y panel of which are aluminum honeycomb core materials and the other four are aluminum plates. Each plate is fixed on an aluminum structure with 3mm thick thermal insulations. Four cubes are fixed on the corners of the -Z panel to attach the TCS with the test isolator.

External orthogonal heat pipe network is installed inside the +Y panel with two heat pipes in the direction of X axis and four in the direction of Z axis. The X direction heat pipes are installed on the internal surface of +Y panel and the Z direction heat pipes on the top of X heat pipes. All heat pipes are installed with high thermal conductivity silicon rubber.

Two Traveling Wave Tubes (TWT) are installed on the two heat pipes parallel to X axis using silicon rubber inside the +Y panel. The two TWTs are all thermal simulation models with one electric heater inside each one to simulate its heat dissipation. The external surfaces (except the installation face) of TWTs are sprayed with high emissivity (not less than 0.85) black paint.

Two Solid State Power Amplifiers (SSPA) are installed on the internal surface of –Y panel using silicon rubber. The thermal characteristics of the SSPAs are the same with the TWTs.

The internal surfaces of each panel are pasted with polyimide film with aluminum coating except the instrument areas. Two heat flux simulation heaters are installed on the external surface of +Y panel with polyimide film with aluminum coating outside. Others external surfaces are covered with 10 units Multi-Layer Insulation (MLI).

73 thermocouples, including 47 inside the satellite, 2 for +X panel external heater, 4 for external surfaces, 8 for satellite – adapter interface, 4 for isolator, 4 for calrod heaters, and 4 for rails of the vacuum chamber, are installed for the satellite TB test.

Two constant-temperature-type radiometers are installed on the external surface of +Y panel for solar simulation cases (the first stage, as described below).

Eight thermal-insulation-type radiometers are install on the six external surfaces for calrod heater cases (the second stage), 2 for +X and +Y surfaces each and 1 for other 4 surfaces each.

A heat flux heater is installed on the external surface of +X MLI for the electric heater simulation cases (the third stage).

C. Thermal Analysis

Thermal analysis of the TCS was conducted by the software Thermal Desktop version 4.7. Some assumptions were made to simplify the Thermal Mathematical Model (TMM):

All equipments were simplified to hexahedron according to their equivalent surface area;

All heat pipes were simplified to cuboid;

The inside and outside of radiating surfaces were divided into nodes separately;

The inside of plate with MIL and outside of MIL was divided into nodes separately;

Only the thermal conduction between nodes of inside and outside surfaces of honeycomb plates, and conduction between nodes of inside and outside of radiating surfaces were considered in the calculation. The thermal conduction between nodes of external surface of MIL was neglected;

Only the thermal conduction along the thickness direction of honeycomb plate was considered while the parallel direction neglected.

Totally 244 nodes were built for the satellite.

Generally, the thermal network model for the satellite can be defined as:

$$c_i M_i \frac{dT_i}{dt} = \sum_i E_{ij}(T_j^4 - T_i^4) + \sum_j D_{ij}(T_j - T_i) + q_{in} + q_{orbit}$$

which,

T_i as temperature of node *i*;

t as time;

c_i as heat capacity of node *i*;

M_i as mass of node *i*;

E_{ij} as radiation hear transfer coefficient between node *i* and *j*;

D_{ij} as thermal conductivity between node *i* and *j*;

q_{in} as internal heat source;

q_{orbit} as external heat flux ;

The internal heat source q_{in} and node heat capacity $c_i M_i$ can be determined by specific parameters. The radiation heat transfer coefficient can be calculated by the thermal analysis software.

D. Test Cases

Generally, solar simulation, IR technique and electrical heater should be compared under the same test case. The test cases were determined for the following considerations:

- The background heat flux for each method should be calibrated without external heat flux. One case for solar simulation (case 1A in Table I) and one case for calrod heater (case 3A) were conducted. The background heat flux for electric heater was the same with that for solar simulation.
- The three methods were compared under the same solar inclination, the same external heat flux and the same heat dissipation. Altogether 9 combination for two solar inclinations (20° and 23.5°), two heat fluxes (1.0 SC and 1.3 SC) and two heat dissipations (25W and 40W) were

designed, which were comparisons for 20° inclination, 1 SC heat flux, 25W heat dissipation (case 1B, 2B and 3B in Table I), for 23.5° , 1 SC, 40W (case 1C, 2C and 3C), and for 23.5°, 1.3 SC, 40W (case 1D, 2D and 3D).

