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RADIATION THERMOMETRY OF METAL IN HIGH TEMPERATURE FURNACE

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Abstract − This study aims to develop a practical radiation thermometry system of metals moving through in a high temperature furnace. In order to achieve this study, two problems; emissivity compensation of a target and elimination of background radiation noise filled in a furnace must be sorted out. We have successfully developed a method for simultaneous measurement of emissivity and temperature by use of polarized directional properties of the radiance from the target, in this case, stainless steel, and moreover a technique to eliminate background radiation noise using a pseudo blackbody installed in a furnace.

Keywords : emissivity, polarization, furnace

1. INTRODUCTION

Temperature measurement and its control are important for production lines to enable the improvement of the quality of products as well as the economy of energy consumption. This study aims to develop a practical radiation thermometry system of metals moving through in a high temperature furnace such as a continuous annealing furnace. In order to achieve this study, two problems must be sorted out; that is, emissivity compensation of a target and elimination of background radiation noise filled in a furnace.

Radiation thermometry is a non-contact temperature measurement method that is suitable for moving target. When the emissivity of the target varies, however, it causes serious temperature error in radiation thermometry. In addition, in a high temperature furnace, the temperature of the furnace wall is nearly equal to or higher than the temperature of the target, in general. That means that the furnace is filled with enormous amount of background radiation noise. Therefore, a radiometer is unable to detect true radiance of the target without exclusion of background radiation noise.

This paper describes a method for simultaneous measurement of emissivity and temperature by use of polarized directional properties of radiance of the target, in this case, stainless steel, and moreover a technique to eliminate background radiation noise by use of a pseudo blackbody installed in a furnace, and subsequent experimental results of the method and the technique.

Stainless steel as a specimen is oxidized and the oxide film is grown on its surface when it is heated. Large variations of p-polarized and s-polarized emissivities are caused by the multiple reflection of radiation between the specimen and film surface [1].

Under some spectral and directional conditions, it is found that there is one-to-one correspondence between an emissivity and a ratio of p- and s-polarized radiances of stainless steel during heating. This relation has successfully led to the formation of emissivity-compensated radiation thermometry for stainless steel, even though large emissivity changes occur.

Introduction of a pseudo blackbody made of a heat-resistant material like alumina into a high temperature furnace enables to remove background radiation noise filled in the furnace as well as it supplies constant reference radiance to a radiometer. Thus, the principle for emissivity compensated radiation thermometry is maintained even inside the furnace as well.

According to experimental results achieved at the laboratory, the measurements of emissivity and temperature were possible with about 9,0 % and 1,3 % errors, respectively at temperature region over 1000 K.

2. MEASUREMENT PRINCIPLE AND EXPERIMENT

2.1. Emissivity compensation method

Let T be the temperature of the specimen. Let $E_p(\theta)$ be the p-polarized radiance signal that is emitted by the specimen and detected by a radiometer with a p-polarizer from a direction θ to the normal of the specimen surface. Then the following equation holds.

$$E_p(\theta) = k_p \varepsilon_p(\theta) L_{\lambda,b}(T), \tag{1}$$

where $\varepsilon_p(\theta)$ is p-polarized emissivity of the specimen at a wavelength λ and a direction θ; k_p is a constant factor that converts the p-polarized radiance into the electrical output signal $E_p(\theta)$; $L_{\lambda,b}(T)$ is a spectral blackbody radiance at temperature T and wavelength λ.

Similarly, the s-polarized radiance signal $E_s(\theta)$ is obtained as

$$E_s(\theta) = k_s \varepsilon_s(\theta) L_{\lambda,b}(T). \tag{2}$$

The ratio of (1) and (2) is shown as

$$\frac{E_p(\theta)}{E_s(\theta)} = (\frac{k_p}{k_s})(\frac{\varepsilon_p(\theta)}{\varepsilon_s(\theta)}) = k \cdot R_{ps}. \tag{3}$$

As k is constant, the ratio R_{ps} of p-polarized and s-polarized emissivities is derived from the measurements of $E_p(\theta)$ and $E_s(\theta)$. If there is one-to-one correspondence between a spectral emissivity $\varepsilon_\lambda(\theta)$ and the ratio R_{ps} for stainless steel during heating [2], the emissivity $\varepsilon_\lambda(\theta)$ of the specimen can be obtained by measuring the ratio R_{ps}.

