# Research on dynamic error compensation for an armored K type thermocouple

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**Abstract**: A new method was proposed, in which a high-power $CO_2$ laser modulated by high frequency was used as the driving source to heat up a surface-temperature sensor. The continual beam and the pulsed beam sent out by the same laser could be used in the same system to carry on the static calibration of the radiation thermometer and the dynamic calibration of the temperature sensor to be checked. The frequency-response characteristics of high-speed radiation thermometer surpassed that of the temperature sensor, therefore it could be used as the reference value to calibrate the latter and let system error be corrected. Differences in the environment of the sensor installing and the error caused by the change of thermo-physical property could be avoided. Thus, the difficult problem of traceable dynamic calibration of temperature was solved. In experiment, to obtain the frequency characteristics of the thermocouple and the dynamic performance of the K type thermocouple, which could compensate the dynamic characteristics of the sensor, the sensor was dynamically corrected by using the method, and then the mathematical model was established.

**Key words**: thermocouple; surface-temperature; dynamic calibration; error compensation; traceability

**CLD number**: TN248.4 **Document code**: A
**Article ID**: 1674-8042(2014)04-0010-06 **doi**: 10.3969/j.issn.1674-8042.2014.04.003

## 0 Introduction

In a dynamic temperature test, due to the thermal inertia and finite heat conduction of heat responsive element in a temperature sensor, the real change of the measured temperature field could be responded quickly in the measurement system. The high-frequency components of the measured temperature signals were filtered, and the steep parts of temperature variation curves were replaced by smooth curves, therefore, dynamic errors arose.

To study dynamic response characterists of various temperature sensors, the temperature signals which changed quickly were used for thermocouple dynamic response error compensation, and the measured temperature results were corrected approximating to the real temperature signles, thus dynamic response error was reduced[1]. Traceability was a process that measurement instruments or measured values which were displayed on the measurement system could be traced back to national standard by certain measurement uncertainty and a series of calibrations. The effectiveness of measurement results could be verified by traceability[2].

## 1 Composition of dynamic calibration system

The composition of the designed dynamic calibration system is shown in Fig. 1 The radiation thermometer (infrared detector) and calibrated temperature sensor were placed on two conjugate foci of the optical focusing system. The thermal shield placed between the radiation thermometer and the calibrated temperature sensor could be used to avoid thermal radiation conduction. The optical focusing system was a reflector which was plated with metal coatings such as gold, silver and aluminum on the front of spherical glass substrate to increase the reflectance of infrared radiation. A hole for laser heating pulse with the aperture being not less than

* **Received date**: 2014-06-11
**Foundation item**: Research Project Supported by Shanxi Scholarship Council of China (No. 2012-068); Taiyuan Science and Technology Agency (No. 120247-20); Surface-temperature Sensor Dynamic Measurement and Calibration Technology Research of National Defense Fundamental Scientific Research
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3 sr was opened on the spherical glass substrate to make sure that the laser could be collected effectively through a fixed angle.

In Fig. 1, the radiation thermometer was a photoconductive Hg-Cd-Te infrared detector. The sensitive wavelength ranges from 3 μm to 5 μm, corresponding to the maximum radiation wavelength of surface-temperature range in most cases. To make full use of the energy of high power laser, the total reflection mirror and the collecting mirror were fixed to collect the laser energy which was input to the calibrated sensor finally. To heat the rapid-response surface temperature sensor being calibrated to high temperature instantly, the heating source should have enough power and ability of high-frequency modulation. DIAMOND K-500 Laser by Technology of Coherent Inc., Laser Manufacturing Company had been used as the heating source to achieve the dynamic calibration of temperature sensor[3]. The related parameters are as follows: power range, 25 − 500 W; peak effective range, 250 − 1 500 W; pulse frequency, 0 − 100 kHz.

