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Research on Calibration Technology of Radiation Heat Flow Sensor

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Abstract: *Calibration radiation heat flux sensor before use is an important way to ensure accurate measurement and consistent values. This article studies the calibration technology of radiation heat flux sensors, focusing on the working principles of radiation temperature meters and standard heat flux sensors, as well as the design principles of radiation sources. It also elaborates on the calibration methods, data processing, and calculation methods of radiation heat flux sensors.*

Keywords: *Radiation Heat Flux, Calibration, Gordon Meter*

1. Introduction

The physical quantity describing the aerodynamic heating is the heat flux density, which is defined based on the mode of heat transfer[1]. Heat transfer is the energy transfer caused by temperature difference, according to the second law of thermodynamics. When there is a temperature difference between a certain object or two objects, heat will be spontaneously transferred from the high-temperature part to the low-temperature part, or from the high-temperature object to the low-temperature object. The three basic modes of heat transfer are conduction, convection, and radiation. The heat flux of conductive heat transfer is represented by Fourier's law, the heat flux of convective heat transfer is represented by Newton's cooling formula, and the heat flux of radiative heat transfer exists at any time in any object, and its output form is also relatively complex[2].

The reason for thermal radiation is the oscillation and transition of electrons in atoms or molecules that constitute matter. Radiation energy is emitted by consuming internal energy in the object, relying on electromagnetic waves or photons for transmission, without medium, and achieving the most effective transmission in vacuum. Radiation is the energy emitted by matter at a certain temperature, and when the radiation energy is projected onto the surface of an object, absorption, reflection and projection phenomena will also occur. Radiation manifests both as light and as heat. Therefore, the expression for blackbody radiation ability has (1) and (2), and when the temperature of a certain object and its environment are fixed, its radiation photoelectric form is determined.

Spectral radiation: $$E = \int_0^{\infty} E_{\lambda} d\lambda \tag{1}$$

Thermal radiation: $$E = \varepsilon \sigma T^4 \tag{2}$$

2. Radiation Heat Flux Sensor Overview

2.1 Classification of Heat Flux Sensors

The classification of heat flux sensors according to their working principles is shown in Figure 1. The commonly used working-level heat flux sensors are nine types, including water calorimeters, thin-wall calorimeters, plug block heat flux sensors, thin film heat flux sensors, coaxial thermocouples, zero-power calorimeters, thermal resistance heat flux meters, Gordon meters, and plug-type calorimeters. In theory, the above heat flux sensors can receive all types of heat flux. When the airspeed above the sensor surface is low, convective heat transfer can be neglected. It can also be separated from convective heat transfer by increasing isolation shields. The most commonly used for radiation heat flux measurement is the Gordon meter, which is directly referred to as a radiation heat flux sensor in military calibration specifications.