Fig.1 shows an experimental arrangement to find a characteristic curve between $\varepsilon_\lambda(\theta)$ and R_{ps}. In the experiment, several radiometers that are sensitive at 0,9 μm (Si sensor), at 1,55 μm (InGaAs sensor) and at wide range from 3 to 4 μm (PbSe sensor) are used.

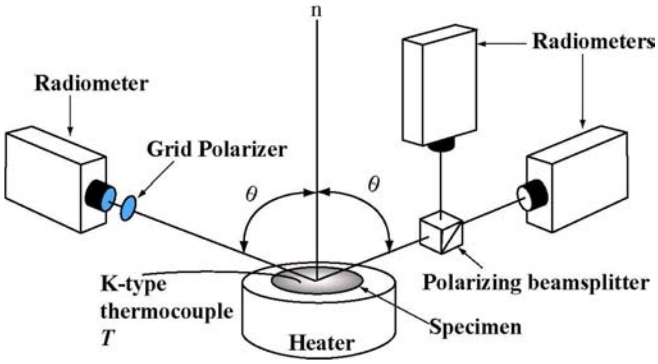
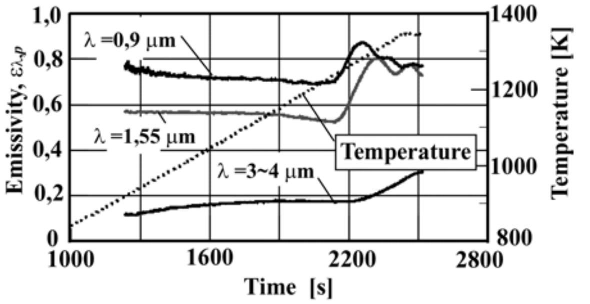
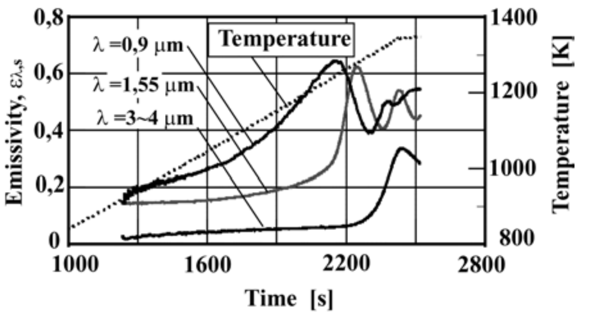


Fig.1 Experimental arrangement to find a characteristic curve between $\varepsilon_\lambda(\theta)$ and R_{ps}.



(a) p-polarized emissivity

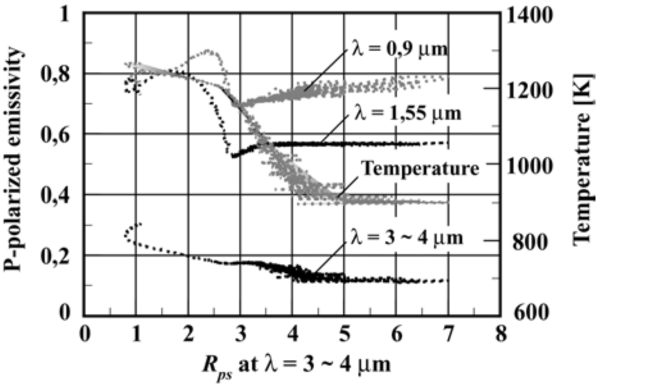


(b) s-polarized emissivity

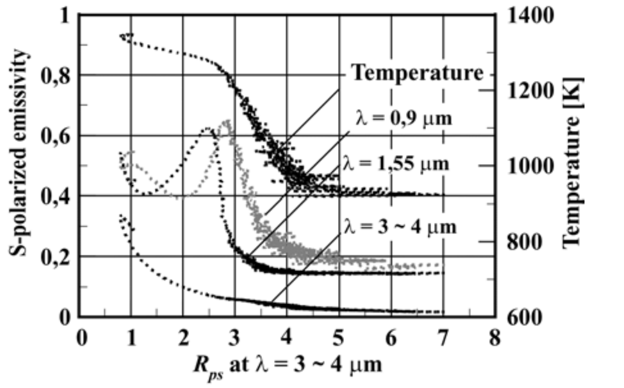
Fig.2 Experimental results of spectral polarized emissivities of a specimen with increasing temperature in air. (specimen: stainless steel (SUS430)).

