Accuracy Advancement of Non-Contact Temperature Measurement with Differential Technology

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Abstract. Generally, accuracy of non-contact temperature measurement is not high because of the effects of ambient temperature and surface thermal emissivity of measured target. Differential measurement technology is measuring both temperature of a reference target and a measured target with the same temperature measurement device. As ambient temperature, rays and surface thermal emissivity of heating unit have nearly the same effects on two targets, actual measurement error of reference temperature actual value can be used to correct temperature error of measured target. When working environment of reference target and measured target are basically the same, differential measurement can eliminate most measurement error caused by environmental factors. This method is mainly used in non-contact temperature measurement requiring high accuracy.

1. Introduction

Compared with other methods, non-contact temperature measurement shows great advantage in its high measuring speed, in addition, measurement is beyond the limit of the measured target's working state. Therefore, non-contact measurement is widely applied to temperature measurement of special condition, such as dynamic object, far-distance object, high-temperature object, flash temperature, etc, as in [1-4]. However, many factors such as ambient temperature, ambient light, ambient reflection, heating feature and surface thermal emissivity of heating unit (degree of blackbody) can affect measurement, so the accuracy is largely affected by measuring time, measuring situation, weather environment and measuring skills. Though some new temperature measuring methods and environment compensating measures are taken in non-contact temperature measurement device, as in [3-5], its measurement accuracy of long-time working is still not high. For measurement requiring high accuracy of continuous working, ordinary non-contact radiation measurement device cannot satisfy measurement requirement.
2. Basic principle of differential non-contact temperature measurement

2.1. Basic Principle

Principle of differential non-contact temperature measurement introduced in this paper is as follows: choose a reference temperature actual value \( T_r \) that can be measured accurately by contact method, then measure the reference temperature \( T_r \) with non-contact method and obtain the reference temperature observation value \( T_r^* \). Thus, relative linear error observation \( \Delta T_r^{rl} \) and absolute equivalent observation error \( \Delta T_r^{ae} \) produced in the non-contact measurement process can be calculated through reference temperature actual value \( T_r \) and reference temperature observation value \( T_r^* \). Then use relative linear observation error \( \Delta T_r^{rl} \) and absolute equivalent observation error \( \Delta T_r^{ae} \) of reference temperature actual value to correct target temperature observation value \( T_t^* \), and obtain target temperature actual value \( T_t \). Figure 1 shows basic principle of non-contact temperature measurement by differential method, and it also shows relative relationship of reference temperature actual value \( T_r \), target temperature actual value \( T_t \), reference temperature observation value \( T_r^* \) and target temperature observation value \( T_t^* \).

It should be pointed out: reference temperature observation value \( T_r^* \) and target temperature observation value \( T_t^* \) are obtained by non-contact method and contain error caused by environment and radiation blackbody, while reference temperature actual value \( T_r \) is obtained by contact method and is of higher accuracy. Moreover, in order to decrease measurement error, working environment and surface thermal emissivity of reference target is similar to that of the measured target.

In the measuring process, reference temperature actual value \( T_r \) and target temperature actual value \( T_t \) are measured separately by the same non-contact temperature measurement device. As reference temperature actual value \( T_r \) is known, when reference temperature observation value is \( T_r^* \), absolute equivalent observation error of reference temperature actual value measurement is:

\[
\Delta T_r^{ae} = T_r - T_r^*
\]  

Relative linear observation error of reference temperature actual value measurement is:

\[
\Delta T_r^{rl} = \frac{\Delta T_r^{ae}}{T_r}
\]  

