Automatically emissivity-compensated radiation thermometry

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Abstract. This study developed emissivity-compensated radiation thermometry. The principle of this method is based on the combined utilization of effective radiance and a specular reflection parameter. The former value is derived from multiple reflections of radiant flux between a specimen surface with an unknown spectral emissivity and a reflector. The latter value is derived from the reflection pattern of a specimen surface for incident light flux. The measurement system was composed of a radiation thermometer, a cylindrical cavity for multiple reflections, and a laser to obtain the specular reflection parameter. This system enabled the simultaneous measurement of temperature and emissivity of a specimen with any surface irregularities.

1. Introduction

Emissivity determination is crucial but difficult for radiation thermometry. To reduce the difficulty, many methods for radiometric temperature measurement have been studied [1], such as emissivity enhancement using a reflector [2-3] or optical fibre [4]. Emissivity-compensated methods can be divided between passive and active techniques, which typically make use of empirical relations between two wavelengths [5-6], polarization properties [7-8], or photothermal effects [9].

One of the authors previously devised a simultaneous measurement system for temperature and emissivity that was composed of a radiation thermometer and a cylindrical cavity that induced multiple reflections of radiant flux within it [10]. As a passive method, however, this system required that a specimen-specific parameter be determined in advance for successful use.

This study employed an active method to develop a novel emissivity-compensated radiation thermometry that uses a laser to measure the degree of specular reflection of a specimen independently. As a result, this method can be widely applied to various specimens. This paper details the principle and procedure of this method, experiments to demonstrate it, and some applications are discussed.

2. Measurement principle

Figure 1 shows the cavity effect that embodies some of the measurement principle of this method. When a radiation thermometer directly observes a specimen, as shown in figure 1(a), the spectral radiance $L_1$ detected by the radiation thermometer is described as

$$L_1 = \varepsilon_\lambda L_{b,\lambda}(T)$$

(1)
where \( \varepsilon_\lambda \) is the spectral emissivity of a specimen at wavelength \( \lambda \) and \( L_{b,\lambda}(T) \) is the blackbody spectral radiance at temperature \( T \) and wavelength \( \lambda \).

When a cylindrical cavity is inserted between the thermometer and the specimen, as shown in figure 1(b), the spectral radiance \( L_2 \) detected by the thermometer is depicted as

\[
L_2 = \varepsilon_\lambda + \varepsilon_\lambda \rho \gamma (1 - \varepsilon_\lambda) + \varepsilon_\lambda \rho^2 \gamma^2 (1 - \varepsilon_\lambda)^2 + \ldots \}
\]

\[
= \frac{\varepsilon_\lambda}{1 - \rho \gamma (1 - \varepsilon_\lambda)} L_{b,\lambda}(T) = \varepsilon_{\text{eff}} L_{b,\lambda}(T)
\]

where \( \varepsilon_{\text{eff}} \) is the effective spectral emissivity enhanced by the multiple reflections of radiant flux between the cavity and the specimen and described by equation (3), \( \rho \) is the effective reflectance of the cavity, and \( \gamma \) is a specular reflection parameter for the specimen surface.

\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_\lambda / \rho \gamma}{\varepsilon_\lambda + (1 / \rho \gamma - 1)}
\]  

As \( \gamma \) approaches 1, the specimen surface becomes specular.

Let a parameter \( \alpha \) and a ratio \( R_L \) of radiances be as shown in equations (4) and (5), respectively, then \( \varepsilon_\lambda \) and \( \varepsilon_{\text{eff}} \) are replaced as equations (6) and (7), respectively.

\[
\alpha = 1 / \rho \gamma - 1
\]  

\[
R_L = \frac{L_2}{L_1}
\]  

\[
\varepsilon_\lambda = \frac{\alpha + 1 - \alpha R_L}{R_L}
\]  

\[
\varepsilon_{\text{eff}} = \frac{(\alpha + 1) \varepsilon_\lambda}{\varepsilon_\lambda + \alpha}
\]

