Research and development of surface heat flux sensor for high speed aircraft

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Abstract. A water-cooled high temperature and high heat flow sensor was developed to meet the requirements of high heat flow measurement under ultra-high temperature conditions on the surface of high speed aircraft. This type of sensor is based on the measurement principle of circular foil heat flow sensor. Cooling water is introduced through structural design optimization to ensure that the structure, measurement accuracy, sensitivity, linearity and other indicators of the sensor do not change at ultra-high temperature of 1600℃, so as to achieve extremely high heat flow measurement on the surface of the aircraft. Through the test verification, the heat flow sensor can withstand 1600℃, heat flow measurement range up to 1000KW/m², measurement accuracy is better than 5%.

1. Introduction
Heat flow sensor is divided into many kinds according to the different installation position, measuring principle, structure and using purpose. In general, the measurement methods of heat flow sensors can be divided into two methods: temperature difference method (steady-state method) and temperature rise method (unsteady state method). According to the different measuring principles of heat flow sensors, the heat flow sensors commonly used in practice are divided into thermal resistance type heat flow sensors, radiation type heat flow sensors, fluid transport process heat flow sensors and transient heat flow sensors.

Thermal resistance heat flow sensor is one of the most popular heat flow sensors. It is based on the principle of steady-state heat conduction, when the heat flow passes through the heat flow probe, the temperature gradient is generated on the thermal resistance layer of the probe. According to Fourier's law, the heat flux through the heat flux probe can be obtained. Therefore, as long as the temperature difference between the two sides of the thermal resistance layer is measured, the heat flow value through the heat flow sensor probe can be obtained. Thermal resistance of the heat flux sensor manufacturing process, fix the thermocouple or thermopile heat flux sensor probe, the heat flow through the measuring head, produce thermoelectric potential and measured temperature difference and temperature difference is proportional to the heat flow density and temperature difference value proportional to the size of thermoelectric potential and, to the thermoelectric potential could be used directly to reflect the size of the heat flux density [1].

At present, the surface of hypersonic aircraft is subjected to different degrees of aerodynamic heating when flying in the atmosphere. Accurate quantification of the energy transfer process of aerodynamic heating is the basis of thermal protection design, and also a key link to further optimize structural efficiency and improve flight performance. As an input parameter for structural heat transfer calculation, the heat flux of aerodynamic heating is derived from the reasonable assumptions of
computational fluid dynamics model or the finite approximation of various high-speed wind tunnel equipment, showing different degrees of "deviation" from the real flight state [2]. Therefore, the heat flux of flight test is the only test reference for verifying and perfecting the aerodynamic heating calculation method and establishing the flow field parameter correlation mechanism of wind tunnel equipment. Hypersonic flight has its unique physicochemical process, and coupling effect exists at both ends of material and environment. The measurement of heat flux in flight will provide an excellent entry point for the in-depth study of a series of extremely complex interaction processes of hypersonic flight.

In order to solve the above problems, this paper studies the heat flow measurement sensor and develops a kind of sensor for the measurement of extremely high heat flow in ultra-high temperature environment. This type of sensor is based on a circular foil heat flow sensor. Through structural optimization, it is able to withstand 1600℃, the maximum heat flow measurement range can reach 1000KW/m², the measurement accuracy is better than 5%, and the response time is less than 1s.

2. Principle of heat flow sensor

Circular foil heat flow sensor, also known as Gardon heat flow meter, it is a device developed by Robert Gardon in 1952 to measure radiation heat flow [3]. The heat flux meter is mainly composed of circular copper-nickel alloy (constantan) flakes, copper heat sink and central copper wire.

![Schematic diagram of Gardon heat flow meter](image)

The working principle of Gardon heat flux meter is: uniform heat flux q flows vertically to constantan plate, flows along the center to the edge in the interior of constantan plate, making the center and edge of constantan plate will produce a temperature difference delta T, according to the theory of Gardon heat flux meter. The temperature difference has a linear relationship with heat flow:

\[
q = \frac{4\lambda S}{R_G^2} \Delta T = \frac{4\lambda S}{R_G^2} (T_1 - T_2)
\]

(1)

λ, S and RG are respectively the thermal conductivity, thickness and radius of constantan plate. According to the constitution principle of thermocouple, the thermocouple of temperature difference between copper and constantan (i.e., t-type thermocouple) is formed at the center and edge of constantan plate. By measuring the electric potential difference between the central copper wire and the copper heat sink, the temperature difference between the center and the edge of the constantan sheet can be obtained, and the heat flow value of the surface of the constantan sheet can be deduced. Therefore, the relationship between the output voltage E of the heat flow meter and heat flow q is as follows:

\[
E = \alpha (T_1 - T_2) = \frac{R_G^2}{4\lambda S} q = K \cdot q
\]

(2)

In the formula, is the output signal constant of thermocouple, and K is the output signal constant of Gardon heat flow sensor. Before heat flow measurement, K coefficient in the formula needs to be
calibrated. The response time of Gardon heat flow sensor itself is related to the properties of structure and material, and its expression is:

\[ \tau_0 = \left( \frac{\rho C_p}{4 \lambda} \right) R_G^2 \]  

(3)

\( \rho \) is the density and specific heat of constantan. When the temperature is low, the physical properties of copper and constantan materials change very little, and the response time of the heat flow meter is only proportional to the square of the diameter of constantan sheet, but when the temperature is high, the response time will change with the material properties [4].