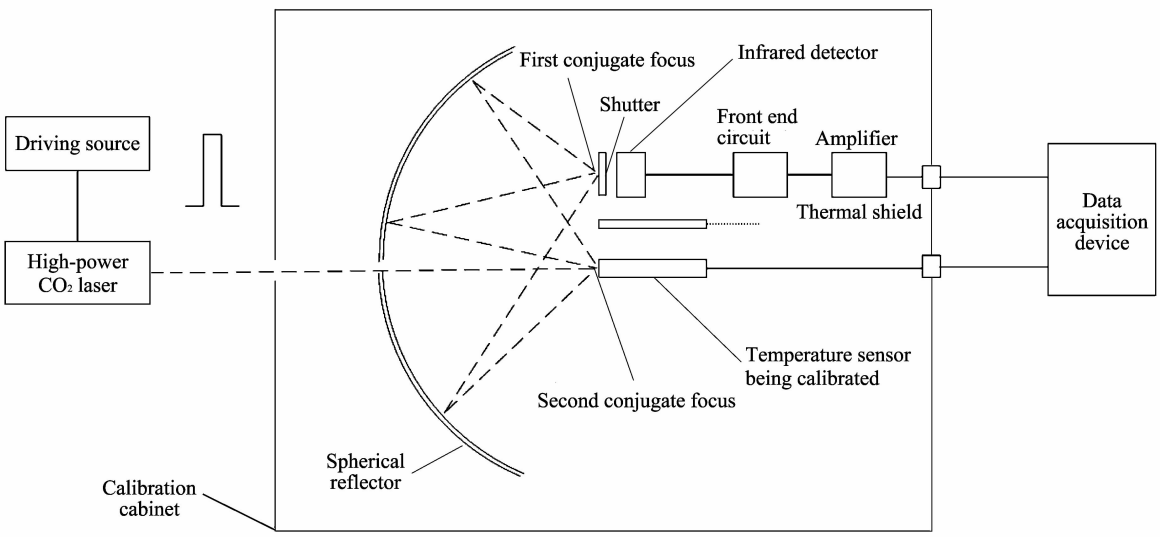



**Fig. 1 Composition of dynamic calibration system**

In addition, in order to reduce external interference from the laser source the other electromagnetic devices to the signal modulation circuit and recorder, the calibration system was shielded by the calibration cabinet and grounded well to ensure the accuracy of traceable dynamic calibration.

## 2 Dynamic calibration process

There were three steps for traceable dynamic calibration of the temperature sensor[4]:

1) Static calibration of temperature sensor;
2) Static calibration of radiation thermometer;
3) Dynamic calibration of temperature sensor.

The traceability of temperature calibration could be ensured by the first two steps. International temperature scale could be conducted from the standard thermocouple to the temperature sensor being calibrated, and then to the radiation thermometer.

### 2.1 Static calibration of radiation thermometer

First of all, the calibrated sensor was calibrated by the standard thermocouple in a thermostatic oven, and the temperature-voltage curve of the calibrated sensor cen be seen in Fig. 2. Then the calibrated sensor and the radiation thermometer were placed on two conjugate foci of spherical reflector, the surface of the calibrated temperature sensor was irradiated for a certain period of time by continuous laser from DIAMOND K500 Laser. The surface temperature rose after absorbing heat transferred inward and the temperature data were collected. Thermal infrared radiation from the surface of the calibrated temperature sensor focused on the radiation thermometer through the spherical reflector at the same time. In the case of thermal equilibrium, radiation focusing signal could be received by the radiation thermometer at the moment of shutter opening. The voltage output of the radiation thermometer was recorded and the corresponding relationship of the voltage output between the surface-temperature and the radiation thermometer was obtained. Thus, the static calibration of the radiation thermometer was completed. The voltage amplitude was recorded and the corresponding voltage output of the radiation thermometer was obtained through opening the shutter when the output of the laser pulse width was reset and the temperature was stable again. The static calibration data of the radiation

thermometer in a certain temperature range could be obtained through repeating the process[3].

