Simulation and experimental research on the thermal resistance of Cernox sensors in different bonding ways based on a high-precision cryogenic temperature measuring system

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Abstract. The model for measuring thermal resistance according to self-characteristic between the Cernox thin-film sensors and the test sample is established by the precise cryogenic thermostat, and the simulation is as well accomplished by COMSOL solid heat transfer module. Furthermore, thermal resistance comparison experiments using three different mounting mediums, namely GE Varnish 7031, TRA Bond 2115, Apiezon N grease, and one no glue or grease are researched in various cryogenic temperatures and exciting currents. The measuring data and uncertainty are analyzed and corrected by the multi-current method. Depending on the experimental results, the proposal of the sensor installation medium is presented for different cryogenic environments and requirements.

1. Introduction

The thermal effect is generated when the current flows through the thin-film sensor causing a noticeable temperature fluctuation, which cannot be neglected in the cryogenic or high-precision measuring environment. The self-heating effect is closely related to the thermal resistance of sensors. Normally, the thermal resistance of the sensor depends primarily on two components, one of which is derived from the self-characteristic, including the properties of internal structure such as surface roughness and package pressure, the other is between the sensor and surroundings due to the installation ways and mounting medium which is extremely difficult to make an effective calculation as the remounting and the thickness of the medium is hard to be quantified [1].

SS Courts et al [2] described the thermal resistance measurement procedure for a mounted temperature sensor and measured the thermal resistance at 1K~300K. As for an extension of paper [2], Yeager C J et al [3] presented thermal resistances data and analysis for temperatures ranging from 50 mK to 1 K in vacuum on germanium, ruthenium oxide and Cernox resistance temperature sensors. X Zhang et al [4] measured the thermal resistance of the Cernox temperature sensors using a high-precision cryostat with GM- refrigerator and theoretically derived the calculation formula of the uncertainty of thermal resistance. Based on the previous research [4, 5], this paper principally does the following innovative study: (1) COMSOL solid heat transfer module is applied to simulate the temperature change of Cernox sensors and test sample. Moreover, the thermal resistance depending on the properties of the contact surface is simulated and analyzed. (2) Three different mounting mediums
of Cernox are used to investigate the variation of measuring temperature and thermal resistance, which depends on the mounting ways. Furthermore, the multi-current method is used for thermal resistance correction. It should be pointed out that this paper focuses on the difference in thermal resistance of the different mounting medium, nor self-heating effect correction, so that the optimal exciting current is not calculated since it’s out of the content of this paper.

2. Modeling and simulation

2.1 Modeling
Heat flow generated by the excitation current dissipates to the protective cover of the sensor and then enters into the temperature measuring environment, resulting in a temperature difference between the sensor and the measured area, so the measured value $T$ of the sensor is higher than the real value $T_0$ of the temperature of the measured area. Suppose that $R_t$ is the thermal resistance between the sensor and the measured area, then the temperature gradient caused by the self-heating effect of the sensor can be expressed as follows:

$$\Delta T = T - T_0 = QR_t = I^2 RR_t$$  \hspace{1cm} (1) \\
$$R_t = R_{ti} + R_e$$  \hspace{1cm} (2)$$

Where $R_{ti}$ is the target of the COMSOL simulation resulting from internal structure associated with the design of the sensor, $R_e$ is caused by the mounting ways researched in the following experiments.

Cernox sensors are tight adhered together with the groove of an aluminum test sample as shown in Figure 1. The pin and wires of Cernox here are omitted as well as the adhesive which is not contained in the internal structure. According to the texture of material in the installation instructions, the Cernox sensors are simplified to copper blocks which can be seen as a whole with test sample owing to the modeling design. By adding different heat flow caused by applying a series of various exciting currents to the sensors, the transient temperature change of the model could be presented in the heat transfer module. Figure 2 shows a schematic of the resulting simulation domain along with the governing differential equation and boundary condition which are built-in settings in COMSOL. Here Cernox sensors SN67973 and $T=7K$ are presented to be an example as the modeling sensor and surrounding temperature of the test sample. Based on calibration data, heat consumption could be calculated.

![Figure 1. Diagram of Cernox sensors mounting way.](image1)

![Figure 2. Section used as the simulation domain, the governing equations and the boundary conditions.](image2)
Thermal contact research is added to the solid heat transfer module. The contact attributes in the contact surface model are defined. Four parameters including \( p \), \( H_{\text{mic}} \), \( \sigma \), \( m \) are studied by parametric sweep. The physical quantity and reference value of conductivity at the junction are shown in Table 1.

### Table 1. The physical quantity and reference value of conductivity at the junction

| Symbol | Physical quantity | Reference value |
|--------|-------------------|-----------------|
| \( p \) | Pressure          | \((0.1,0.05,1)\) kPa |
| \( H_{\text{mic}} \) | Micro-hardness    | \((0.1,0.05,0.5)\) MPa |
| \( \sigma \) | RMS surface roughness | \((0.01,0.05,0.5)\) \(\mu m\) |
| \( m \) | Mean absolute surface slope | \((0.01,0.01,0.1)\) |
| \( K_s \) | Contact thermal conductivity | Table 1 |
| \( K_{\text{gap}} \) | Gap thermal conductivity | 0.031 W/(m·K) |
| \( Y \) | Mean surface plane separation | - |
| \( M_{\text{gap}} \) | Molecular weighs of the gas | - |
| \( C_1 \) | Vickers micro-hardness coefficient | 6.23 GPa |
| \( C_2 \) | Vickers micro-hardness coefficient | -0.23 |
| \( \sigma' \) | \( \sigma/\sigma_0 \) | \(\sigma_0 = 1 \mu m\) |