In summary, the signal strength and response time of the Gardon heat flow sensor are proportional to the square of the constantan plate radius, so the response time cannot be shortened while improving the signal strength. In actual use, structural parameters of heat flow meter should be flexibly designed according to measurement requirements [5].

3. Design and development of water-cooled heat flow sensor

The heat flow sensor developed in this paper is mainly used to measure the extremely high heat flow on the surface of spacecraft due to the aerodynamic effect of high-speed flight. According to the actual requirements, the heat flow sensor shall meet the technical indicators such as heat flow density range of 0-500kw/m² and maximum measurement error not exceeding ±5%. In the design of sensor, the choice of diameter and thickness of constantan plate and the design of integrated structure are the key.

3.1 Heat flow sensor matrix material selection

At present, several factors should be taken into consideration in the selection of matrix material of heat flow sensors commonly used at present, such as melting point temperature of matrix material, thermal conductivity coefficient of matrix material, density of matrix material and specific heat of matrix material. Table 1 lists physical property parameters of some materials [6].

| Material | Melting Point (°C) | Heat Conductivity (W/m•K) | Density (kg/m³) | Specific Heat (J/kg•°C) |
|----------|-------------------|--------------------------|-----------------|-------------------------|
| Iron     | 1535              | 76.2                     | 7870            | 440                    |
| Platinum | 1769              | 69.1                     | 21450           | 184                    |
| Copper   | 1083              | 385                      | 8900            | 385                    |
| Tungsten | 3370              | 163.3                    | 19300           | 134                    |
| Diamond  | 1500              | 2090                     | 8500            | 1670                   |

The best material for making matrix is diamond, but its own and processing costs are very high. Tungsten is second, but difficult to obtain and expensive. Copper was selected as the matrix for the test. The material was nominal high temperature resistance of 1083°C, and the thermal conductivity was large. After cooling 500KW/m² heat flux radiation for 30min with water cooling cycle, the surface was intact without deformation.

3.2 Selection of sensitive components for the heat flow sensor

The sensitive element of the heat flow sensor is an ant string t-type thermocouple composed of copper wire, constantan foil and copper heat sink. The thermal radiation is directly projected on the surface of constantan foil, absorbed by it, and then converted into electrical signal output [7]. The emissivity and absorptive of constantan foil surface are affected by its surface treatment, which affects its thermal radiation properties, as well as the efficiency and error of heat flow measurement. The monochromatic emissivity of metal objects decreases with the decrease of its resistance and decreases with the increase of wavelength. The emissivity of constantan is shown in table 2. If the sensor's constantan r foil end surface is exposed to the air, the change in surface emissivity caused by the change in the
oxidation degree of constantan foil will change the heat absorption of the sensor, thereby affecting the measurement of heat flow by the sensor\cite{8}. In the case of different temperature and different radiation wavelength, the surface emissivity of black paint changes very little, and the surface emissivity of black paint is greater than the surface emissivity of other coatings, so choose to spray black paint on the surface of constantan foil, to improve the absorption rate of different wavelengths of the sensor, and ensure the stability of the sensor.

3.3 Structure integration design for the Heat flow sensor

According to the classification of structure, heat flow sensors mainly include wire-wound heat flow sensors, semiconductor heat flow sensors, thin-film heat flow sensors and other types. The circular foil heat flow sensor selected in this paper is wire-wound. The structural design of the circular foil heat flow sensor enables it to meet the requirements of high heat flow measurement on the surface of spacecraft, with a small response time constant and high structural strength and reliability.

As shown in figure 2. Heat flow sensor includes black constantan foil, red copper heat sink, heat sink shell, copper lead, cooling water channel. A copper block with a cylindrical hole in the center of the shell of the thermal sink is used to carry the copper thermal sink. The red copper thermal sink is installed in the cylindrical hole at the center of the shell of the thermal sink, which is used to carry the coated black constantan foil. Black constantan foil is welded and fixed on the top center of red copper heat sink for receiving heat flow. A t-type thermocouple is formed by the positive electrode lead introduced through the center hole of the red copper thermal sink and the black-coated constantan foil. Red copper thermal sink and black constantan foil form another T-type thermocouple. The bottom surface of the red copper thermal sink leads out the negative electrode lead, and through the positive electrode lead and the negative electrode lead, the voltage value generated by the temperature gradient formed after receiving the heat flow of the t-type thermocouple at the two places is measured. Heat flux density can be obtained by calibrating it.