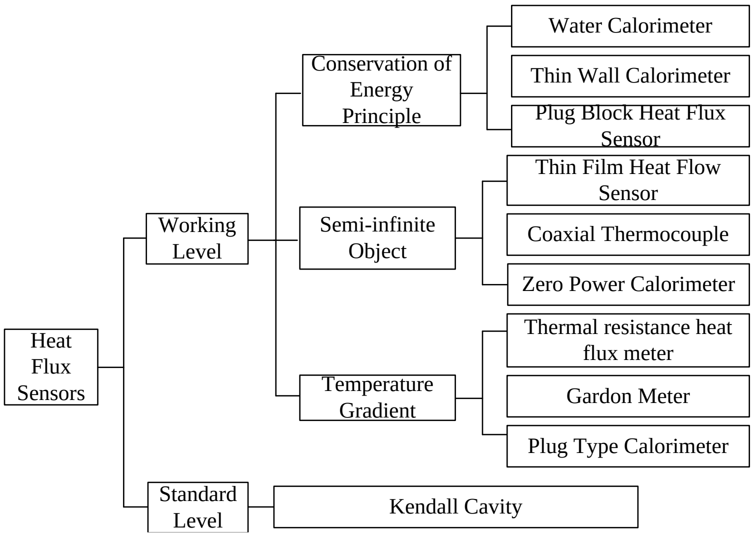

Figure 1: Classification of heat flux sensors

2.2 Operating principle of Gordon meters

Gordon meters have a simple appearance structure, a large measurement range, a small time constant, good repeatability, high structural strength, and can be used at high temperatures. The continuous use can increase water-cooled structures and is suitable for high heat flow measurement. The core of a Gordon meter consists of a copper-constantan foil and a copper heat sink. The copper wire, copper-constantan foil, and copper heat sink actually form a copper-constantan-copper differential temperature thermocouple. The structure is shown in Figure 2. The foil senses the heat that flows radially upward from the center and distributes in a parabolic manner with the highest temperature at the center and decreasing radially outward. The output voltage is proportional to the heat flux density absorbed by the sensing surface.

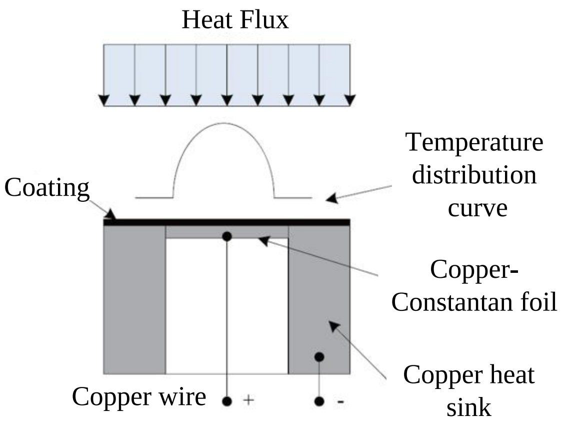

Figure 2: Circular Foil Heat Flux Sensor

The structure of the Gordon section is shown in Figure 3. The upper end of the circular foil sensitive element is insulated by a ceramic plate, and the receiving part is sprayed with high-temperature black paint to improve the absorption rate of heat flow. The positive electrode wire is welded to the center of the circular foil, and insulated by an insulated ceramic tube at the rear end. The pure copper heat sink is hollow and connected to a water-cooled pipe to cool the sensor. There is an air insulation layer between the protective shell and the heat sink to prevent heat exchange between the heat sink and the external environment.

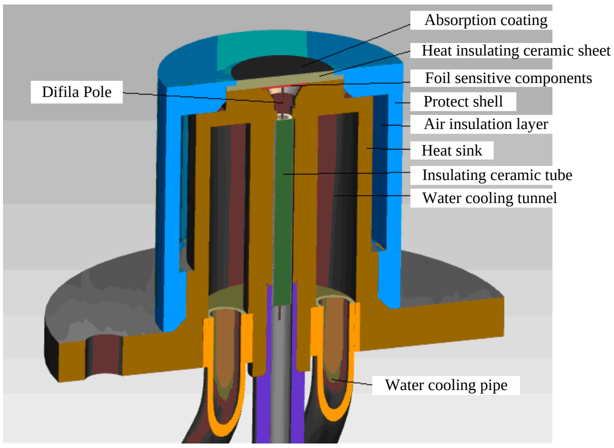

Figure 3: Circular Foil Heat Flux Sensor Profile

3. Calibration methods for heat flux sensors

Calibration of heat flux sensors serves two purposes:

1) By undergoing calibration, it becomes possible to determine the response characteristics and conversion coefficients of various heat flux sensors. This, in turn, provides a technical foundation for enhancing the accuracy and reliability of heat flux measurements conducted during aerodynamic heating and thermal protection tests.

2) Calibration also enables the establishment of data traceability for heat flux measurement standards, including radiation measurement standards and temperature measurement standards. This traceability serves as a crucial basis for ensuring the authenticity and reproducibility of heat flux measurement data[3].

Calibration methods include absolute methods and comparative methods. Absolute methods are used to calibrate heat flux sensors in a strictly controlled heating environment using optical theoretical calculations or thermoelectrical calibration methods to obtain the heat flux on the sensor surface, achieving direct calibration traceability to other physical measurement standards such as temperature or current voltage standards currently only possible at relatively low heat flux measurement ranges. Comparative methods are commonly used for large heat flux calibration. This method uses a standard heat flux sensor and a calibrated sensor in the same heat source to compare their numerical values.

