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Research on nanosatellite thermal cycling test applicability

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Abstract: In order to verify the spacecraft performance in extreme temperature and vacuum, and to screen spacecraft early defect, generally spacecraft TV (Thermal Vacuum) test should be carried out before launch. Designed in small size and with low cost, nanosatellite is made from a large number of COTS (Commercial off the shelf) components; therefore, the test should be low-cost, simple and quick. With the intention of screen out early defects of the product in lower cost, nanosatellite developers usually use TC (Thermal Cycling) test to partially replace the TV test because TV test is more expensive. However, due to the air convection, TC test is different from TV test in heat transfer characteristics, which may be over-test or short-test in TC test. This paper aims to explore the applicability of different nanosatellites in TC/TV test. Using rule number analysis method, Heat Transfer model in vacuum and ambient environment has been built to analyse the characteristics of heat transfer under different temperature and characteristic length, and to deliver the recommended limits on using TC test instead of the TV test. The CFD and test methods are applied to verify the rule number analysis above.

1 Introduction

Limited by cost, time and other constraints, nanosatellites developers generally avoid long time TV (Thermal Vacuum) test in TV chamber. Some developers shorten the test by reducing the number of cycles or soak time; while others try to simplify the TV test by vacuum test, TC (Thermal Cycling) test and high and low temperature start-up test[1]. Firstly, a vacuum test, including system electrical performance test, is carried out in a small vacuum chamber (no 1: 2 limit) to verify the ability of the system working in vacuum and at high temperatures. Secondly, a TC test (including TC tolerance and TC performance) is applied to screen early defects of the system and to verify the system performance at

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low temperatures. Finally, a hot and cold start-up test is employed to verify the start ability of the system at high and low temperature [2]. To sum up, a large, complex, high-cost test could be cut into multiple small, simple, low-cost test in nanosatellite verification; as showed in Table 1, different tests meet different purposes of TV test.

Table 1. Test replacement

TV Test Purpose	Nanosatellite test
Screening early defects	TC test
Verify the ability to work at high temperatures coupled with the vacuum environment	vacuum test
Verify the ability to work at low temperatures coupled with the vacuum environment	TC test
Verify the ability to withstand extremely high and low temperature in non-operating state	TC tolerance test
Verify system startup capability at high and low temperature	hot/cold start-up test

As showed in the table above, some purposes can be achieved by a simple test: the TC test and TV test can achieve the same purpose in screening early defect; vacuum test can also perfectly achieve the purpose of verifying the ability of system working in the environment coupled with extremely high temperature and vacuum (via heating device in satellite); Hot/Cold start-up test can verify the system start in high and low temperature; and TC tolerance test can verify the ability of system survive extremely high and low temperature in non-operating state.

However, regarding "verifying system the ability to work at low temperatures coupled with the vacuum environment", there are certain differences between the TC and TV test. Initially, the TC test has no vacuum environment, which is a test condition and can only be tailored. Secondly, because of natural convection, heat transfer characteristics in the satellite should have some differences between TC and TV test. This paper describes the internal temperature distribution differences between TV test and TC test of nanosatellite via rule number analysis method, and validate the model by CFD simulation and test.

2 Rule number analysis

In international standards draft "Space Systems — Design Qualification And Acceptance Tests Of Small-Scale Satellite And Units Seeking Low-Cost And Fast-Delivery", the rule number analysis method was employed for nanosatellite TC applicability research, and a $50W/m^2$ heat flux threshold was set for TC test. It is mainly for a single external shell temperature (300K) and completely radiation heat transfer state[3], which has certain differences with the actual test environment. This paper constructs concentric sphere model to simulate heat transfer in satellite: the inside sphere is heat source, which has heat power Q(w), radius R1(m) and temperature T1 (k); while the outer sphere is satellite shell, which has radius R2(m) and temperature T2 (k). The model is showed in Figure 1:

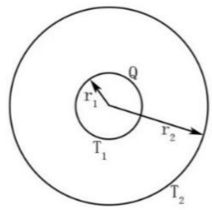


Figure 1. Heat transfer model

According to the basic formula of heat transfer, the heat flux through the inner shell in TV test can be expressed by the following equation,

$$\frac{Q}{A_1} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{A_1}{A_2}} \tag{1}$$

Where A_1 is internal surface area(m^2), A_2 is the external surface area(m^2), ε_1 and ε_2 are the inner and outer surface emissivity. σ is Stefan-Boltzmann constant. The heat flux through the inner shell in TC test can be expressed by the following equation,

$$\frac{Q}{A_1} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{A_1}{A_2}} + Nu\frac{k_{air}}{r_2 - r_1}(T_1 - T_2) \tag{2}$$