- The background heat flux for the space simulator results that the absorbed heat flux by the satellite higher than 1 SC if the power of solar simulator executed for calibrated 1 SC. Thus the power of solar simulator must be decreased so as the sum of solar simulator and background heat flux reach 1 SC (case 1E, 2E and 3E in Table I).

Altogether 13 cases were designed for the comparison test. The vacuum chamber should represurize to ambient four times to adjust the solar inclination or replace the heat flux simulator:

- Stage 1: Solar simulator TB tests for 20° inclination, including 1 high temperature case and 1 low one.
- Stage 2: Solar simulator TB tests for 23.5° inclination, including 3 high temperature cases.
- Stage 3: Electric heaters TB tests, including 4 high temperature cases.
- Stage 4: Calrod heaters TB tests, including 4 high temperature cases and 1 low one.

Thermocouples on instruments and heat pipes are control points for the thermal balance determination. Other thermocouples are monitoring points.

Thermal balance criteria: temperatures of control points fluctuate less than ±0.5°C or vary monotonically less than 0.1°C/h in 4 hours continuously.

TABLE I
TEST CASES

Case No.	Heat Flux Type	Inclination of Satellite X Axis with Chamber Axis	Heat Flux	Heat Dissipation
1A	Solar simulator	20°	0	40W for TWT1, 0 for others
1B	Solar simulator	20°	1 SC (1350W/m^2)	25W for TWT1, 0 for others
Vacuum chamber represurize to ambient				
1C	Solar simulator	23.5°	1 SC	40W for TWT1, 0 for others
1D	Solar simulator	23.5°	1.3 SC (1755W/m^2)	40W for TWT1, 0 for others
1E	Solar simulator	23.5°	1 SC (with background heat flux)	40W for TWT1, 0 for others
Vacuum chamber represurize to ambient				
2B	Electric heaters	0°	Measured value in 1B	25W for TWT1, 0 for others
2C	Electric heaters	0°	Measured value in 1C	40W for TWT1, 0 for others
2D	Electric heaters	0°	Measured value in 1D	40W for TWT1, 0 for others
2E	Electric heaters	0°	Measured value in 1E	40W for TWT1, 0 for others
Vacuum chamber represurize to ambient				
3A	Calrod heaters	0°	0	40W for TWT1, 0 for others
3B	Calrod heaters	0°	Measured value in 1B	25W for TWT1, 0 for others
3C	Calrod heaters	0°	Measured value in 1C	40W for TWT1, 0 for others
3D	Calrod heaters	0°	Measured value in 1D	40W for TWT1, 0 for others
3E	Calrod heaters	0°	Measured value in 1E	40W for TWT1, 0 for others

III. TEST EQUIPMENTS

A. Space Simulator

The TB test of the small satellite was done in a small space simulator. The simulator is a horizontal chamber with a length of 3000mm and a shroud diameter of 1200mm, as shown in Fig. 1. The size of the simulator can meet the requirement of the satellite and relevant MGSE (Mechanical Ground Supplement Equipment). The working pressure of the simulator is less than 1.3×10^{-3}Pa. The shroud temperature is less than 100K. The emissivity ε_s is higher than 0.9.

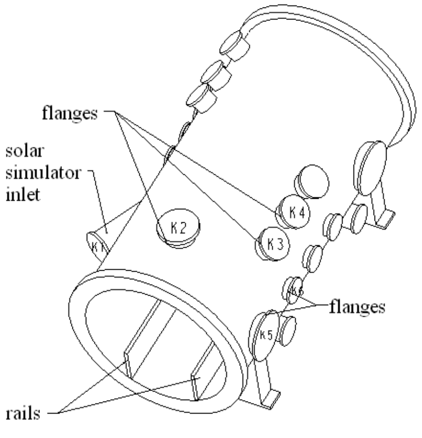

Fig. 1 Diagram of the small space simulator

B. Solar Simulator

The space simulator is equipped with a small off-axis solar simulator with the following index:

Irradiation area: Φ600mm;
Irradiation thickness: 600mm;
Irradiation intensity: 650W/m^2 ~ 1760W/m^2;
Area non-homogeneity: less than ±4%;
Thickness non-homogeneity: less than ±5%;
Instability: less than ±2%/h;
Collimating angle: ±2°;
Spectrum: amended xenon lamp spectrum;

C. Satellite adapter

The adapter is designed in truss frame in order to eliminate the barrier to the shroud. The adapter is constructed of upper and lower parts with a ruler on the lower part (Fig. 2). The required angle of the satellite to the simulated sun light can be gained by the turning of the upper part.

