The Design and Performance of Heat Flux Sensor Calibration Equipment

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Abstract. This paper introduces the methods of heat flux sensor calibration and gives detailed descriptions of absolute and transfer techniques. The transmission of standard heat flux is realized by comparing the calibrated heat flux sensor with standard heat flux sensor based on a flat plate furnace. Furthermore, we design a heat flux sensor calibration equipment using absolute method which contains a sodium heat pipe blackbody with 50-mm-diam cavities. Thus heat flux sensor calibration can be traceable to the temperature standard using the absolute equipment.

1. Introduction

Heat flux sensor measures the density of radiant heat flux and the radiation heat flux density of specific position at particular moment can be obtained through measuring output signal of heat flux sensor. Heat flux sensors are widely used in areas such as aviation, energy and chemical industry etc. As the heat flux sensor works in high temperature and harsh environment, it is necessary to calibrate it regularly to ensure the accuracy of measurement.

The methods used to characterize heat flux sensors fall into two categories: transfer method and absolute method. The transfer method which compares the calibrated heat flux sensor with standard heat flux sensor is one of secondary calibration methods. The sodium heat pipe blackbody is used as a transfer source for the standard heat flux sensor calibration through absolute calibration. The heat flux sensors absolute calibration method is one of primary calibration methods. The radiance at the sensor surface can be calculated by knowing the blackbody temperature, enclosure geometry, and the surface emissivity.

We develop techniques to calibrate heat flux sensors to meet the current calibration needs of Chinese science and industry. The transfer calibration technique employs a flat plate furnace to calibrate heat flux sensors. While a standard heat flux sensor and the sensor to be calibrated are
mounted on opposite sides of its graphite plate with the same view factor. The transmission of standard heat flux is realized by comparing the calibrated heat flux sensor with standard heat flux sensor. Furthermore, the equipment using absolute method employs a traceable blackbody radiant source based on a sodium heat pipe blackbody with 50-mm-diam cavities, thus heat flux sensor calibrations are traceable to the temperature standard using the equipment. The traceability chain involves multiple steps, shown in figure 1.

![Figure 1. Traceability of heat flux sensor calibrations](image1)

2. **The transfer calibration equipment and calibration principle**

The transfer calibration equipment employs an electrically powered heater, with a designed graphite plate installed between two water-cooled copper electrodes under short-circuit condition. Because of the high power, we adopt low voltage but large current supply for safety reasons. The flat plate furnace can be operated up to the temperature of about 2600°C, the heated section is 80mm long and 60mm wide. Figure 2 shows a schematic layout of the flat plate furnace apparatus.

![Figure 2. Schematic layout of the flat plate furnace apparatus](image2)

A flat plate furnace is used to calibrate heat-flux sensors, while a secondary standard heat flux sensor and the working-standard heat flux sensor are mounted on opposite sides of the graphite plate with the same view factor. The relationship between the secondary standard heat flux sensor and working-standard heat flux sensor can be expressed with the following equation (1):

\[
\frac{q'}{q} = \frac{\sigma \cdot \varepsilon_p \cdot T_2^4}{\sigma \cdot \varepsilon_p \cdot T_1^4}
\]  

(1)
where \( q \) is the heat flux of secondary standard heat flux sensor, \( q' \) is the heat flux of working-standard heat flux sensor, both with units of \( \text{kW/m}^2 \), \( \sigma \) is constant of proportionality in the expression in the Stefan-Boltzmann law for calculating the radiative heat flux from the absolute temperature, which is equal to \( 5.67 \times 10^{-8} \text{ W/(m}^2 \cdot \text{K}) \), \( \varepsilon_p \) is the emissivity of graphite material, \( T_i \) is the temperature of graphite plate mounted secondary standard heat flux sensor, \( T_j \) is the temperature of graphite plate mounted working-standard heat flux sensor, both with units of K.

The equipment is designed based on past experiences, and the equipment is now available to the calibration service, hundreds of sensors calibration so far show good repeatability of the technique with an expanded uncertainty of 3 %, corresponding to a coverage factor of \( k = 2 \).

3. The absolute calibration equipment and performance evaluation

The absolute calibration equipment employs a traceable blackbody radiant source based on a sodium heat pipe blackbody with 50-mm-diam cavities, thus heat flux sensor calibrations are traceable to the temperature standard using the equipment. The sodium heat pipe blackbody transfers heat by internal working medium whose coefficient of thermal conductivity is higher than others. The design provides a uniform temperature distribution along the cavity length of the sodium heat pipe. The recommended operating temperature which is measured by standard platinum-10% rhodium/platinum thermocouple (TYPE-S) for blackbody radiant source is from 600°C to 900°C, through the absolute calibration equipment with an expanded uncertainty of 2%, corresponding to a coverage factor of \( k = 2 \), the maximum flux-level is approximately 140kW/m².

![Figure 3](image1.png)  
**Figure 3.** The axial temperature distribution of blackbody radiant source

![Figure 4](image2.png)  
**Figure 4.** The temperature fluctuation of blackbody radiant source

Figures 3 shows the measured temperature at different distances from the blackbody bottom. The axial temperature distribution becomes more uniform with the temperature of blackbody increasing. The optimum location for the sensor is at a distance of about 100mm from the cavity bottom.

After the blackbody temperature is stabilized at the set value, it is also necessary that the blackbody temperature is stable over the measurement time interval, so measurements are recorded for a period of 0min to 5min at approximately 0.5min intervals using a standard platinum-10% rhodium/platinum thermocouple. The temperature stability is within ±0.2°C of the set temperature shown in Figure 4.

4. The absolute calibration principle
The absolute calibration principle employs in-cavity calibration instruments, using a sodium heat pipe blackbody with 50-mm-diam cavity as blackbody radiant source, thus heat flux sensor calibrations are traceable to the temperature standard.

Heat flux sensors used here are circular foil type and water-cooled. The secondary standard heat flux sensor is extended into the cavity, Hence, the radiation from the blackbody will be close to spherical space radiation, excluding the effect of view factor. Figure 5 shows a schematic layout of the absolute calibration equipment.

According to Stephen Boltzmann's law, shown in equation (2), the standard temperature value is converted into the heat flux value, thus realizing the calibration of heat flux sensor.

\[ q = \sigma \varepsilon_b T_b^4 \]  

where \( q \) is the heat flux of secondary standard heat flux sensor, with units of \( \text{W/m}^2 \), \( \sigma \) is constant which is equal to \( 5.67 \times 10^{-8} \text{ W/(m}^2\cdot\text{K}) \), \( \varepsilon_b \) is the emissivity, \( T_b \) is the temperature of blackbody radiant source, with units of K.

5. Conclusion
This paper focuses on the heat flux sensor calibration techniques, the transfer calibration equipment employs a flat plate furnace to calibrate heat flux sensors, which is not only available to calibration service, but also can implement the comparison experiment between different types of heat flux sensor. Furthermore, the absolute calibration equipment employs a sodium heat pipe blackbody, thus heat-flux sensor calibrations are traceable to the temperature standard, providing reference for heat flux calibration traceability chain.

6. References
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