Where k_{air} is air thermal conductivity (W/m·K), *Nu* is the Nusselt number, can be expressed by the following equation[4],

$$Nu = 2 + \frac{0.589(GrPr)^{1/4}}{(1 + (0.469 / Pr)^{9/16})^{4/9}} = 2 + \frac{0.589(gPr)^{1/4}}{(1 + (0.469 / Pr)^{9/16})^{4/9}} \times (\frac{al^3\Delta t}{\nu})^{1/4} \tag{3}$$

Due to the small changes of the Prandtl number *Pr* with temperature, when consider it as 0.7, the *Nu* can be simplified as follow,

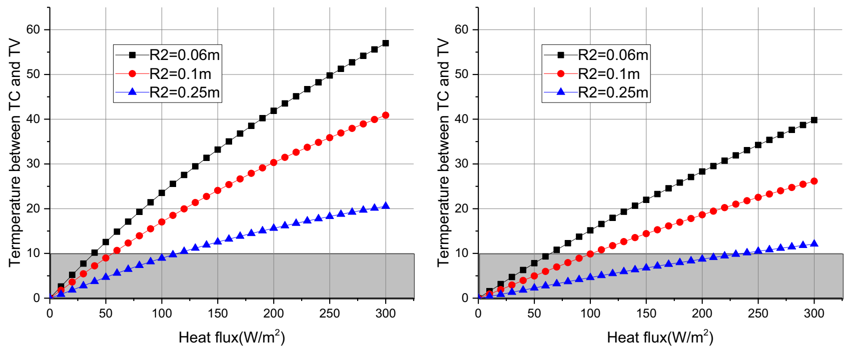
$$Nu = 2 + \frac{0.589(gPr)^{1/4}}{(1 + (0.469 / Pr)^{9/16})^{4/9}} \times (\frac{al^3\Delta t}{\nu})^{1/4} \approx 2 + 0.7344 \times (\frac{l^3\Delta t}{T\nu})^{1/4} \tag{4}$$

Where l is characteristic length (m), Δt is temperature difference(℃), T is qualitative temperature(K), ν is kinematic viscosity (m^2/s). When qualitative temperature and kinematic viscosity changed little, Nusselt number can be considered only relieve with temperature difference Δt and characteristic length *l*, When assuming thermal conductivity changes little when temperature changed. Convection heat transfer can be considered only relieve with temperature difference Δt and characteristic length *l*, heat flux in TV and TC can be expressed as follow,

$$\frac{Q}{A_1} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{A_1}{A_2}} \tag{5}$$

$$\frac{Q}{A_1} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{A_1}{A_2}} + (2 + (\frac{0.7344}{T\nu})^{1/4} \times l^{3/4}\Delta t^{1/4})\frac{k_{air}}{r_2 - r_1}(T_1 - T_2) \tag{6}$$

Heat flux was selected for x-axis, temperature difference between inner and outer shell was selected for y-axis. Outer shell temperature was set to 258K according to the literature [2] low temperature test condition, and the inner shell radius was set to 0.05m. The temperature difference curve between TC and TV test with outer shell radius of 0.06, 0.1, 0.25m in 258K have been drew like Fig. 2-a, and curve in 300K have been drew in Fig. 2-b.



a Shell temperature=258K b shell temperature=300K

Figure 2. The difference between TC and TV test in various characteristic length

As showed in Figure 2, temperature difference between inner and outer shell increase with heat flux of nanosatellite heat source, and heat exchange increase when outer shell reduced in diameter. The temperature curve also has some differences between 258K and 300K. According to existing test standards [5,6], "If the worst-case temperature difference between the two environments is greater than 10°C, TV testing shall be performed ".To ensure the maximize temperature difference below 10°C,the heat flux should below 50w/m^2 when shell temperature is 300K, and below 40W/m^2 when shell temperature is 258K. TC test mentioned in Table 1 should attain the purpose of verifying the ability of system performance at low temperatures. The estimated heat flux limits should be in accordance with the temperature difference under cold conditions. Therefore, the heat flux of the heat source in nanosatellite should below 40W/m^2.Nanosatellite power density range is generally 0.3 ~ 2W/kg [7]. Consequently, not all the nanosatellites heat flux can meet the requirements of less than 40W/m^2.

As to a general nanosatellite, its heat source power is about 1-5W, and its heat transfer is mainly in radiation. the TC alternative test threshold should be 40W/m^2, or look up in Figure 2 using heat flux and characteristic length ratio.

