Study on quick detection method of external heat flux simulator for spacecraft

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Abstract. According to the mathematical model of the heating power of the polyimide film heater and the maximum power density of the polyimide, the risk point of the heating circuit of heat flux simulator can be found. The current range of different heating circuit can be calculated and the range can be reduced in case of the detection efficiency. After the constant current is input to the heating circuit, the temperature profile of the heating circuit is given according to the heating circuit design. Compared with the observation result of the thermal imager, it is quick to judge whether the heating circuit of heat flux simulator is correct and find the problem location as while. The new method ensures the detection of safety while improving the detection efficiency.

1. Introduction
The heat flux simulator for spacecraft is an important device for the simulation of the space environment. It is widely used in the environmental testing of spacecraft [1, 2]. The production process is to paste the polyimide film heaters on the 100μm thick polyimide film and weld them into a heating circuit [3]. The heating element is a polyimide thin film type heater, and each polyimide thin film type heater generates different heat according to the current, thereby raising the heated body to a certain temperature [4, 5]. Before it is put into use, it is necessary to check the correctness of the heating circuit. This article will give the detection basis and detection methods to quickly determine whether the heating circuit is correct, and intuitively determine the location of the heater with problem.

Figure 1. These is film heaters.  Figure 2. This is a heat flux simulator.
At present, there are two methods to detect the correctness of the heating circuit of heat flux simulator. First, measure the resistance of the heating circuit to determine whether it is the same as the design value. Second, put the circuit on to check whether all the heaters in the circuit are heating. But both methods are flawed.

For the first method, the resistance of a heating circuit is correct cannot prove that the heating circuit is correct. Such as the two heat flux simulators in Figures 3 and 4, each of which contains two heating circuits, and the specifications of the polyimide film heaters constituting the two heating circuits are the same. The resistance of the heating circuits 1 and 2 in Figure 3 is the same as that of the heating circuits 1 and 2 in Figure 4, but the two circuits are different for heat flux simulator [6].

![Figure 3](image1.png)

**Figure 3.** This is heating circuit 1.

![Figure 4](image2.png)

**Figure 4.** This is heating circuit 2 which has the same resistance as circuit 1.

For the second method, we can only determine whether a polyimide film heater is welded into the heating circuit, but cannot determine the correctness of the heating circuit. And because the input current is empirically given without theoretical guidance, there is a risk of damaging the heating circuit.

2. The New Detection Method
In order to overcome the shortcomings of the above two methods, this paper will show a more intuitive and more efficient detection method based on the second method. In this method we need the heating circuit design drawings, a constant current power supply and a thermal imager [7].
**Figure 5.** This is a heating circuit design

**Figure 6.** This is a divided heating circuit design drawing shown in Figure 5.
First, we need to process the design drawings. For example, there is a heating circuit design drawing shown in Figure 5.

Then what we need to do is as follows:
1. Divide the design by the heating circuit location (shown in Figure 6).

When current is input to the heating circuit, with a thermal imager, we can easily observe whether all the heaters in the heating circuit are working [8], and whether there are heaters that should not be in the working state are working.

2. Draw the temperature distribution field diagram according to the heater heating power.

Compare the temperature distribution field diagram of the heating circuit and the observation results of the thermal imager can determine whether the position of the heater is correct.

3. Heating Efficiency Model

How to draw a temperature distribution field diagram, first of all we need to know the relationship of temperature level of different heaters in a heating circuit, according to the power calculation formula showed in formula 1.

\[ P = mC_p(T - T_0)t^{-1} \] (1)

In formula 1, \( m \) is the mass of the object to be heated. \( C_p \) is the specific heat of the material. \( T \) is the operating temperature. \( T_0 \) is the initial temperature, and \( t \) is the time required to heat the object from the initial temperature to the operating temperature.

Due to

\[ P = I^2R \] (2)

\( I \) is the energizing current and \( R \) is the heater resistance.

Therefore

\[ I^2R = mC_p(T - T_0)t^{-1} \] (3)

So for the same heater, the higher current \( I \) and heater resistance \( R \) are, the faster the heating rate (\( T - T_0 \))/\( t \). So in unit time, the higher the \( I \) and \( R \) are, the higher the temperature of the polyimide film heater. For different heaters, \( m \) is only related to the heater area \( S \) due to the same manufacturing process, and \( m \) is proportional to the heater area \( S \).

Therefore

\[ I^2RS^{-1} = \rho C_p(T - T_0)t^{-1} \] (4)

\( \rho \) is a positive factor of \( S \) and \( m \), and for all heaters it is a constant value.