#### 2.2 Simulation results and analysis

The thermal resistance determined by different physical quantities is shown in Figure 3. It has to say that compared with the \( R_{te} \) measured in the formal research [2, 3, 4], the shrinkage and gap thermal resistance of \( R_{ti} \) are extremely smaller than the \( R_{te} \) in the order of magnitude, therefore the thermal resistance \( R_t \) could be reduced to \( R_{te} \) which would be researched in the experiments.
3. Experiments

3.1. Experimental apparatus and procedure

The high-precision cryogenic temperature measurement system with GM cryocooler mainly consists of the cryogenic thermostat, temperature measure and control system, and data acquisition system. Based on the previous research [4,5], because the cryogenic thermostat is required to be stable at a certain temperature between 4k~20K, the Polytetrafluoroethylene (PTFE) fixed between the second stage and test sample is used to reduce the temperature fluctuation by 3mK. The auxiliary heating method is adopted and Ni-Cr wire is chosen here as the heating resistance while the Pho/Bronze 4 Cond 36awg twist wires are connected with the sensors.

Figure 4 shows the sensors mounting ways and the wires winding ways. TRA Bond 2115, GE varnish 7031, and Apiezon N grease are used to attach three sensors to one side of the sample, another two sensors with no glue or grease and one additional sensor for temperature control are installed on the other side. In order to guarantee the same amount of usage, a mini-spoon is adopted here to collect the adhesive. No load is applied to the sensors owing to the precise sensing elements, but secured with cryogenic tapes. Heating wires are wound around the upper part of the sample which could reduce the influence on the wires of sensors. The experimental system before assembly is shown in Figure 5.
During the experiments, the temperature of the sample is controlled, stable successively at 4.20 K, 8.54 K, 12.73 K and 16.15 K at least one hour, then we set the excitation current of the sensors and record the resistance data in 1594 A thermometer. At 16.15 K measuring point, 100 μA, 150 μA, 200 μA, 250 μA, 300 μA, and 350 μA are arranged to be the exciting current owing to the negative temperature coefficient of Cernox resistance sensors while the smaller excitation currents 10 μA, 20 μA, 40 μA, 60 μA, 80 μA and 100 μA are selected for the other temperature zones. After recording one group of data for about one hour, the next exciting current will be modified and recorded. The data of the last 40 minutes of each hour will be adopted as the final experimental data. In this way, each sensor will have about 400 resistance data at the same temperature and excitation current which meets the requirements of the Bessel method.

3.2. Experimental results and discussion

Figure 6 below presents the average measured temperature and the difference of average temperature increasing under different exciting currents. It can be derived that the average temperature increasing difference of X141257 with no grease becomes much higher along with the increase of exciting currents. Under three adhesives, the measured temperature of TRA-Bond is comparatively lower than the others at 4.2K. However, when at the higher region, it climbs larger than the other adhesive in which the best performance is Apiezon N grease.
Figure 6. Average measured temperature and difference of average temperature increasing under different exciting currents

To eliminate the influence of exciting current selection on the calculation results, the multi-current method is adopted to calculate and modify the thermal resistance. The formula can be written as:

$$R_t = \frac{n \sum_{i=1}^{n} I_i^2 R_i - \sum_{i=1}^{n} T_i \sum_{i=1}^{n} I_i^2 R_i}{n \sum_{i=1}^{n} I_i^4 R_i^2 - \sum_{i=1}^{n} T_i R_i \sum_{i=1}^{n} I_i^2 R_i} \quad (3)$$

Matlab programming is used to calculate the above equation, and contact thermal resistance at different measurement temperatures could be obtained. The calculated results are shown in Figure 7 below. With the increase of temperature, the thermal resistance obviously becomes lower, which means that the situation of the measured contact surface has improved. It’s mainly because the thermal expansion and cold contraction of the material would cause the surface material, thermometer package surface material, and installation medium inflate at higher temperatures. Thus the condition of the contact area between the sensors and the measured region becomes better.

Under four different temperatures, the thermal resistance of the sensors with no adhesive is much larger than the other sensors, where the disparity is about 10 orders of magnitude. The thermal resistance of TRA-Bond 2115 is evidently smaller than 7031 and N grease. The advantage is more prominent when the temperature is lower while it still has superiority when the temperature is higher.

What could be found in the process of the installation and removal of sensors is that the Apiezon N grease only has a slight viscosity at room temperature, which needs to be fixed with auxiliary measures, but it can mount the sensors under cryogenic temperature along with curing. GE Varnish 7031 will be solidified in a short period of time at room temperature, but the strength is not enough, and it will be cleared immediately after soaking with ethyl alcohol. The curing time of TRA-Bond 2115 at room temperature is 24 hours, and it belongs to the permanent installation in which the cured hardness is very high. Furthermore, it could be concluded that GE Varnish 7031 and TRA-Bond 2115 in different temperature zones have good thermal contact conditions suitable for permanent installation. Apiezon N grease is adapted to where additional fixing measures could be used and remounting is needed. GE Varnish 7031 at room temperature can also mount sensors well and could be removed by using organic solvents. Hence, it’s applied to the situation that can't add additional fixed measures and needs remounting.
4. Summary
This paper established the measurement model of thermal resistance of internal structure based on COMSOL and deployed thermal resistance contrast experiments of different mounting ways of Cernox sensors. Based on the corrected results, TRA-Bond 2115 is relatively optimal in reducing thermal resistance under different temperature regions.

5. References
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