If \( \alpha \) of a specimen is known in advance, its spectral emissivity can be obtained by equation (6), resulting in the determination of a true temperature \( T \) from equation (1). If \( \alpha \) of a specimen is unknown or varies during measurement, a new technique is required to independently determine \( \alpha \), which is the main part of the measurement principle presented here, resulting in construction of a new method for emissivity-free radiation thermometry.
where $I_{01}$ and $I_{02}$ are the reflected light intensity signals at angles $\theta_0(=0^\circ)$ and $\theta_1$, respectively, for the incident light intensity signal $I_0$ normal to the surface. Parameter $\gamma$ is strongly related to the surface roughness of a specimen. If $\rho$ is assumed to be constant and the quantitative relation between $\gamma$ and $\alpha$ holds, then $\alpha$ can be derived from the measurement of $\gamma$, which is independent from $\varepsilon_l$.

3. Experimental apparatuses and measurements

Figure 3 illustrates the brass cylindrical cavity that was used for the measurement of spectral radiance $L_2$. The openings for the top and bottom measured $d=5$ mm and $D=30$ mm in diameter, respectively. The inside surface of the cavity was gold-plated to produce a highly reflective surface. A radiation thermometer with an InGaAs detector sensitive at a wavelength of 1.35 µm measured spectral radiances $L_1$ and $L_2$ of a specimen in accordance with the conditions of figures 1(a) and (b), respectively.

Figure 4 illustrates the apparatus for obtaining parameter $\gamma$ defined by equation (8); the setup used a semiconductor laser operating at a wavelength of 532 nm. By sandblasting stainless steel surfaces (SUS430), specimens specified as Raw, #40, #600, and #1000 with different surface roughness were prepared for the experiment.

The experimental procedure for obtaining the relation between $\gamma$ and $\alpha$ is described below.

First, the surface temperature $T$ of a specimen was measured by a K-type thermocouple, from which the spectral blackbody radiance $L_{b,\lambda}(T)$ was obtained. While spectral radiances $L_1$ and $L_2$ were measured by the radiation thermometer in accordance with equations (1) and (2), respectively, the spectral emissivity $\varepsilon_l$ of a specimen was calculated using $L_1$, $L_{b,\lambda}(T)$, and equation (1). The radiance ratio $R_L$ was calculated using $L_1$, $L_2$, and equation (5). The parameter $\alpha$ was calculated using $\varepsilon_l$ and $R_L$ from

$$\alpha = \frac{1 - \varepsilon_l}{R_L - 1}$$

Finally, a relation between $\gamma$ and $\alpha$ was constructed using the values for $\gamma$ measured at $\theta_0 = 0^\circ$ and $\theta_1 = 10^\circ$ in equation (8) and the values for $\alpha$ determined by equation (9).

Figure 5 shows the experimental relation between $R_L$ and $\varepsilon_l$ that was obtained using specimens with different surface irregularities, as identified by the values for $\alpha$ specified for the dotted curves.
Experiments were carried out at temperatures between 673 K and 973 K. Similarly, figure 6 shows the experimental relation between $\gamma$ and $\alpha$ for these specimens prepared. After the quantity $\gamma$ was measured, the parameter $\alpha$ was determined according to the dotted line, then the spectral emissivity $\varepsilon_\lambda$ of a specimen was obtained by equations (5) and (6), resulting in a true surface temperature $T$ of the specimen by equation (1).

Figure 5. Experimental relation between $R_L$ and $\varepsilon_\lambda$.

Figure 6. Experimental relation between $\gamma$ and $\alpha$.

4. Concluding remarks

We have briefly presented a newly developed emissivity-free radiation thermometry that utilized a cylindrical cavity for enhancing the emissivity of a specimen and a laser for measuring the specular reflection parameter $\gamma$ of a specimen. This method can be widely applied to various materials, including steel, aluminium, silicon, and so on. To apply this method to an industrial process, an efficient apparatus for measuring parameter $\gamma$ is necessary. Currently, we are focusing our effort on developing such an apparatus and also on performing an uncertainty analysis for this method.

5. References

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