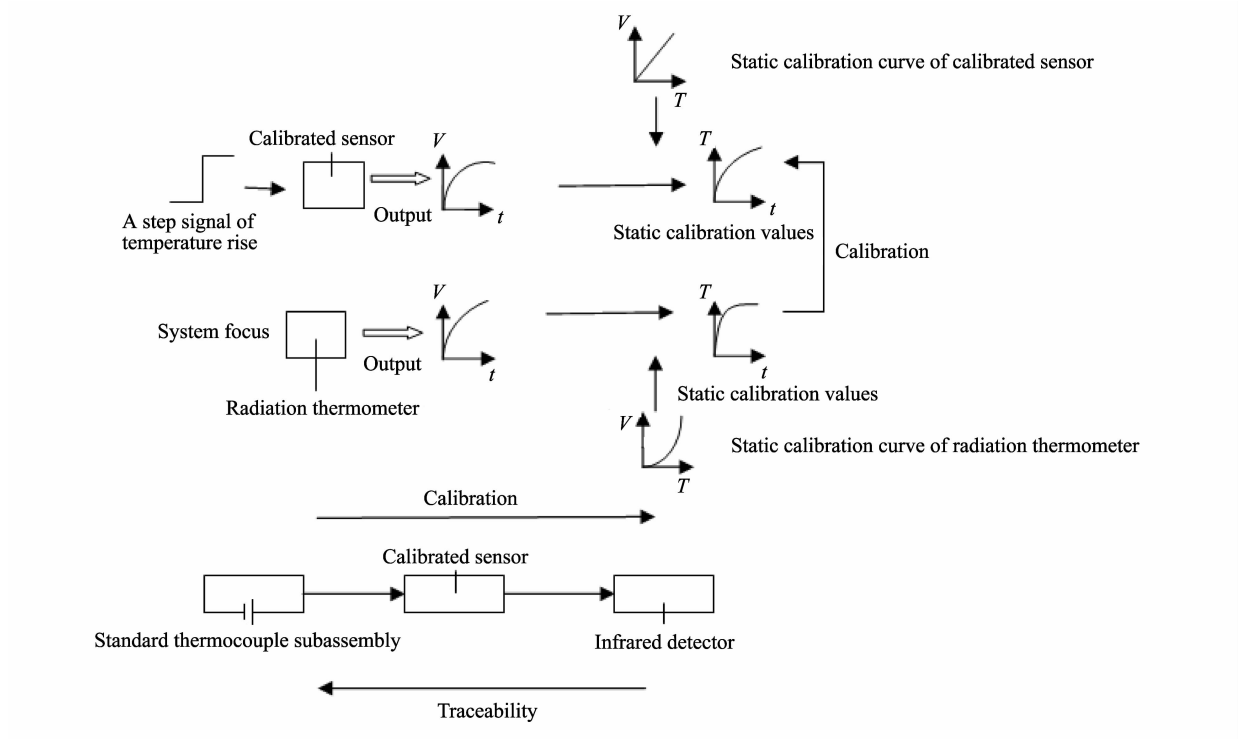



**Fig. 2 Dynamic calibration process**

## 2.2 Dynamic Calibration of a K type thermocouple

The calibrated K type thermocouple and Hg-Cd-Te radiation thermometer were placed on the two conjugate foci, as shown in Fig. 1. They were driven by a step signal of temperature rise irradiated by DIAMOND K-500 $CO_2$ laser. The output curve of temperature variation is shown in Fig. 3. The frequency band of the calibrated thermocouple could be covered by the frequency band of Hg-Cd-Te radiation thermometer, therefore, the experimental conditions of the dynamic calibration could be satisfied absolutely.

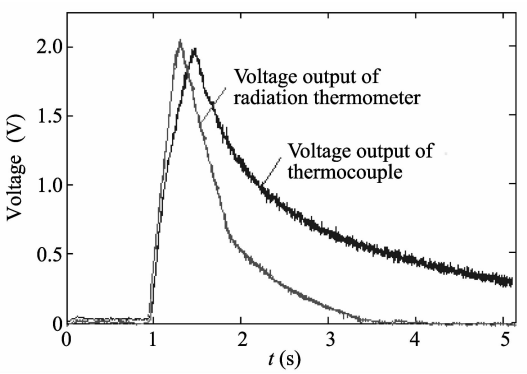



**Fig. 3 Outputs of thermocouple and radiation thermometer**

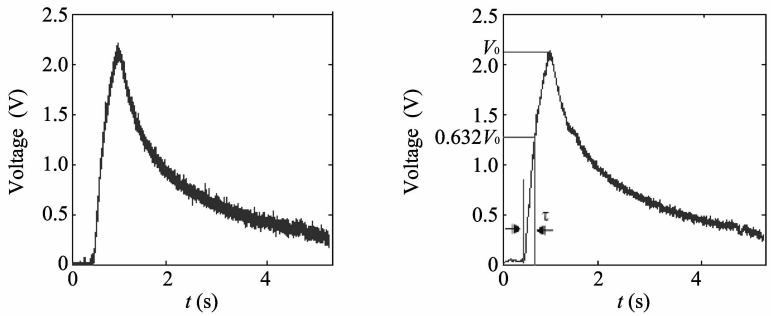
### 2.2.1 Pretreatment of the experimental data obtained dynamic calibration