According to the formula (3) and (4), for the same heater, \( mC_p \) is a constant value [9], \( I^2 \) and the heating rate \( (T - T_0)/t \) is approximately linearly proportional. For different heaters, \( I^2R/S \) and the heating rate \( (T - T_0)/t \) is approximately linearly proportional, and when the current of each heater is the same, \( R/S \) and the heating rate \( (T - T_0)/t \) is approximately linearly proportional.

To verify this, select four heaters to test. Their resistances are 3.24Ω, 12.82Ω, 30.13Ω, 60.19Ω and their areas are respectively 73 × 67mm, 245 × 86mm, 144 × 94mm, 195 × 93mm. Measure the temperature rise of the heaters in 15s every 0.1A, see Table 1.

Process the data in Table 1, and establish a coordinate system with \( I^2 \) as the ordinate and \( (T - T_0)/t \) as the abscissa. The curves of the relationship between current and the heating rate are shown in Figure 7.

For the same heater, since the curve approximates a straight line, so the conduction current \( I^2 \) is approximately linearly proportional to the heating rate \( (T - T_0)/t \) is verified. For different heaters since the heating rate from fast to slow followed by 60.19Ω, 30.13Ω, 3.24Ω, 12.82Ω, it can be verified that \( R/S \) is proportional to the heating rate \( (T - T_0)/t \).

Because there are only two types of circuits: series circuit (shown in Figure 8) and parallel circuit consists of several series circuits (shown in Figure 9), according to the statistical result of multiple satellite platforms.

In the series circuit, since the current of each heating plate is the same, so the higher the resistance
of the polyimide film heater, the higher the temperature.

**Table 1.** A table shows temperatures of the heaters in the test.

| Current (A) | Resistance(Ω) | T₀ (°C) | T (°C) | T-T₀ (°C) | T₀ (°C) | T (°C) | T-T₀ (°C) | T₀ (°C) | T (°C) | T-T₀ (°C) |
|------------|----------------|--------|--------|----------|--------|--------|----------|--------|--------|----------|
| 3.24(73×67mm) | 12.82(245×86mm) | 30.13(144×94mm) | 60.19(195×93mm) |
| 0.1 | 23.0 | 23.0 | 0 | 24.6 | 24.6 | 0 | 25.8 | 25.8 | 0 | 21.7 | 21.8 | 0.1 |
| 0.2 | 23.7 | 23.9 | 0.2 | 24.1 | 24.2 | 0.1 | 25.3 | 26.5 | 1.2 | 22.1 | 23.0 | 0.9 |
| 0.3 | 24.1 | 24.5 | 0.4 | 24.3 | 24.9 | 0.6 | 25.3 | 27.2 | 1.9 | 23.5 | 25.2 | 1.7 |
| 0.4 | 23.5 | 25.3 | 1.8 | 24.6 | 25.7 | 1.1 | 26.4 | 30.0 | 3.6 | 23.7 | 26.8 | 3.1 |
| 0.5 | 23.5 | 26.4 | 2.9 | 25.4 | 27.2 | 1.8 | 24.1 | 29.8 | 5.7 | 23.7 | 29.4 | 5.7 |
| 0.6 | 24.1 | 28.3 | 4.2 | 22.5 | 25.4 | 2.9 | 23.9 | 32.6 | 8.7 | 24.1 | 32.6 | 8.5 |
| 0.7 | 23.6 | 29.4 | 5.8 | 23.0 | 27.2 | 4.2 | 23.9 | 35.5 | 11.6 | 23.5 | 36.3 | 12.8 |
| 0.8 | 24.0 | 31.5 | 7.5 | 23.7 | 29.1 | 5.4 | 23.8 | 39.1 | 15.3 | 25.5 | 42.9 | 17.4 |
| 0.9 | 24.0 | 33.5 | 9.5 | 23.3 | 30.1 | 6.8 | 22.1 | 40.6 | 18.5 | 23.5 | 46.0 | 22.5 |
| 1.0 | 23.9 | 35.3 | 11.4 | 24.2 | 32.7 | 8.5 | 25.6 | 47.8 | 22.2 | 24.2 | 52.5 | 28.3 |

| R/S (Ω/mm²) | 6.624×10⁻⁴ | 6.075×10⁻⁴ | 2.226×10⁻³ | 3.319×10⁻³ |

![Figure 7](image7.jpg) **Figure 7.** This is the heating rate curve which shows the relationship between current and the heating rate.

![Figure 8](image8.jpg) **Figure 8.** A series circuit.

![Figure 9](image9.jpg) **Figure 9.** A parallel circuit.