When the internal heat source directly installed on a deck which was like a heat sink, it is assumed that one side of the device (20% area) has thermal conductivity with deck, as showed in Figure 3. The heat conduction will be more significant, which will not change between TC and TV test. Hence, the TC alternative test threshold should be much larger.

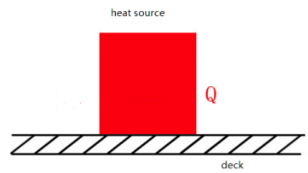


Figure 3. Heat source directly install on a deck

The contract was set to be dry contract. The deck was a honeycomb plate within 1cm thickness, and its equivalent thermal conductivity can be expressed by the following equation,

$$K = \frac{1}{\frac{1}{g} + \frac{l}{\lambda}} = \frac{1}{\frac{1}{50W\ /\ m^2 \bullet K} + \frac{0.01m}{1.5W\ /\ m \bullet K}} = 37.5W\ /\ m^2 \bullet K \tag{7}$$

where g is contact heat transfer coefficient(W/m^2·°C) and is set to 50W/m^2·°C for dry contract. Meanwhile, λ is honeycomb equivalent thermal conductivity (W/m·°C) and l is honeycomb plate thickness.

Heat flux in TV and TC test can be expressed by the following equation,:

$$\frac{Q}{A_1} = \frac{\sigma\ T_1^4 - T_2^4}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{A_1}{A_2}} \times 0.8 + \ T_1 - T_2\ \times k \times 0.2 \tag{8}$$

$$\frac{Q}{A_1} = [\frac{\sigma\ T_1^4 - T_2^4}{\frac{1}{\varepsilon_1} + \left(\frac{1}{\varepsilon_2} - 1\right)\frac{A_1}{A_2}} + (2 + (\frac{0.7344}{T\nu})^{1/4} \times l^{3/4}\Delta t^{1/4})\frac{k_{air}}{r_2 - r_1}(T_1 - T_2)] \times 0.8 + \ T_1 - T_2\ \times k \times 0.2 \tag{9}$$

where k is equivalent thermal coefficient (set to 37.5 W/m^2·°C). The curve of temperature difference between TV and TC test in different conditions is drew as Figure 4。

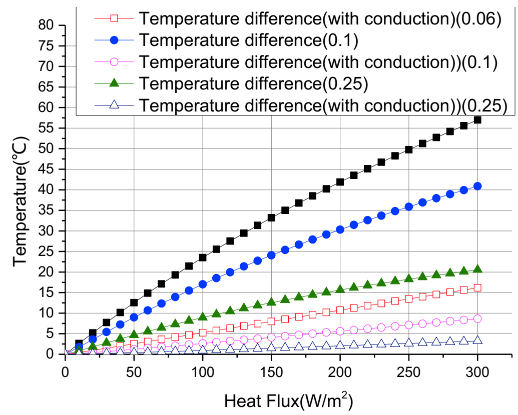


Figure 4. Temperature difference in TC and TV test

From the graph above, when the heat source set directly on the deck of nanosatellite, heat flux threshold can be enlarged to 100W/m^2 to ensure the difference between TV and TC test under 10°C. Concerning a higher characteristic length ratio or larger test article, heat flux threshold could be greater, which can be calculated by equ.9.

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3 Validation

3.1. CFD simulation

A Fluent model was used to verify the rule number analysis, including four units (two amplifiers and two TWT, traveling-wave tube) and six heat pipes in cabin body. The model was a rectangular cuboid which dimensions are 600(L)×400(W)×300(H)mm, whose appearance and internal mesh showed below:

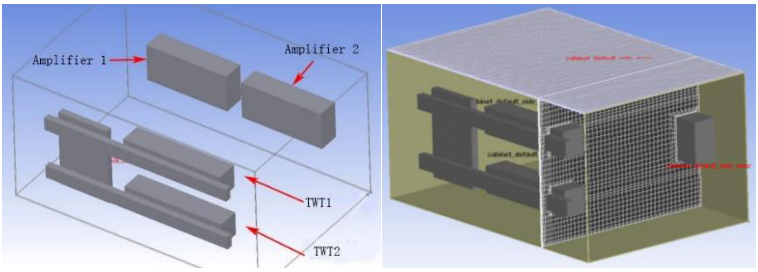
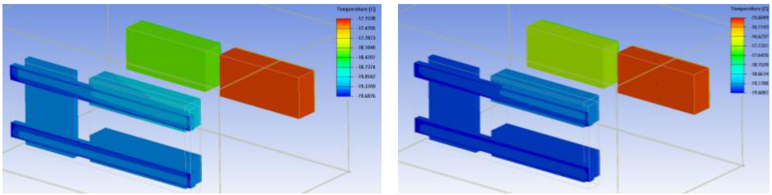


Figure 5. Simulation model and mesh

When the temperature of the outer shell is -20°C, the internal temperature distribution in TV and TC are given in Figure 6.