Absolute equivalent observation error \( \Delta T_r^{ae} \) and relative linear observation error \( \Delta T_r^{rl} \) obtained from (1) and (2) are not caused only by measuring environment and surface thermal emissivity of the target, and actually, they are integrated observation error \( \Sigma \Delta T_r^{ae} \) and \( \Sigma \Delta T_r^{rl} \). Similarly, when the same non-contact measurement device and method is applied to the measured target, the corresponding absolute equivalent observation error \( \Delta T_t^{ae} \) and relative linear observation error \( \Delta T_t^{rl} \) are necessarily produced. So, target temperature observation value \( T_t^* \) also contains component of absolute equivalent observation error \( \Delta T_t^{ae} \) and relative linear observation error \( \Delta T_t^{rl} \). According to differential principle, target temperature actual value \( T_t \) can be calculated by eliminating \( \Delta T_t^{ae} \) and \( \Delta T_t^{rl} \) from \( T_t^* \). In the correction process, absolute equivalent observation error \( \Delta T_t^{ae} \) and relative linear observation error \( \Delta T_t^{rl} \) of reference temperature actual value are essentially different. Actually, in
any measurement system, absolute equivalent observation error $\Delta T_{ae}$ and relative linear observation error $\Delta T_{rl}$ exist in component form. That is to say, any measurement error contains component of absolute equivalent observation error and relative linear observation error. Therefore, when making corrections for target temperature actual value, calculus of differences should be carried out based on reasons causing measurement error. Generally, the following correction formula is applied.

$$T_i = T_i^* + \frac{T_i^*}{T_i} \Delta T_{ae} (1 - \alpha) + \Delta T_{rl} \times \alpha$$

(3)

Solving (3), obtain,

$$T_i = \sqrt{(T_i^* + \Delta T_{ae} \times \alpha)^2 + 4T_i^* \times \Delta T_{rl} \times (1-\alpha)/2} + (T_i^* + \Delta T_{ae} \times \alpha)/2$$

(4)

Here, $\alpha$ is weight coefficient of correction for absolute equivalent error and relative linear error, and its value is $0 \leq \alpha \leq 1$. The value of $\alpha$ should be determined according to environment situation. If the value of $\alpha$ is big, absolute equivalent observation error is the main composition. Otherwise, relative linear observation error is the main composition. In (3) or (4), $\Delta T_{ae} \times \alpha$ corrects absolute equivalent observation error, while $T_i^*/ T_i \Delta T_{rl} \times (1-\alpha)$ corrects relative linear observation error.

2.2. Single Observation Error and Average Observation Error

It should be pointed out: absolute equivalent observation error $\Delta T_{ae}$ and relative linear observation error $\Delta T_{rl}$ obtained from (1) and (2) are errors of single measuring result. Therefore, target temperature actual value $T_t$ calculated by (3) or (4) is also single measuring result. But in actual application, multiple measuring of reference temperature actual value $T_r$, observation value $T_r^*$ and $T_t^*$ is usually carried out. Thus, reference temperature observation average value $\overline{T_r}$, target temperature observation average value $\overline{T_t}$ and reference temperature actual average value $\overline{T_r}$ can be obtained after corresponding data processing. As accuracy of reference temperature observation average value $\overline{T_r}$, target temperature observation average value $\overline{T_t}$ and reference temperature actual average value $\overline{T_r}$ is higher than that of their respective corresponding value of single measuring $T_r^*$, $T_r^*$ and $T_r$, absolute equivalent average error $\overline{\Delta T_{ae}}$ and relative linear average error $\overline{\Delta T_{rl}}$ are obtained by substituting $\overline{T_r}$ and $\overline{T_t}$ for $T_r^*$ and $T_t^*$ in (1) and (2). Then target temperature actual average value $\overline{T_t}$ can be obtained by substituting $\overline{\Delta T_{ae}}$, $\overline{\Delta T_{rl}}$ and $\overline{T_r}$ for $\Delta T_{ae}$, $\Delta T_{rl}$ and $T_r^*$. In theory, accuracy of target temperature actual average value $\overline{T_t}$ is higher than that of target temperature actual value $T_t$ of single measuring.

