The Working Performance of Radiant Cooler in Thermal Vacuum Test

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In this paper a mathematical module is achieved to predict the working performance of radiant cooler in thermal vacuum test. The temperature and the emissivity of the cold shield, two influencing factors are discussed. The working performance of a parabolic cylinder radiant cooler on different thermal vacuum test conditions is given in picture.

INTRODUCTION

It is well known that the radiant cooler is a kind of mini-cooler used in space, with the advantages of light weight, no moving parts, long life and negligible power consumption etc. The radiant coolers have been developed for application to the cooling of infrared detector, optical systems, components, and other devices in spacecraft. Cryogenic radiator temperature can, of course, only be obtained in orbit, which provides sufficiently low sink temperature. The low temperature heat sink provided by a space environment is about 4K and the emissivity is about 1. The test set-up does not totally simulate the on-orbit configuration or environment. To predict the real working performance of radiant cooler in space by test result, the analytical thermal model is established to match the test configuration [1].

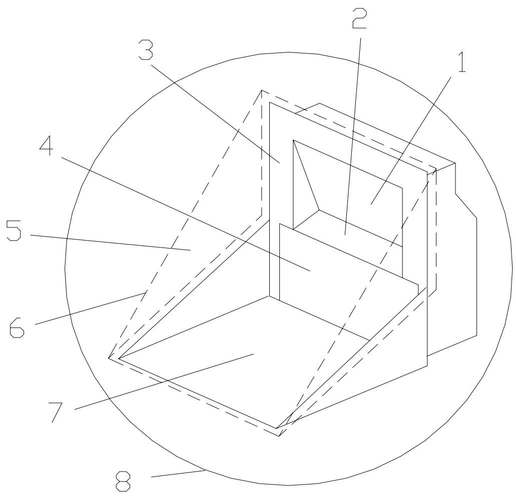
The working performance of radiant cooler can be predicated in thermal vacuum test on earth. The thermal vacuum test chamber is a cylinder in certain diameter. A pressure of 5×10^{-5} Pa is maintained inside the thermal vacuum chamber in order to make the convective transfer effects insignificant. The temperature of inter-well of cylinder is as high as that of liquid nitrogen. There is a big piece of black honeycomb board, called cold shield, covering the mouse of radiant cooler. The cold shield could be cooled to lower than 20K by a refrigeration system based on gaseous helium. The side gap between cold shield and cooler is covered with black pained aluminum plate, which connected with cold shield.

THERMAL ANALYSIS

A thermal model is established to analysis heat transfer between the radiant cooler and the cold shield during the thermal vacuum test. The thermal model included a detailed representation of the radiator components as well as appropriate surrounding chamber surface. The radiant cooler discussed here has two stages. The radiant cooler mainly consists of housing, earth shield, first stage radiator, second stage patch and support system. The sketch of the radiant cooler during thermal vacuum test is given in Figure1.

A closed cavity is made up with the inner surface of the earth shield, the first stage radiator, the second stage patch, the first reflecting screen, the front radiator surface of housing, the cold shield and side covers. In the thermal model, the following assumption is made: The earth shield and the first reflecting screen are low emissivity highly specular surfaces. The other surfaces are diffuse radiation. All surfaces are grey-body radiation.

The thermal balancing temperature can be reached by sending and receiving heat flows in thermal vacuum test. For instance, the heat loading to the patch includes radiant heat from parabolic cylinder reflector and the inner surface of first stage, the conductive heat from support and electric cable, and simulating heat of optical loading. To balance the heat loading, the patch gets cold from the cold shield by radiation. The temperature of the patch and the first radiator can be determined by the energy balance equations [2]. Two equations define the heat flows to the locations of interest:



1.First reflecting screen
2.Patch
3.Front white radiator
4.First radiator
5.Side cold shield
6.Cold shield
7.Earth shield
8.Thermal vacuum test chamber

Figure.1 Schematic plan of radiant cooler in thermal vacuum chamber

The first radiator:

$$\begin{aligned}
&\sigma A_{one} E_{one-cold}(T_{one}^4 - T_{cold}^4) + \sigma A_{one} E_{one-side}(T_{one}^4 - T_{side}^4) + \sigma A_{one} E_{one-two}(T_{one}^4 - T_{two}^4) \\
&= \sigma A_{one} E_{one-shield}(T_{shield}^4 - T_{one}^4) + \sigma A_{one} E_{one-screen}(T_{screen}^4 - T_{one}^4) + \sigma A_{one} E_{one-front}(T_{front}^4 - T_{one}^4) \\
&- F_{m2}(T_{one}^4 - T_{two}^4) + F_{m1}(T_{out}^4 - T_{one}^4) - F_{c2}(T_{one} - T_{two}) + F_{c1}(T_{out} - T_{one}) + Q_{one}
\end{aligned} \tag{1}$$