![Figure 2. Schematic diagram of heat flow sensor structure](image)

The cooling water channel is arranged on both sides of the shell of the thermal sink and open with the central cylinder hole. The diameter of black constantan foil is 4 mm, the thickness is 0.2 mm, the surface is black paint, the absorption rate is greater than 0.9. Red copper thermal sink is a hollow cylinder made of red copper, chrome-plated on the surface, with a height of 20 mm and a diameter of 16 mm. Black constantan foil and red copper thermal sink are fixed by tin welding. Red copper thermal sink and red copper thermal sink shell are fixed and sealed by metal glue. Both positive electrode lead 4 and negative electrode lead 5 are copper wire or other metal wire with section diameter of 0.2 mm, and the insulation layer of the lead is glass fiber or other high-temperature resistant materials, as shown in figure 3 below.
4. Test verification and result analysis

4.1 Heat flow calibration test-Calibration equipment and calibration method
Calibration of heat flow sensor uses arc lamp calibration equipment of heat flow sensor built by 304 institute of aviation. Main technical indexes of calibration equipment: heat flow range is 100kW/m² ~ 10MW/m². The calibration mode is transient calibration and steady-state calibration. Standard uncertainty ≤ 2%. The Gordon gauge calibrated by the room temperature electrical calibration radiometer is used as the standard heat flow sensor in the calibration. Under the same arc lamp radiation state (represented by arc current), the standard heat flow sensor and the designed heat flow sensor are used successively to measure the heat flow at the same position at the outlet of the optical integrator. The performance of the heat flow sensor to be calibrated is compared and analyzed.

4.2 Heat flow calibration test- The calibration results
The sensor body is a 304 stainless steel cylinder with diameter of 6.4 mm and length of 40 mm. The comparison method was used for the test, and the standard Gordon heat flow sensor was used as the measurement standard. The test device consists of high temperature infrared lamp array, guide rail, standard heat flux meter, and protective plate device and so on. The heat flow sensor and standard heat flow meter will be placed on the guide rail during measurement. The high temperature infrared lamp array is lit, and the sensor is tested on the guide rail successively. The accuracy of the sensor is obtained by comparing the measured results. The calibration test curve is shown in figure 4 below, and it is compared by the fitted curve. The measurement accuracy of the sensor is better than 5%, and the response time is less than 1S, meeting the design index of the sensor.
4.3 Heat flow test capability verification
According to the design index of heat flux density of 500KW/m². In order to verify the structural performance of the heat flow sensor and the soldered joint reliability between the con-copper foil and the central copper lead. The heat flow shock test of the designed heat flow sensor was carried out. Build a set of high heat flow loading test system. It consists of power supply system, power regulator, temperature controller, serial port server, signal amplifier, infrared lamp array and heat flow control system.

The test system is shown in figure 5. When the heat flow sensor is tested, the computer adjusts the output of the regulator through the temperature controller to control the brightness of the infrared lamp, so as to heat the surface of the analog part. The generated heat flow is fed back to the heat flow sensor, which sends the signal back to the serial port server, which forms a closed-loop control loop with the temperature controller and computer. In this test, two heat flow sensors, one s-even temperature measuring point, are installed on the surface of the simulation part. The heat flow sensor is connected to the water channel with M8 copper pipe. As the temperature is higher than 1200℃, heat insulation blanket is used to wrap the signal wire lead of the heat flow sensor to prevent short circuit and circuit break of the signal wire.

Figure 4. Calibrate heat flow curves

Figure 5. Heat flow sensor performance test system

Figure 6. Measured heat flow curve, temperature curve
Test results: the heat flow value and temperature value of the heat flow sensor are shown in the figure above. The maximum test is 331KW/m², corresponding to the measurement point temperature of 1216℃.

Error analysis: heat flow sensor is mainly used to measure radiant heat flow and total heat flow (radiant heat flow + convective heat flow) under small convective component. In the experiment, although there is no wind, there is still air convection, which affects the stability of heat flow during the experiment and causes measurement errors [9].

5. CONCLUSION
In this paper, a water-cooled heat flow sensor is developed for the measurement of extremely high heat flow on the outer surface of high-speed aircraft and round-trip aircraft. The sensor is made of copper, constantan, peek insulation material, etc. By use of building thermal load test system, validated the performance of the sensor, the results show that the type of heat flux sensor can realize the heat resistance of 1600 ℃, 1000 kw/m² heat flux measurement range, measurement of relative error is not more than ± 5%, and has good real-time performance, short response time and meet the sensor design index, have application in high heat flux measurement of high speed flight vehicle surface conditions.

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