For parallel circuits, the individual heater area power is calculated as follows:

\[ P_i = I_i^2R_i = I^2R(R_nR_i)^{-1} = SpC_p(T - T_0)t^{-1} \]  \hspace{1cm} (5)

\( P_i \) is the power of a certain polyimide film heater. \( I_i \) is the current of the same polyimide film heater. \( R_i \) is the resistance of the same polyimide film heater. \( I \) is the total current, that is, the input current of the parallel circuit. \( R \) is the total resistance of the parallel circuit. \( R_n \) is the total resistance of the single series circuit that the polyimide film heater is in.

Since \( I \) and \( R \) are the same for all polyimide film heaters in the parallel circuit, the temperature is only relevant to \( R_i(R_n^2S)^{-1} \). When \( R_n \) is the same for all series circuits, the temperature is only relevant
to $R_0 S^{-1}$.

Using custom software, the temperature distribution field diagram can be quickly generated by inputting the heating circuit design drawing and the resistances of all polyimide film heaters. For example, the temperature distribution field diagram of circuit 4 in Figure 5 is shown in Figure 10[10, 11, 12].

4. Current Calculation

Still a problem needs to be solved in order to use this method, that is how to calculate the input current, in ensuring the safety of the heating circuit[13], and make the polyimide film heaters quickly reach the detectable temperature.

In order to clarify the safety range of the energizing current and heating efficiency, it is necessary to study the power permissible range of the heater and the relationship between the current $I$ and the heating time $t$. First, the working temperature of each heater need to be cleared in the design process, so as to calculate the required power needed in order to raise the temperature of heated objects to appropriate value within the expected time and maintain [14].

According to Figure 11, the working capacity of the heater can be measured by the power of per square centimeter $P S^{-1}$ ($S$ is the effective area of the heater), that is, when the fixed mode of the heater and ambient temperature are certain, the inputted electric energy a heater can withstand is inversely proportional to the power of per square centimeter.

For

$$P S^{-1} = I^2 R S^{-1}$$

(6)

So the smaller the $R S^{-1}$ of the heater is, the greater the allowable current $I$.

In the series circuit, since the current of each heater is the same, the heater with lowest current tolerance is the dangerous point of the whole circuit[15]. The maximum current that can be allowed by it is the maximum current that can be allowed for the whole circuit. According to the formula (6), when the current $I$ is the same, the heater with highest $R S^{-1}$ bear the greatest risk, when all the heaters are heated to the same temperature.

For parallel circuits, the power of per square centimeter is calculated as follows:

$$P_i S_i^{-1} = I_i^2 R_i S_i^{-1} = I_i^2 R_i (R_{n}^2 S_i)^{-1}$$

(7)

For any heater in the circuit, the value of $IR^2$ is the same, so the maximum current that can heater with highest $R_i(R_{n}^2 S_i)^{-1}$ bear is $I_i$, $I R_i R^{-1}$ is the maximum current $I$ that can allowed to input to the whole parallel circuit. When the resistance of each branch is the same, the formula can be reduced to $k I_i$ ($k$ is the number of branches).

Thus, when the $R_i S_i^{-1}$ of the heater is known, the temperature rise curve of the heater can be
estimated approximately so as to determine the input current. For example, when the resistance of a heater is 6Ω and the area is 90 × 80mm, so the $R/S = 8.333\times10^{-4}\Omega/mm^2$ can be calculated. Therefore, the temperature rise curve can be estimated as shown in Figure 12. To rise the temperature 10°C in 15s, the current can be chosen 0.6 ~ 0.7A.

![Figure 12. A temperature rise curve estimation for heater whose resistance is 6Ω.](image)

In the inspection process, determine the type of circuit first. When the circuit is in series, calculate the $R/R_1^{-1}$ of each heater, and find the maximum value of it. Estimate the temperature curve, and select the appropriate input current $I$ for the heating rate. When the circuit is in parallel, calculate the $R(R_2^{-1}S_1)^{-1}$ of each heater, and find the maximum value of it. Estimate the temperature curve, and select the appropriate input current $I$ for the heating rate. At this time the detection current of the circuit is $I_1R_1R_n^{-1}$. When the resistance of each branch is the same, the formula can be reduced to $kI_1$.

5. Conclusions

In this paper, by studying the principle of the circuit of heat flux simulation for spacecraft, the detection method is put forward, and the safe current is given at the same time. In the detection process, the information of heat flux circuit, heaters’ resistances and areas, a constant current output power and an infrared thermometer need to be provided. The specific measurement methods and steps are as follows: Get the information of heat flux circuit, heaters’ resistances and areas. Calculate the highest $R/S_1^{-1}$ or $R(R_2^{-1}S_1)^{-1}$ of different circuits. Estimate the temperature rise curve to determine the input current. Divide the design by the heating circuit location. Draw the temperature distribution field diagram. Input current to circuits in turn, and compare the thermal imaging with the temperature distribution field diagram.

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