Fig.2 shows measurement results of spectral polarized emissivities at 0,9, 1,55 and 3~4 μm and at a direction of θ=70° using Si, InGaAs and PbSe sensors, respectively, where (a) p-polarized and (b) s-polarized emissivities. The measurements were carried out with increasing temperature of the specimen. It is observed from Fig.2 that oscillating changes of both p- and s-polarized emissivities occur at a high temperature more than 1200 K and the changes start at a short wavelength (λ=0,9 μm) at first, then at λ=1,55 μm, and finally at λ=3~4 μm.

Using the experimental results of Fig.2, the characteristic curves between $\varepsilon_\lambda(\theta)$ and R_{ps} were obtained as shown in Fig.3, where (a) R_{ps} versus $\varepsilon_{\lambda,p}$ and (b) R_{ps} versus $\varepsilon_{\lambda,s}$.



(a) Relation for p-polarized emissivity



(b) Relation for s-polarized emissivity

Fig.3 Characteristic curves between R_{ps} and $\varepsilon_\lambda(\theta)$ derived from the experimental results of Fig.2. (specimen: stainless steel (SUS430)).

From several characteristic curves between R_{ps} and $\varepsilon_\lambda(\theta)$ shown in Fig.3, the most reliable and reproducible relation is the characteristic curve between R_{ps} at λ=3~4 μm and s-polarized emissivity $\varepsilon_{\lambda,s}(\theta)$ at λ=1,55 μm that meets the requirement most for one-to-one correspondence between the ratio R_{ps} and the emissivity. The second preferable relation is the one between R_{ps} at λ=3~4 μm and s-polarized emissivity $\varepsilon_{\lambda,s}(\theta)$ at λ=0,9 μm.

According to experimental results achieved in air, the measurements of emissivity and temperature were possible with about 9,0 % and 1,3 % errors, respectively at temperature region over 1000 K.

2.2. Measurement method in high temperature furnace

Fig.4 shows a schematic of a system for emissivity compensated radiation thermometry in a high temperature furnace based on the principle described above. In order to exclude background radiation noise filled in the furnace and supply the reference radiation is introduced to the furnace. The pseudo-blackbody that is installed inside the furnace and a radiometer whick is set outside the furnace are symmetrically disposed each other at an angle θ to the normal n of a specimen surface.

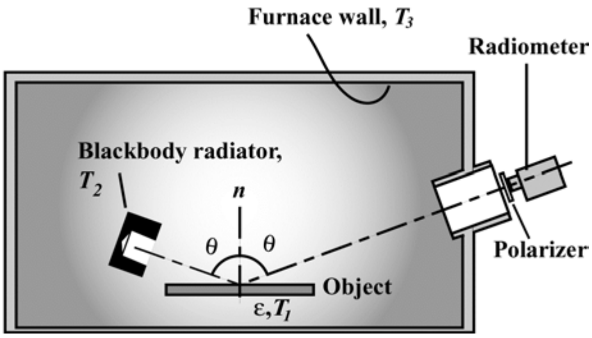


Fig.4 Schematic of a system for emissivity compensated radiation thermometry in a high temperature furnace

Let T_1, T_2 and T_3 be temperatures of the specimen, the blackbody radiator and the wall of the furnace, respectively.

The radiance signal $E_p(\theta)$ detected by the radiometer equipped with a p-polarizer is described as follows,

$$\begin{aligned} E_p(\theta) &= k_p\{\varepsilon_p(\theta)L_{\lambda,b}(T_1) + p_1(1-\varepsilon_p(\theta))L_{\lambda,b}(T_2) \\ &\quad + p_2(1-\varepsilon_p(\theta))L_{\lambda,b}(T_3)\} \\ &= \varepsilon_p(\theta)E_{p,\lambda,b}(T_1) + p_1(1-\varepsilon_p(\theta))E_{p,\lambda,b}(T_2) \\ &\quad + p_2(1-\varepsilon_p(\theta))E_{p,\lambda,b}(T_3), \end{aligned} \tag{4}$$

$$E_{p,\lambda,b}(T_i) = k_p L_{\lambda,b}(T_i), \qquad i = 1,2,3., \tag{5}$$

where the second term of the right side of (4) is the radiance signal that leaves the blackbody at temperature T_2 and is reflected on the specimen and detected by the radiometer; The third term is the radiance signal that leaves the wall of the furnace at temperature T_3 and is reflected on the specimen and detected by the radiometer; p_1 and p_2 ($0<p_1$, $p_2 \le 1$) are coefficients that represent degrees of specularly and diffusely reflecting characteristics of the specimen for p-polarization, respectively.

