Modelling and infrared radiation compensation for non-contact temperature measurement

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Abstract. Beyond the conventional non-contact temperature measurement with ambient temperature compensation and our previous work of multi-sensors compensation, two compensation schemes are proposed and compared. An infrared radiation measurement module with several temperature sensors are built and calibrated with ambient compensation to investigate the dynamic temperature distribution under moving of module from one place to another. The new approach we proposed including the infrared radiation exchanges model between the target, sensor and the optical path thorough temperature monitoring and two fast temperature measurement schemes with dynamic compensation. After careful calibrations and verification of several experiment conditions, our models of two dynamic compensation schemes both show an excellent agreement with the measuring data. The experimental data of compensation scheme reach a stable reading value of target temperature down from 40 min to 2 min for the differential scheme compensation and 6 min for multi-sensors scheme compensation with temperature error around 0.2 °C.

1. Introduction

Temperature plays a significant role as an indicator of the condition both in manufacturing, quality control and medical diagnosis. We can divide temperature sensor into two types for contact temperature sensor and non-contact temperature sensor. Among different kinds of temperature measurement devices, thermopile-type and infrared thermometers for non-contact temperature measurement are highly developed sensors. Everything above the absolute zero produces infrared radiation, a phenomenon known as thermal radiation. So far, infrared sensing technology has been utilized successfully in industrial processing and research. Thermopile sensor and focusing lens are used to measure the temperature of high-voltage switch contactors as a security device [1]. Furthermore, freely-suspended micro channels with integrated thermopiles has been used to make a highly-sensitive thermal flow sensor with ambient temperature-gradient compensation [2]. Thermopile has the features of linear thermoelectric signal transduction and low sensing range limit make it attractive for many low-cost commercial application products [3-6].

Conventionally, the infrared thermometer is operated under a stable state. While the ambient temperature will change, it causes a drawback of measurement for many infrared instruments under this thermal non-equilibrium state. It should take a long time to wait for ambient temperature to achieve stability with infrared instruments. To overcome this drawback, we have to consider the thermal radiation between the target, surrounding and ambient under this non-equilibrium state.
2. Theory and modelling

2.1. Principles of infrared temperature measurement

The source of thermal radiation is the thermal motion of charged particles. The thermal motion will produce thermal which will be converted into the energy form of electromagnetic radiation. That means thermal radiation can exchange heat without medium and without contact. There are many radiation laws that describe the basic characteristics of thermal radiation. The basic characteristics of blackbody radiation describes the heat radiation frequency depends on the temperature of the object. Planck's Law describes every object emits radiation at all times and at all wavelengths. Besides, Planck's Law mentions the relationship between emissivity and frequency of electromagnetic radiation emitted by a black body at different temperatures. The Stefan-Boltzmann Law states that the total amount of energy per unit area emitted by an object is proportional to the 4th power of the temperature. We can derive the radiation equilibrium relationship for non-contact temperature measurement based on these theories.

We propose two novel infrared compensation schemes, one for check the exchange of infrared radiation between the surrounding environment and sensor, the other for verifying the temperature difference of thermopile sensor under thermal non-equilibrium state. In the new proposed non-contact temperature measurement model, there are several temperature-monitoring sensors include the temperature of blackbody, surrounding environment and thermopile sensor at ambient temperature which are denoted as $T_b$, $T_s$ and $T_a$. The infrared radiation exchanges between blackbody and thermopile sensor is denoted as $\Phi_{ba}$ and $\Phi_{ab}$, while the exchanges between surrounding environment and thermopile sensor is denoted as $\Phi_{as}$ and $\Phi_{sa}$. The infrared radiation exchange relationship are shown in figure 1.

![Figure 1. Infrared radiation exchange between target, environment and sensors.](image)

2.2. Mathematical model of radiation exchange

To build the mathematical model, firstly an unbalanced temperature difference between surrounding and sensor is proposed under a dynamic ambient temperature change. We should pay attention to the dynamic process between steady-state to another steady-state. During the dynamic temperature measurement, we need to consider the change of the relative radiation between the blackbody, the thermopile sensor and the surrounding environment. We denote the total infrared radiation thermopile sensor received as $\Delta \Phi$ in equation (1), which will later processed and indicate the blackbody target temperature. The total infrared radiation $\Delta \Phi$ comprise of four major terms as $\Phi_{ba}$, $\Phi_{ab}$, $\Phi_{as}$ and $\Phi_{sa}$. According to Stefan-Boltzmann law, we can express the relative radiation from equation (2) To equation (5).