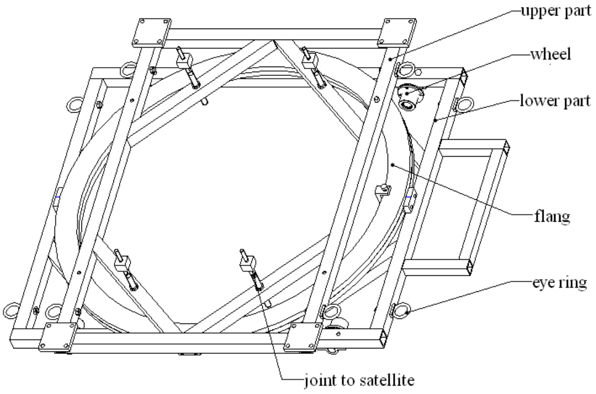

Fig. 2 Diagram of the adapter

D. Test Status

The small satellite was installed in the space simulator with the adapter with +Z panel upward and +X panel to the gate, as shown in Fig. 3.

During the solar simulator cases (stage 1 & 2), the center of the satellite was coincident with the center of the solar beam with a angle of 20° (stage 1) and 23.5° (stage 2). The +Y and –X panels were all in the range of the solar beam (shadows in Fig. 3).

During the electrical heater cases (stage 3) and the calrod cases (stage 4), the angle of +Y panel was aligned with the axis of the simulator.

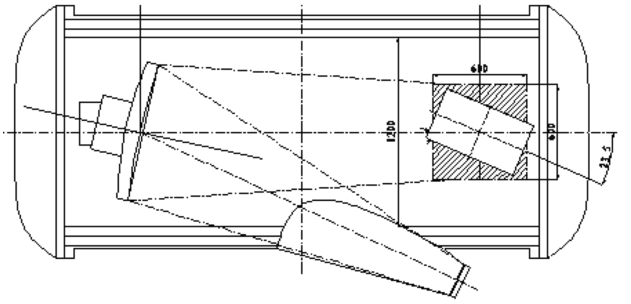

Fig. 3 Diagram of the satellite in the space simulator

IV. TEST RESULTS

A. Test Facility Status

The TB tests were conducted in the small space simulator. During the 4 stages, the pressure of the vacuum chamber was kept lower than 1.3×10^{-3}Pa (generally lower than 10^{-5}Pa).

The shroud temperatures were kept lower than 100K. The status of the space simulator was well enough for the TB tests.

B. Non-homogeneity of solar simulator and calrod heaters

The external heat fluxes of +Y panel (radiator panel) and –X panel (MLI) were supplied by the solar simulator during stage 1 and 2. Two radiometers were placed on the +Y panel. The absorbed heat fluxes of the radiator panel of the 5 cases were shown in Table II. The solar simulator was very stable during all the cased. The non-homogeneity of the solar simulator was less than ±1%.

TABLE II
MEASURED HEAT FLUX OF THE SOLAR SIMULATOR (W/M^2)

Case No.	Heat flux of radiometer 1 (W/M^2)	Heat flux of radiometer 2 (W/M^2)	non-homogeneity (%)
1A	37.4	36.9	067
1B	203.7	204.4	0.17
1C	240.1	241.0	0.18
1D	303.4	304.7	0.21
1E	204.9	205.1	0.05

The external heat flux of +Y panel (radiator panel) was supplied by the calrod heaters during stage 4. The arrived heat fluxes of the radiator panel of the 5 cases were shown in Table III (the . The non-homogeneity of the calrod heaters was relatively higher than that of the solar simulator, which was 5.63% for low temperature case and 3.39 for the high temperature cases.