Similarly, the radiance signal $E_s(\theta)$ detected by the radiometer equipped with a s-polarizer is described as

$$\begin{aligned} E_s(\theta) &= k_s\{\varepsilon_s(\theta)L_{\lambda,b}(T_1) + s_1(1-\varepsilon_s(\theta))L_{\lambda,b}(T_2) \\ &\quad + s_2(1-\varepsilon_s(\theta))L_{\lambda,b}(T_3)\} \\ &= \varepsilon_s(\theta)E_{s,\lambda,b}(T_1) + s_1(1-\varepsilon_s(\theta))E_{s,\lambda,b}(T_2) \\ &\quad + s_2(1-\varepsilon_s(\theta))E_{s,\lambda,b}(T_3), \end{aligned} \tag{6}$$

$$E_{s,\lambda,b}(T_i) = k_s L_{\lambda,b}(T_i), \qquad i = 1,2,3., \tag{7}$$

where s_1 and s_2 ($0<s_1$, $s_2 \le 1$) are coefficients representing degrees of specularly and diffusely reflecting characteristics of the specimen for s-polarization, respectively.

From the thermal equilibrium condition, the following relations can be guided,

$$p_1 + p_2 = 1, \tag{8}$$

$$s_1 + s_2 = 1. \tag{9}$$

As diffusely reflecting coefficients p_2 and s_2 are negligibly small compared with specularly reflecting coefficients p_1 and s_1 for bright stainless steel such as SUS430, the third terms of the right sides of (4) and (6) can be neglected [3]. Then equations (4) and (6) are reconstructed as follows,

$$E_p(\theta) - k_p p_1 L_{\lambda,b}(T_2) = k_p \varepsilon_p(\theta)\{L_{\lambda,b}(T_1) - p_1 L_{\lambda,b}(T_2)\} \tag{10}$$

$$E_s(\theta) - k_s s_1 L_{\lambda,b}(T_2) = k_s \varepsilon_s(\theta)\{L_{\lambda,b}(T_1) - s_1 L_{\lambda,b}(T_2)\} \tag{11}$$

Taking the ratio of (10) and (11),

$$\begin{aligned} &\frac{E_p(\theta) - k_p p_1 L_{\lambda,b}(T_2)}{E_s(\theta) - k_s s_1 L_{\lambda,b}(T_2)} \\ &= \frac{k_p}{k_s}\frac{\varepsilon_p}{\varepsilon_s}\frac{L_{\lambda,b}(T_1) - p_1 L_{\lambda,b}(T_2)}{L_{\lambda,b}(T_1) - s_1 L_{\lambda,b}(T_2)}. \end{aligned} \tag{12}$$

When surface irregularity of a specimen is random, just as the case of stainless steel (SUS430), coefficient p_1 is equal to s_1. Thus, equation (12) is expressed as

$$\frac{E_p(\theta) - p_1 E_{p,\lambda,b}(T_2)}{E_s(\theta) - p_1 E_{s,\lambda,b}(T_2)} = \frac{k_p}{k_s}\cdot\frac{\varepsilon_p}{\varepsilon_s} = k \cdot R_{ps}. \tag{13}$$

As each term of the left side of (13) can be measured and computed if coefficient p_1 is known, the ratio R_{ps} of the right side of (13) can be obtained. This means that the principle of emissivity compensation as shown in (3) is available even in a high temperature furnace.