The patch:

$$\begin{aligned}
&\sigma A_{two} E_{two-cold}(T_{two}^4 - T_{cold}^4) + \sigma A_{two} E_{two-side}(T_{two}^4 - T_{side}^4) \\
&= \sigma A_{two} E_{two-shield}(T_{shield}^4 - T_{two}^4) + \sigma A_{two} E_{two-screen}(T_{screen}^4 - T_{two}^4) + \sigma A_{two} E_{two-front}(T_{front}^4 - T_{two}^4) \\
&+ \sigma A_{two} E_{two-one}(T_{one}^4 - T_{two}^4) + F_{m2}(T_{one}^4 - T_{two}^4) + F_{c2}(T_{one} - T_{two}) + Q_{two}
\end{aligned} \tag{2}$$

The terminology for equations is given below.
Variables：
σ: Stefan-Boltzmann constant, A: Area, E_{x-y} : The radiation transfer coupling coefficient between surface of X and Y, T: Temperature, F_{m1}: Coefficient of radiation transfer between the inner first radiator and inner housing with multiplayer insulation. F_{m2}: Coefficient of radiation transfer between the inner first radiator and inner patch with multiplayer insulation. F_{c1}: Coefficient of conduction transfer between the first radiator and housing through support and wire. F_{m2}: Coefficient of radiation transfer between the first radiator and the patch through support and wire. Q: Constant heat leak
Subscripts：
One: the first radiator, Two: the patch, Cold: the cold shield, Shield: the earth shield, Side: the cover between the cold shield and radiator cooler, Screen: the first reflecting screen, Front: the front radiator surface of housing, Out: the housing.

The radiation exchange factors are calculated with the program utilizing a Monte-Carlo ray trace technique in this paper. A simulating program is compiled to calculate the equilibrium temperature of the radiator cooler by inputting environment parameters of test.

RESULTS

In general, there are two methods to indicate the working performance of radiator cooler in thermal vacuum test. One is the useful cooling capacity, that is, the thermal load when the patch works in the scheduled temperature. The other is the lowest temperature of the patch can be reached while the thermal load is scheduled. In this paper, the second method is used.

In the simulating program, it is supposed that the temperature of the housing is constant. The lowest temperature of the patch depends on many factors, such as the temperature of cold shield, the emissivity of related surfaces and the position of the cold shield. The temperature and the emissivity of cold shield are different according to various test conditions. The equilibrium temperature of the patch is regarded as baseline on the thermal test condition, which the temperature of the cold shield is 4K and the emissivity is 1. On other test conditions, the working performances of radiator cooler are indicated by the temperature difference to baseline.