In the dynamic calibration experiment, the temperature signal measured by the thermocouple could be influenced by the electromagnetic interference in varying degrees, so the measurement data should be dealt with based on noise reduction method through wavelet transform. The different results could be obtained through analyzing the same signal based on various wavelet bases in practical noise reduction application. Thus, the selection of optimal wavelet basis was crucial. In non-stationary signal processing, the wavelet basis of dbN and coifN worked well in the aspect of noise reduction[5]. Orthogonal wavelet db3 with phase shift was chosen. The 's' soft threshold and the voltage output curves of thermocouple were obtained respectively before and after the wavelet noise reduction process through decomposing the signal into three wavelet layers. The spikes and mutational parts of the signal with noise were filtered by wavelet noise reduction process and then the curve became smoother, as shown in Fig. 4. The time constant of the thermocouple approximates 0.186 s, and the temperature gradient was about 600 ℃[6].

### 2.2.2 Dynamic error compensation and software simulation

The output signal of Hg-Cd-Te radiation thermometer was regarded as the input, and the output

signal of the thermocouple temperature sensor as the output. The parameter model of the calibrated sensor was obtained, whose amplitude-frequency curve is shown in Fig. 5[7].




(a) Before wavelet noise reduction (b) After wavelet noise reduction

**Fig. 4 Wavelet noise reduction for output of thermocouple**

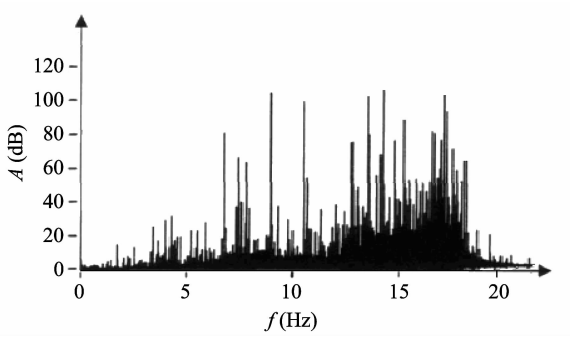



**Fig. 5 Amplitude-frequency curve of K type thermocouple**

The parameter model of the system was complex due to irregularity of the amplitude-frequency curve, and the particular parameter model was hardly gained by system identification method. Therefore, the dynamic characteristics of the sensor were compensated by using Matlab.

The static calibration data of the infrared detector were carried out in Matlab based on three-polynomial fitting of the least square, the fitting formula of the temperature changing with the voltage is

$$T = 7.327 \times 10^{-6} X^3 - 1.012\,78X^2 + 7.567\,8X - 841.24. \tag{1}$$

The principle of dynamic error compensation is that a larger amplification coefficient part and a temperature-sensitive element constitute a series circuit in high-frequency area to expand the pass band of the whole system[8-11].

According to the principle of dynamic error compensation and the characteristics of thermocouple temperature sensor, the dynamic error of thermocouple temperature sensor could be compensated and the flow chart is shown in Fig. 6.

In Fig. 6, first, the laser signal is emitted to the measurement system, and the calibrated thermocouple temperature sensor is radiated by the laser, thus the input signal $x(t)$ and the output signal $y(t)$ of the calibrated thermocouple temperature sensor are obtained.