TC test TV test

Figure 6. Temperature distribution

The outer shell temperature was set 253K. When the amplifiers power was 0.5W, 1W, 2W, 5W and 10W, the model had been simulated under two different conditions - heat source contracting with wall or not contracting with wall. The temperature difference between TV and TC test can be seen in Table 2.

Table 2. Temperature comparison

Power(W)	Heat Flux(W/m^2)	Without Conduction			With Conduction		
		TV(°C)	TC (°C)	Difference (°C)	TV(°C)	TC (°C)	Difference (°C)
0.5	7.94	-16.97	-19.31	2.34	-19.19	-19.46	0.27
1	15.89	-15.23	-18.85	3.62	-18.50	-19.01	0.52
2	31.77	-11.75	-17.95	6.20	-17.11	-18.12	1.01
5	79.43	-1.90	-15.25	13.35	-12.96	-15.44	2.48
10	158.85	13.31	-10.78	24.08	-6.14	-10.99	4.86

The simulation results and the rule number analysis in table above follow same trend. When heat flux of heat source is greater than 40W/m^2 and without contracting with walls, there may be a significant temperature difference between TV and TC test(> 10°C). It may be in consequence short-test for article. The threshold should be much greater than 40W/m^2 for a unit directly contracting to deck and could be estimated by equ.9 using heat flux and characteristic length ratio.

3.2. Test

The comparative test was carried out in BISEE; specifically, the TC test was done in thermal cycling chamber and TV test was completed in thermal vacuum chamber. test article was a rectangular cuboid which dimensions are 600(L)×400(W)×300(H)mm. Inner structure of the article was same as the model in 3.1. The test article and test system are showed in Figure 7. There were four programmable power supplies and film heaters used to simulate the heat source. Also, sixteen thermal couples were set on test article to measure the temperature.

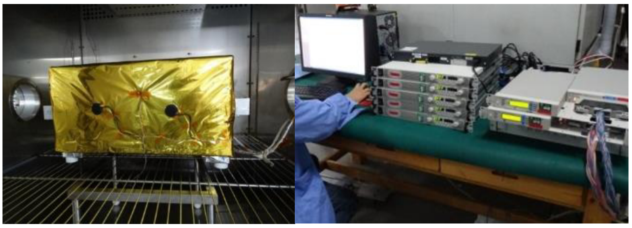


Figure 7. Test article and test system

When the shell temperature was 273K and 353K separately, the temperature difference between TC and TV test was calculated by equ.9. The curves are showed in Figure 8.

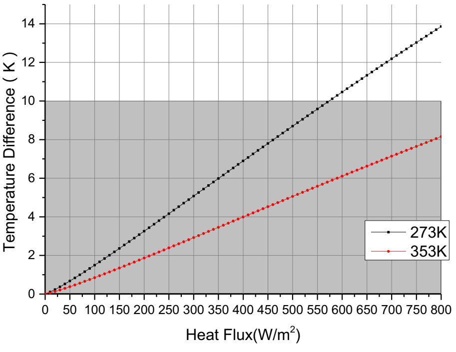


Figure 8. Temperature difference between TC and TV test

To verify the analysis, heat flux of the heat source was set to 750W/m^2. According to the analysis, temperature difference between TC and TV test will be less than 10°C in 353K case, and it will be more than 10°C in 273K case. The test result is showed in Table 3.

Table 3. Temperature difference in TC and TV test

Case	Temperature difference between shell and heat source(°C)		
	TV test	TC test	Delta
273K	43.89	20.37	23.52

353K	20.89	19.34	1.55

It can be seen that test result follow same trend with the rule number analysis. The temperature difference between TV and TC in low temperature was larger than in high temperature case. If a heat source thus set on deck directly, the heat flux threshold for alternative thermal cycling test can be calculated by the rule number analysis method.

4 Conclusion

In this paper, an internal heat transfer model coupled radiation, convection, conduction has been built by simplified nanosatellite model. Via rule number analysis method, it describes the applicability of using TC instead of TV for nanosatellite whose characteristic length and heat source size are different. Analysis results show it is feasible to use alternative TC test for nanosatellites with inner heat source flux less than $40W/m^2$. For a nanosatellite with internal heat source directly installed on deck, the threshold could be extended to $100W/m^2$, which can be calculated by rule number analysis method. The results of CFD and test method used to verification are consistent with the rule number analysis. The analytical method in this paper could be a positive choice in test method of nanosatellite in the future.

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