If once the emissivity $\varepsilon_p(\theta)$ is derived from a relation between $\varepsilon_p(\theta)$ and R_{ps} by use of (13), the following equations are derived from dividing (4) by $\varepsilon_p(\theta)$.

$$\begin{aligned} \frac{E_p(\theta)}{\varepsilon_p(\theta)} &= k_p\{L_{\lambda,b}(T_1) + \frac{p_1(1-\varepsilon_p(\theta))}{\varepsilon_p(\theta)} L_{\lambda,b}(T_2) \\ &\quad + \frac{p_2(1-\varepsilon_p(\theta))}{\varepsilon_p(\theta)} L_{\lambda,b}(T_3)\} \\ &= E_{p,\lambda,b}(T_1) + \frac{p_1(1-\varepsilon_p(\theta))}{\varepsilon_p(\theta)} E_{p,\lambda,b}(T_2) \\ &\quad + \frac{N_{p,r}}{\varepsilon_p(\theta)} E_{p,\lambda,b}(T_3), \end{aligned} \tag{14}$$

$$N_{p,r} = p_2(1-\varepsilon_p(\theta)), \tag{15}$$

where $N_{p,r}$ is a noise factor.

The temperature T_1 of the specimen is calculated from the right side terms of following equation (16) by use of compensated p-polarized emissivity $\varepsilon_p(\theta)$.

$$E_{p,\lambda,b}(T_1) = \frac{E_p(\theta)}{\varepsilon_p(\theta)} - \frac{p_1(1-\varepsilon_p(\theta))}{\varepsilon_p(\theta)} E_{p,\lambda,b}(T_2). \tag{16}$$

The temperature T_1 derived from (16) includes the error ΔT caused by $N_{p,r}E_{p,\lambda,b}(T_3)/\varepsilon_p(\theta)$, the third component of (14). In order to reduce the measurement error ΔT, the solid angle $d\Omega$, aperture of the pseudo blackbody subtended by a measuring point of the specimen must be designed to be wide as much as possible.

Similarly, the calculation of temperature T_1 can be derived as well by use of compensated s-polarized emissivity $\varepsilon_s(\theta)$ as shown in (17).

$$E_{s,\lambda,b}(T_1) = \frac{E_s(\theta)}{\varepsilon_s(\theta)} - \frac{s_1(1-\varepsilon_s(\theta))}{\varepsilon_s(\theta)} E_{s,\lambda,b}(T_2). \tag{17}$$

The calculation of T_1 by (17) includes the error ΔT caused by background radiation noise $N_{s,r}E_{s,\lambda,b}(T_3)/\varepsilon_s(\theta)$.

$$N_{s,r} = s_2(1-\varepsilon_s(\theta)). \tag{18}$$

2.3. Measurements of solid angle $d\Omega$ and noise factor N_r

In order to estimate background radiation noise, an experimental apparatus shown in Fig.5 has been designed, which can investigate a relation between solid angle $d\Omega$ and noise factor N_r.

In Fig.5 (a), side walls and a ceiling wall except a small aperture made in one of side walls for observing radiance by use of radiometers are attached with black painted plates having effective emissivity of 0,95. The temperature of these walls is maintained at T_3. A substrate of stainless steel (SUS430) whose surface is coated with $BaSO_4$ particles is set at a floor of the furnace, which is utilized as a completely diffusely reflecting surface having effective reflectivity of 0,98 at visible and near infrared range. The rear side of the substrate is water cooled from the bottom side to maintain the surface at room temperature. In Fig.5 (b), small apertures are provided at both side walls, one of them is assumed to be a pseudo-blackbody at room temperature, and constitutes solid angle $d\Omega$. The other is used as an aperture from which background radiation noise is detected by a radiometer. Specimens of as-grown (commercial base product) and oxidized stainless steels are set at a floor, successively.

P-polarized radiance detected by the radiometer in (a) represents radiance $E_{p,\lambda,b}(T_3)$ of the furnace wall and p-polarized radiance derived from (b) shows the third component $\Delta E_p=N_{p,r}\,E_{p,\lambda,b}(T_3)$ of the right side of (4). Thus, a noise factor $N_{p,r}$ is obtained by calculating $\Delta E_p/E_{p,\lambda,b}(T_3)$. Similarly, noise expressions for s-polarized component are given as $\Delta E_s=N_{s,r}E_{s,\lambda,b}(T_3)$ and $N_{s,r}$, respectively.

Fig.6 shows an experimental relation between solid angle $d\Omega$ and noise factor N_r for stainless steel (SUS430) which is heated at 1200 K and oxidized. ΔE_p is measured at T_3=1273 K.