$$\Delta \Phi = \Phi_{ba} + \Phi_{as} - \Phi_{ab} - \Phi_{sa}$$  

(1)
\[ \Phi_{bs} = A_{bs} \varepsilon_b \cdot T_b^4 \]  \hspace{1cm} (2) \\
\[ \Phi_{ab} = A_{ab} \varepsilon_a \cdot T_a^4 \]  \hspace{1cm} (3) \\
\[ \Phi_{bo} = A_{bo} \varepsilon_o \cdot T_o^4 \]  \hspace{1cm} (4) \\
\[ \Phi_{ba} = A_{ba} \varepsilon_a \cdot T_a^4 \]  \hspace{1cm} (5)

where \( A \) represents the geometric factor is a parameter that characterizes the relative influence of various media in the space on the measurement results. It including the geometrical effects of area of sensor, field of view angles, cut on wavelength and transmission of optical lens in our measurement. Besides, \( \varepsilon \) represents the emissivity of different materials.

When the instrument is moved from one place to another, it is necessary to realize the dynamic temperature behaviours for thermopile sensor and surrounding environment. Before the time reach thermal equilibrium, the temperature gradient drift will cause thermal radiation exchange between thermopile sensor and surrounding environment which we denote \( \Delta \Phi_{as} \) in equation (6). While there is at thermal equilibrium \( \Delta \Phi_{as} \neq 0 \), it will cause a temperature error \( \Delta T_b \) between the measured value \( T_b \) and stable temperature \( T_{b0} \) as equation (7).

\[ \Delta \Phi_{as} = \Phi_{as} - \Phi_{sa} = A_{as} \varepsilon_a \cdot T_a^4 - A_{sa} \varepsilon_s \cdot T_s^4 \]  \hspace{1cm} (6) \\
\[ \Delta T_b = T_{b0} - T_b \]  \hspace{1cm} (7)

We can suppose that there is a correction factor \( K \) for the relationship between the temperature error \( \Delta T_b \) as and the thermal radiation exchange \( \Delta \Phi_{as} \). In that way, \( \Delta T_b \) can be derived by Stefan-Boltzmann law as equation (8) and equation (9).

\[ \Delta T_b = K(A_{sa} \varepsilon_s \cdot T_s^4 - A_{sa} \varepsilon_s \cdot T_s^4) \]  \hspace{1cm} (8) \\
\[ = K \varepsilon_s \left[ 4(T_s) \left( T_a - T_s \right) \right] \]  \hspace{1cm} (9)

where \( K = KA_{sa} \varepsilon_s = KA_{sa} \varepsilon_s \) = constant and \( \bar{T} = \frac{T_a + T_s}{2} \)

From the above mathematical deduction that we can conclude the temperature error \( \Delta T_b \) is proportional to temperature difference \( (T_a - T_s) \). It is the basic principle for the multi-sensors scheme of dynamic compensation. Nevertheless, a more powerful compensation scheme, the differential scheme is proposed and described as follows. For a thorough description of thermal behaviour of thermopile sensor and environment, a thermal equilibrium equation is introduced as follows equation (10) and equation (11).

\[ H \frac{\Delta T_a}{\Delta t} + G(T_a - T_s) = P = 0 \]  \hspace{1cm} (10) \\
\[ \frac{\Delta T_a}{\Delta t} \propto (T_a - T_s) \]  \hspace{1cm} (11)

where \( H \) is the thermal sensor conductivity, \( G \) is the convection heat-transfer coefficient between thermopile sensor and surrounding environment. It is obvious to see that the temperature error \( \Delta T_b \) is proportional to both the temperature difference \( (T_a - T_s) \) and \( \Delta T_a \).

3. Experiment setup and results

3.1. Experimental setup and sensor calibration

The new infrared radiation measurement circuit which was built to investigate the thermal behaviour of infrared radiation exchanges between the target, thermopile sensor and surrounding environment is
shown in figure 2. This data acquisition system is designed with an embedded ARM based Cortex M0 micro-controller, NUC120, to control the circuit and communication with PC. A thermopile of TO-5 package is used with a filter 5~14 μm which receive the infrared radiation from a plastic Fresnel lens with a focal length 2.5 cm. The output signal of thermopile is delivered to an amplifier AD8551 with low offset and a 12-bit ADC MCP3202 follows to transfer it into the digital signal then we can get bias voltage of thermopile $V_b$ and bias voltage of inner thermistor $V_a$. Besides of the thermopile, we put a SMD package thermistor attached to the optical tube which serves as a monitor of unbalanced temperature of surrounding environment. We use the embedded ARM microcontroller build in ADC to get the bias voltage of outer thermistor $V_s$.