2.3. Processing of Observation Error

Temperature change is slow, while temperature measuring process is quick, so more observation values can be sampled when measuring temperature parameter. This is the characteristic of temperature measurement. According to error theory, average error $\overline{\Delta T}$ of temperature observation values is related to observation times $n$, that is to say, temperature average error $\overline{\Delta T}$ is small with big $n$. This paper only takes average value algorithm for example to describe data processing method. Average value of $n$ times temperature observation values is calculated by arithmetic average method as follows:

$$\overline{T} = \frac{1}{n} \cdot \sum_{i=1}^{n} T_i$$

(5)

Temperature error $\overline{\Delta T}$ of temperature average value $\overline{T}$ obtained from formula (5) is related to value $n$ and random error distribution density function. According to random error distribution density function of Gaussian error equation:

$$f(t) = \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot e^{-\frac{1}{2} \left( \frac{\Delta T}{\sigma} \right)^2}$$

(6)
Where, $\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (T_i - \bar{T})^2}$, $\sigma$ is standard error of measurement system, and $\triangle T_i$ is error of some observation value. Equation (6) is correct when value $n$ is big, that is to say, the credibility of (6) is related to $n$. Observation error is small when $n$ is big through (6), thus distribution density of random error becomes big. It represents observation value is close to actual value. According to analysis above, distribution density of random error is big when standard error is small, and it represents observation value becomes concentrated.

3. Basic methods of differential non-contact temperature measurement

In order to implement differential temperature measurement, simulated reference temperature $T_r$ and measured target temperature $T_t$ should be measured at the same time with $T_r'$ and $T_t'$ as measured results. According to measurement principle and real-time requirement, double temperature detectors and single temperature detector can be used in non-contact differential temperature measurement.

3.1. Non-contact differential measurement with double temperature detectors

Principle of non-contact differential measurement with double temperature detectors is shown in figure 2. Actual measurement reference temperature $T_r$ and measured target temperature $T_t$ are obtained by using T—Detector-1 and T—Detector-2 to separately measure simulated reference temperature $T_r'$ and measured target temperature $T_t'$. Accurate simulated reference temperature $T_r$ is obtained from T—Transducer. The processing, correction and compensating of $T_r'$, $T_t'$ and $T_r$ are finished by temperature processing and compensating unit. Detectors can focus on measuring points of measured objects well due to stillness of T—Detector-1 and T—Detector-2 by non-contact differential measurement method with double temperature detectors. As a result, measurement accuracy of $T_r'$ and $T_t'$ is relatively higher. However, performance indexes of T—Detector-1 and T—Detector-2 must be very similar when using this method, in addition, the cost of device using two detectors is relatively higher.

![Figure 2. Principle of non-contact difference measurement with double temperature detectors.](image)

3.2. Non-contact differential measurement with single-temperature detector

Principle of non-contact differential measurement with single temperature detector is shown in figure 3. Actual measurement reference temperature $T_r$ and measured target temperature $T_t$ are alternately obtained by using swinging T—Detector to separately measure simulated reference temperature $T_r$ and measured target temperature $T_t$. The function of T—Transducer, temperature processing and compensating unit is similar to the function when using double temperature detectors. But temperature processor is required to send swing control signals to T—Detector and make the measured $T_r$ and $T_t$ synchronous with swing process of T—Detector. Performance error of detectors is eliminated by non-
contact differential measurement method with single temperature detector. Also the cost of temperature measurement is relatively lower. However, focus error and synchronous problem between swing and measurement exist when using this method.

![Diagram of non-contact differential measurement with single temperature detectors.](image)

**Figure 3.** Principle of non-contact difference measurement with single temperature detectors.

T—Detector: Temperature Detector, T—Transmitter: Temperature Transmitter

4. Conclusion

This paper puts forward a non-contact differential temperature measurement method to improve accuracy. The method eliminates most measurement error introduced by ambient factors after differential correction of measured target. Non-contact differential temperature measurement can eliminate 50%~80% of errors introduced by ambient factors after dealing with several key questions above.

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