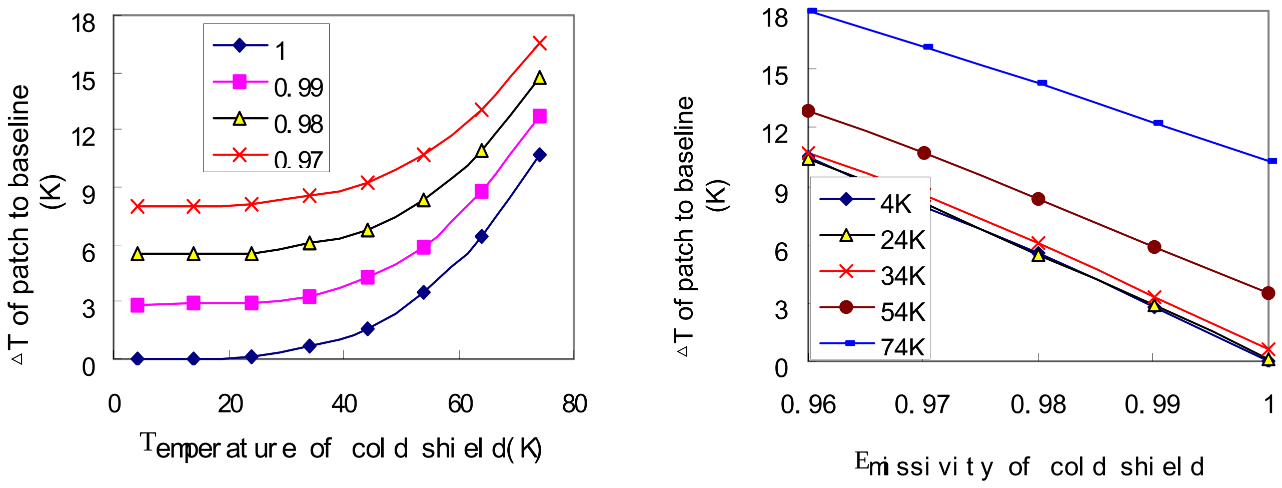


Figure2 Working performance of radiator cooler

The working performance of a kind of parabolic cylinder radiant cooler has been calculated. It is supposed that the housing is 240K in the test process. The cooling capacity is 0.04W. The cold shield temperature varies from 4K to 84K with 10K step length, at the same time its emissivity varies from 1 to 0.96 with 0.01 step length. The effects of these changes in temperature and emissivity of the cold shield on the patch temperature are shown in Figure2.

A smooth curve is drawn through the data points with the same emissivity of the cold shield. There is a little difference in temperature when the cold shield is lower than 24K. The temperature difference increases gradually and greatly with the increasing of the cold shield temperature. For example, as the emissivity is 0.99, the calculated values are 2.78K, 2.89K, 2.92K and 4.26K while the temperature of the cold shield is 4K, 14K, 24K, and 44K respectively. The temperature difference trend of the patch on the temperature of the cold shield is obvious.

A smooth curve is drawn through the data points with the same temperature of cold shield. It can be seen that the working performance of radiator cooler reduces with lowering the cold shield emissivity. The working performance changes linearly with emissivity. A 0.01 change in the emissivity of cold shield results in a change of approximately 2K in patch temperature. The rate of slope is different at different testing condition. The effection of emissivity on the working performance is reducing with raising the cold shield temperature.

To correlating temperature and emissivity of the cold shield, the map of the working performance is obtained, which shown in Figure3. Given the temperature and emissivity of the cold shield in test, the temperature of the patch is determined. For instance, the thermal vacuum test of this kind of parabolic cylinder radiant cooler is conducted. The emissivity of the cold shield is 0.98. The thermal vacuum test is conducted in two stages. In first stage: the cold shield is cooled by a refrigeration system based on liquid Nitrogen to 78K. The equilibrium temperature of patch is 106.1K. In second stage: the cold shield is cooled by a refrigeration system based on gaseous helium to 17K. The equilibrium temperature of patch is 93.7K. The observed temperature difference between those two test conditions is 12.4K. The predicted temperature difference between these two test conditions by the simulating program is 11.9K. The error percentage is within 5%. There is a good agreement between the predictions and the observed test temperature differences. This confirms the validity of the mathematical model.

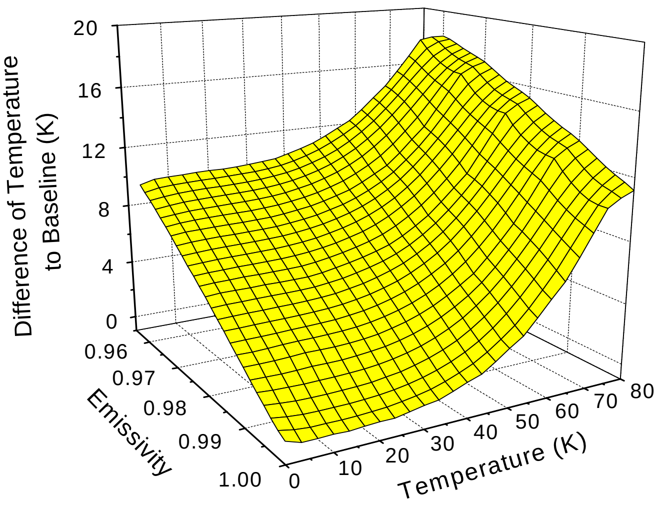


Figure3 Map of working performance

CONCLUSION

The influences of temperature and emissivity of the cold shield to the working performance of radiant cooler in thermal vacuum test have been discussed. It is important to improve the emissivity of the cold shield as it has great influence on the test result. There is little difference in test result when the temperature of the cold shield is lower than 24K. It is well enough that the cold shield is cooled by a refrigeration system based on gaseous helium to about 17K in the thermal vacuum test.

REFERENCE

1. Wang, G. And Han, J., Optimization Design of the Cold-Black Target for Thermal Simulation Test of Space Radiant Cooler, Cryogenics in China (1993) 1 7-13
2. Robert, S. and John, R.H. Thermal Radiation Heat Transfer Hemisphere and McGraw-Hill (1981) 564