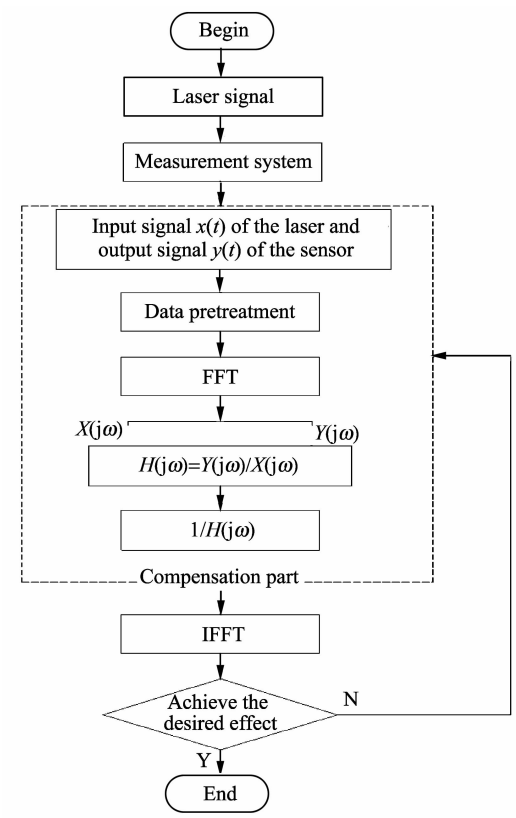



**Fig. 6 Flow chart of dynamic error compensation**

After $x(t)$ and $y(t)$ are transformed with fast Fourier transformation (FFT) algorithm, the system frequency response function $H(\mathrm{j}\omega)$ can be gained by $H(\mathrm{j}\omega) = \dfrac{Y(\mathrm{j}\omega)}{X(\mathrm{j}\omega)}$, where $\dfrac{1}{H(\mathrm{j}\omega)}$ is regarded as a compensation part, which is calibrated constantly according to the actual requirements. And then the compensated output signal is transformed with inverse FFT (IFFT) algorithm. If the output

signal corresponds to the expected results, the dynamic error compensation will be finished. Otherwise, the output signal needs to be compensated again until they satisfy the expected results. Finally, the dynamic characteristic calibration of the sensor system can be achieved through Matlab in the whole process of compensation. The results show that the temperature signal measured by Hg-Cd-Te radiation thermometer is almost equal to the input signal of the calibrated thermocouple temperature sensor in the experiment. The voltage output curves of the thermocouple before and after dynamic compensation are shown in Fig. 7.

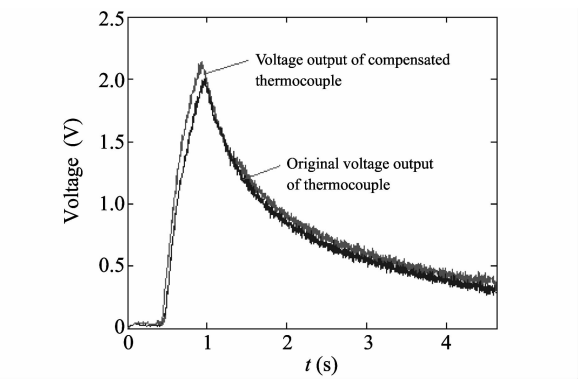



**Fig. 7 Comparison of voltage output curves of the thermocouple before and after dynamic error compensation**

2.2.3 Dynamic calibration experimental data analysis

Compared with the Hg-Cd-Te radiation thermometer, the response speed of the calibrated K type thermocouple was slower and its temperature signal amplitude was lower, but the indicators of the calibrated K type thermocouple could ensure the requirements of measurement. In order to enhance the response speed and temperature signal amplitude, aiming at the situation of the dynamic response characteristics being non ideal, the dynamic response characteristics of the calibrated K type thermocouple could be compensated by software simulation.

In Fig. 7, by comparing the original output curve of the thermocouple with the output curve of the radiation thermometer in Fig. 3, it can be seen that the peak voltage of the thermocouple was 1.98 V, the temperature was 480 ℃ and the rise time was 96.7 ms. After the compensation, the peak voltage of the thermocouple was 2.23 V, the temperature was 540 ℃ and the rise time was 89.9 ms. The rise time, temperature and amplitude appeared in the voltage output curve of the compensated thermocouple were improved. It indicates that the compensation method chosen is feasible.

## 3 Conclusion

1) The traceable dynamic calibration method for the temperature sensor was proposed. It is reasonable and important for the measurement of rapid-response surface temperature.

2) The high-power laser modulated by high-frequency with pulse rise time of 72 μs and pulse wavelength of 10.6 μs was used as the driving source. The output of the radiation thermometer was regarded as the output of the sensor, and the output of the temperature sensor was regarded as the system output. Subsequently, the system function of the calibrated temperature sensor was obtained. The dynamic characteristic of the calibrated temperature sensor was compensated or calibrated by IFFT algorithm. The more real original signal was gained, and better traceable dynamic calibration was achieved.