![Figure 2](image.png)

**Figure 2.** An infrared radiation measurement circuit compensation with sensor embedded.

Both of the temperature sensors including thermopile inner thermistor, outer thermistor and thermopile have to be calibrated before the testing of dynamic measurement. The thermopile inner thermistor is chosen as 30 kΩ and outer thermistor is chosen as 50 kΩ at 25 °C. The bias output voltages of thermopile inner thermistor and outer thermistor are calibrated from 20 °C to 45 °C inside a temperature controlled chamber. The thermopile is chosen as 50 kΩ at 25 °C and we measure the output signal after the amplifier AD8551.

During the thermopile calibration, we use the thermopile inner thermistor to compensate the ambient temperature difference to guarantee thermal radiation exchange only exist between blackbody and thermopile sensor. Then we adjust the standard blackbody with temperature from 20°C to 45 °C and measure the thermopile bias voltage under a stable environment. The calibration results of $V_s$, $V_a$ and $V_b$ vs. temperature are shown as figure 3.

![Figure 3](image.png)

**Figure 3.** Calibration of the output voltage $V_s$, $V_a$ and $V_b$ vs. temperature.
After calibration of temperature sensor for blackbody, surrounding environment and thermopile sensor. We can proceed to the dynamic infrared radiation temperature measurement for moving of measurement module from a higher temperature chamber at 50 °C to room temperature and measure the blackbody target at 38 °C. The dynamic temperature behaviours of blackbody, surrounding environment and thermopile sensor are recorded for 50 minutes and shown as figure 4. One can see that the initial temperature $T_i$ is higher than $T_a$. It is because the outer thermistor touch the surrounding cool air first and it will cool down more quickly.

![Temperature Behaviours](image)

**Figure 4.** Dynamic temperature behaviours of $T_s$, $T_a$ and $T_b$.

### 3.2. Results and discussions

After we get the dynamic temperature of different sensors, we can calculate the temperature difference between inner thermistor and outer thermistor ($T_a - T_i$) and inner thermistor temperature difference $\Delta T_a$ to compare with unbalanced target temperature error $\Delta T_b$ at different time, respectively. The results is shown as figure 5. One can see that both data shows a good agreement relationship between $\Delta T_b$ vs. $(T_a - T_i)$ and $\Delta T_a$. We can get two convert equation to estimate the target temperature error by $(T_a - T_i)$ and $\Delta T_a$.

![Calibration of Target Temperature Error](image)

**Figure 5.** Calibration of target temperature error $\Delta T_b$ vs. $(T_a - T_i)$ and $\Delta T_a$.

Consequently, we can use these two compensation schemes to compensate the dynamic unbalanced target temperature error. The comparison of measurement temperature error and compensate temperature by two compensation schemes is shown as figure 6. After calibrations and verifications, our compensation schemes provide an efficient way to reduce the conventional measuring waiting time for thermal equilibrium from 40 min down to 2 min for $\Delta T_a$ compensation and 6 min for $\Delta T_b$ compensation.
(T_e - T_i) compensation with temperature error around 0.2 °C, which is proved to be a practical technique of non-contact temperature measurement.

![Comparison of measurement temperature error and compensate temperature by two compensation schemes](image)

**Figure 6.** Comparison of measurement temperature error and compensate temperature by two compensation schemes of ΔT_e and (T_e - T_i).

### 4. Conclusions

A non-contact temperature measurement model and two novel and high efficient infrared temperature compensation techniques are proposed in this research work. We calculate the temperature difference between internal and external thermistor to estimate the relative amount of radiation. After careful calibrations and verifications of several experiment conditions, our models of two dynamic compensation schemes both show an excellent agreement with the measurement data. The experimental data of compensation scheme reach a stable reading value of target temperature to 2 min for the differential scheme compensation and 6 min for multi-sensors scheme compensation with temperature error around 0.2 °C.

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