4. Calibration Method for Radiation Thermal Flow Sensor

4.1 Calibration Procedure

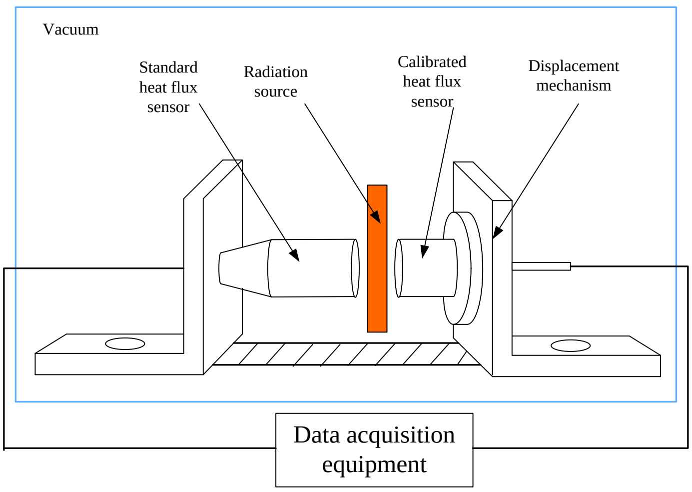

Figure 4: Calibration Principle of Radiation Heat Flux Sensor

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The principle of calibration uses a comparison method, with a calibration system consisting of a standard thermal flow sensor, a radiation thermal source, and a data acquisition system. The standard thermal flow sensor and the calibrated thermal flow sensor are symmetrically placed on both sides of the radiation plate, as shown in Figure 4. The radiation thermal source internal pressure is vacuumed. The heating current is manually controlled to generate heat flow, and when the heat flow output reaches the upper limit of the calibrated thermal flow sensor, the heating current is quickly reduced to zero to complete the calibration process.

4.2 Radiation Thermal Source

The radiation thermal source consists of a double-layer high vacuum chamber, graphite heating plates, heating electrodes, transformers, control devices, infrared temperature controllers, water cooling devices, vacuum devices, and visual systems, as shown in Figure 5.

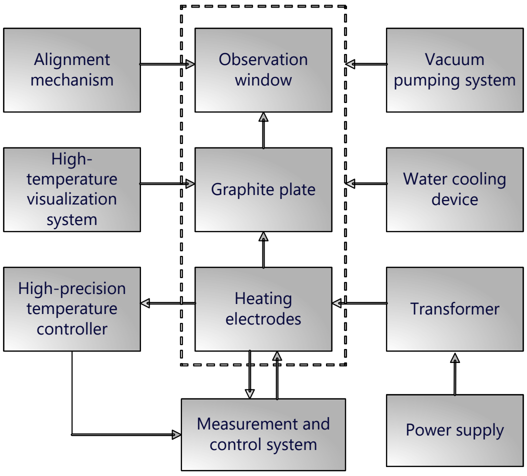

Figure 5: Schematic Diagram of Device Components And Operation

Inside the vacuum chamber of the radiation heat flow source, two conductive columns support the heating electrodes, which are hollow and cooled by circulating water. A graphite heating plate is clamped between the two electrodes, as shown in Figure 6. When the radiation heat flow source is operating, the water cooling device is turned on to prevent heat leakage, and the vacuum chamber is evacuated using a vacuum pump. The alignment mechanism is used to fix the standard heat flow sensor and the calibrated heat flow sensor on both sides of the plate. The infrared temperature controller can monitor the temperature of the heating plate in real-time through the observation window, and the high-temperature visualization system can monitor the changes inside the vacuum chamber[4].