3) The thin diameter thermocouple, of which the thermo wire diameter was less than 0.1 mm, was used more frequently in the dynamic temperature measurement. The thermo wire was thin to ensure the dynamic response characteristics, and the thermo wire was always broken under the influence of vibration, high temperature, corrosion, etc., so the thermo wire diameter was always limited. This problem can partly be solved through dynamic compensation, and relatively rapid temperature variation could be measured by using the thicker thermo wires.

4) The dynamic compensation amplified the high-frequency parts attenuated by the temperature-sensitive element and recovered by the compensation part, so the high-frequency parts almost attenuated to zero by the temperature-sensitive element were not compensated. In addition, the attenuated high-frequency signal amplitudes were too weak to recover and they were influenced by the factors of interference, noise, etc, so the dynamic compensation range was limited.

## References

[1] Eke R, Kavasoglu A S, Kavasoglu N. Design and implementation of a low-cost multi-channel temperature measurement system for photovoltaic modules. Measurement, 2012, 45(6): 1499-1509.

[2] Zimmerschied R, Isermann R. Nonlinear time constant estimation and dynamic compensation of temperature sensors. Control Engineering Practice, 2010, 18: 300-310.

[3] JIA Xiao-wen. The research of optical dynamic calibration technology of temperature sensor which was based on $CO_2$ laser and the reflective surface of off-axis parabolic. Master thesis. Taiyuan: North University of China, 2011.

[4] Keskin M, Kantar E. Dynamic compensation temperatures in a mixed spin-1 and spin-3/2 Ising system under a time-dependent oscillating magnetic field. Journal of Magnetism and Magnetic Materials, 2010, 322 (18): 2789-2796.
[5] Ramana-Murthy C V, Parveen S. Heat and mass transfer in free convection flow past an oscillating plate in porous media. International Journal of Mathematics, 2011, 2 (4): 602-609.
[6] Chamarthy P, Garimella S V, Wereley S T. Measurement of the temperature non-uniformity in a microchannel heat sink using microscale laser-induced fluorescence. International Journal of Heat and Mass Transfer, 2010, 53(15/16): 3275-3283.
[7] Ewinger A, Rinke G, Urban A, et al. In situ measurement of the temperature of water in microchannels using laser Raman spectroscopy. Chemical Engineering Journal, 2013, 223: 129-134.
[8] CHEN Shu-yue, CHENG Rong. Research on temperature measurement by X-ray transmission intensity. Nuclear Instruments and Methods in Physics Research Section B, 2013, 296: 61-65.
[9] Zhang Y F, Chan C C, Sun J. Enhancement of temperature measurement by using photonic bandgap effect. Sensors and Actuators A, 2010, 157(2): 276-279.
[10] Hattori K, Baba J, Mori M, et al. Shibuya. Dimensional temperature measurement on YBCO thin film during S/N transition period by use of $RuO_2$ chip resistor. Physics Procedia, 2012, 36: 1236-1241.
[11] SUN Yi-peng, CHUN Lou, ZHOU Huai-chun. A simple judgment method of gray property of flames based on spectral analysis and the two-color method for measurements of temperatures and emissivity. In: Proceedings of the Combustion Institute, 2011, 33(1): 735-741.

# 铠装 K 型热电偶动态响应误差补偿研究

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**摘　要:** 提出了一种利用同一可高频调制的高功率 $CO_2$ 激光器发出的连续激光和脉冲激光作为激励热源, 在同一系统中进行辐射温度计(红外探测器)静态校准和被校表面温度传感器动态校准的新方法, 由于高速辐射温度计的频率响应特性优于被校温度传感器, 因此以前者的响应作为真值来校准后者并获取系统误差的修正值, 避免了因传感器安装环境差异及热物性的变化所产生的误差, 解决了表面温度传感器动态校准的溯源难题。利用该方法对 K 型热电偶进行了动态校准实验, 建立了数学模型, 获得了该热电偶的频率特性和动态性能指标, 对该传感器的动态特性进行补偿。

**关键词:** 热电偶; 表面温度; 动态校准; 误差补偿; 溯源

**引用格式:** HAO Xiao-jian, XING En-pu, ZAN Qing-bo, et al. Research on dynamic error compensation for an armored K type thermocouple. Journal of Measurement Science and Instrumentation, 2014, 5(4): 10-15. [doi: 10.3969/j.issn.1674-8042.2014.04.003]