TABLE III
MEASURED HEAT FLUX OF THE CALROD HEATERS

Case No.	Heat flux of radiometer 1 (W/M^2)	Heat flux of radiometer 2 (W/M^2)	non-homogeneity (%)
3A	60.1	67.2	5.63
3B	198.4	210.2	2.88
3C	235.0	249.0	2.90
3D	297.3	312.4	2.47
3E	198.4	212.4	3.39

C. Instrument Temperatures on the Satellite (Low Temperature cases)

No external heat flux was executed for low temperature cases. The heat dissipation of the TWT1 was 40W. Table IV showed the instrument temperatures of case 1A (solar simulator) and case 3A (calrod heaters). The instrument temperatures of case 1A were 6^{o}C lower than those of case 3A, which was caught by the additional background heat flux (26.6W/m^2) induced by the calrod heaters.

TABLE IV
INSTRUMENT TEMPERATURES (LOW TEMPERATURE CASES) (^{o}C)

	TWT1-1	TWT1-2	TWT2-1	TWT2-2	SPA1	SPA2
Case 1A	19.59	19.61	35.96	28.06	8.89	11.74
Case 3A	25.78	25.8	42.59	34.87	14.81	18.06
Difference 3A-1A	6.19	6.18	6.63	6.8	5.93	6.32

D. Instrument Temperatures on the Satellite (High Temperature cases)

Table V showed the instrument temperatures of the other cases. Instruments temperatures reached the highest in solar simulator cases, lower in electric heaters cases and lowest in calrod heater cases under the same external heat flux and internal heat dissipation. Temperature differences were larger at low heat flux and heat dissipation (case B/E). Calrod heaters cases were 5~7^{o}C lower than solar simulator cases and electric heaters cases 2~3^{o}C lower. The higher the heat flux and heat dissipation (case C/D) were, the smaller the temperature difference. Calrod heaters cases were 3~5^{o}C lower than solar simulator cases and electric heaters cases 1~2^{o}C lower.

TABLE V
INSTRUMENT TEMPERATURES (HIGH TEMPERATURE CASES) (^{O}C)

	TWT1-1	TWT1-2	TWT2-1	TWT2-2	SPA1	SPA2
Case 1B	38.04	38.08	48.27	43.53	30.73	31
Case 2B	36.69	36.61	45.62	40.86	27.65	27.86
Case 3B	35.57	35.44	43.82	38.89	22.76	25.73
Difference 2B-1B	-1.35	-1.47	-2.65	-2.67	-3.08	-3.14
Difference 3B-1B	-2.46	-2.64	-4.45	-4.64	-7.98	-5.27
Case 1C	62.49	62.53	78.39	70.64	53.6	56.1
Case 2C	62.28	62.14	79.21	71.39	52.25	54.73
Case 3C	59.81	59.85	76.73	68.93	48.28	51.45
Difference 2C-1C	-0.22	-0.4	0.82	0.75	-1.35	-1.38
Difference 3C-1C	-2.68	-2.69	-1.65	-1.71	-5.32	-4.65
Case 1D	72.4	72.44	88.31	80.56	63.94	66.37
Case 2D	70.26	70.15	88.06	80.11	60.55	63.04
Case 3D	69.51	69.55	86.4	78.46	57.83	60.98
Difference 2D-1D	-2.14	-2.29	-0.25	-0.46	-3.39	-3.33
Difference 3D-1D	-2.89	-2.89	-1.91	-2.1	-6.12	-5.39
Case 1E	58.7	58.73	74.37	66.67	49.52	52.15
Case 2E	56.61	56.47	73.03	65.41	46.42	46.67
Case 3E	54.18	54.21	71.23	63.46	42.65	45.84
Difference 2E-1E	-2.08	-2.27	-1.35	-1.26	-3.1	-5.47
Difference 3E-1E	-4.52	-4.52	-3.15	-3.21	-6.87	-6.31

V. CONCLUSIONS

This paper describes TB tests for a small satellite using three different external heat flux simulation methods to evaluate the difference of the three methods. The facility works functionally and meets the test requirements. The test data are effective and reliable. The results shows that the solar simulator is better than calrod heaters for its better collimation, non-homogeneity and stability and is better for a more accurate temperature field under high or low (especially) temperature cases.

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