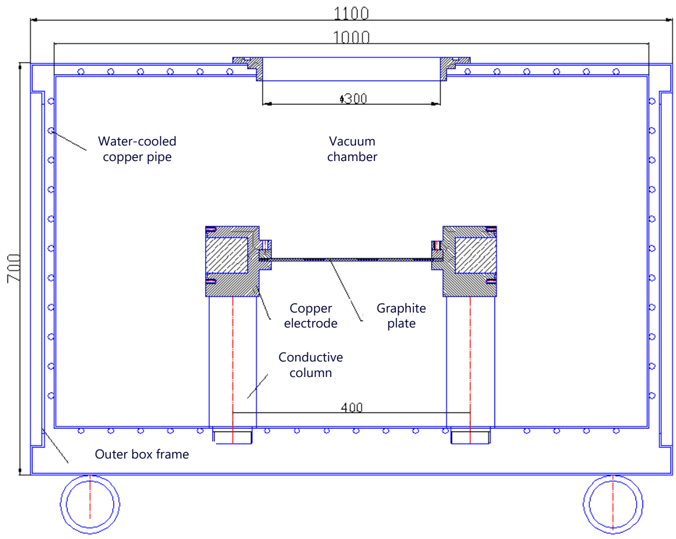

Figure 6: Schematic Diagram of Vacuum Chamber Structure For Radiation Heat Flow Source

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The core of generating heat flow is the graphite heating plate, which has a high emissivity (radiation coefficient) compared to most temperature-resistant materials. Therefore, at the same temperature, the graphite heating plate emits relatively large radiation energy to the outside. When the heating heat flow is turned on, the voltage is reduced through a transformer, and the graphite heating plate is in a state of high current and low voltage. According to Joule's law, the graphite heating plate generates heat and produces radiation heat flow. The temperature distribution of the graphite heating plate is shown in Figure 7, so it can be approximated that the middle area of the graphite heating plate generates uniform radiation heat flow[5].

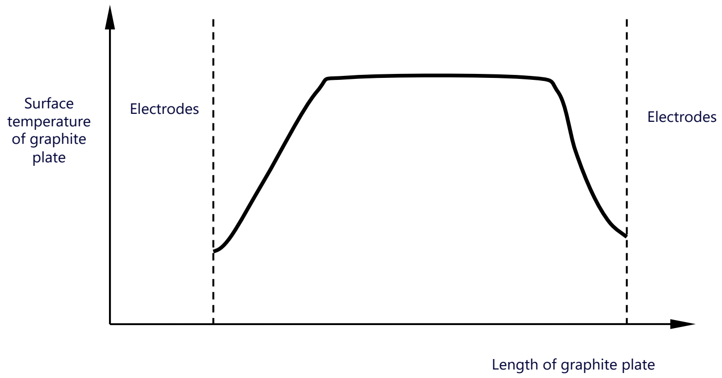

Figure 7: Temperature Distribution Diagram of Graphite Heating Plate

4.3 Calibration Results of Data Processing

Radiation Thermal Flow Sensor can be expressed as indication error or sensitivity. The following are the respective introductions:

(1)The indicated value error

During the calibration process, data acquisition should be conducted using a multi-channel high-speed acquisition device, with the results represented as a time-output curve. Five points should be selected from the output curve of the calibrated heat flux sensor, distributed as evenly as possible throughout the entire measurement range. The heat flux values should be calculated using the sensitivity coefficient indicated on the sensor nameplate, and the corresponding standard heat flux values for the five points should be recorded. The indicated value error should then be calculated using formula (3).

$$\Delta q = q_c - q_s \tag{3}$$

(2)Sensitivity

Sensitivity is a crucial parameter in radiant heat flux sensors, and each sensor can vary individually. Sensitivity is defined as the ratio of radiant heat flux density to the output temperature difference electromotive force, denoted by K. The calculation of radiant heat flux sensor sensitivity involves selecting at least five points within the measurement range and utilizing the least squares method to determine the value, as per formula (4).

$$K = \frac{Q \cdot E}{E^T \cdot E} \tag{4}$$

Where $Q = (q_1, \ q_2, \cdots, \ q_n)^T$, q_i refers to the standard heat flux value measured by the reference heat flux sensor at the selected point, $E = (e_1, \ e_2, \cdots, \ e_n)^T$, e_i refers to the temperature difference electromotive force output by the calibrated heat flux sensor at the selected point.

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5. Conclusion

This article conducted a comprehensive study on the calibration technology of radiation thermal flow sensors, focusing on the working principles of radiation thermometers and standard thermal flow sensors, and the design principles of radiation thermal flow sources. The calibration method, data processing and calculation methods of radiation thermal flow sensors are introduced in detail.

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