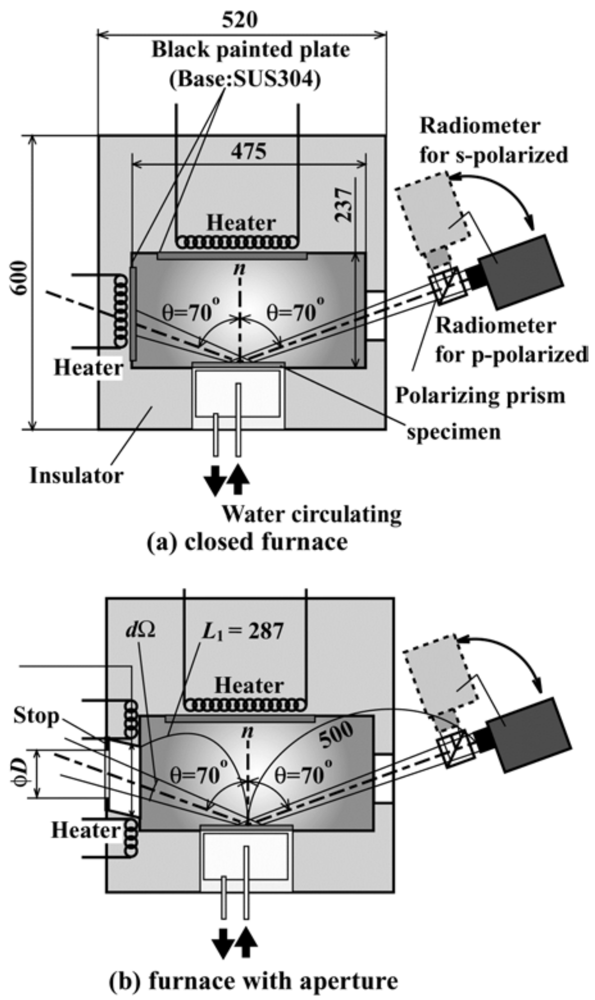


Fig.5 Experimental apparatus for measurements of solid angle $d\Omega$ and noise factor N_r.

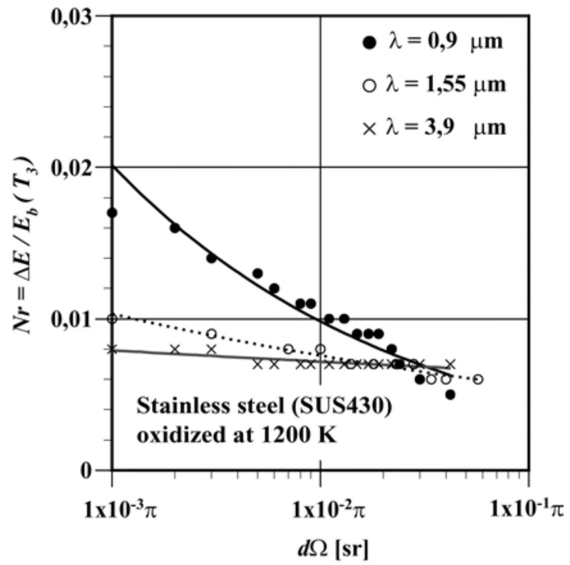


Fig.6 Experimental relation between solid angle $d\Omega$ and noise factor N_r for stainless steel (SUS430) which is heated at 1200 K and oxidized.

Now, the procedure to estimate temperature error $\Delta T=T_a-T_1$ caused by background radiation noise $N_r E_b(T_3)/\varepsilon(\theta)$ is calculated with the following equations for p-polarized and s-polarized radiances, respectively shown in (19) and (20),

$$E_{p,\lambda,b}(T_a)=E_{p,\lambda,b}(T_1)+\frac{N_{p,r}}{\varepsilon_p(\theta)}E_{p,\lambda,b}(T_3) \tag{19}$$

$$E_{s,\lambda,b}(T_a)=E_{s,\lambda,b}(T_1)+\frac{N_{s,r}}{\varepsilon_s(\theta)}E_{s,\lambda,b}(T_3) \tag{20}$$

Fig.7 shows a relation between temperature error ΔT and solid angle $d\Omega$ for p-polarized emissivity compensation. ΔT is calculated by use of Fig.6 and (19), where both T_1 and T_3 are 1273 K. The specimen is SUS430 stainless steel which is oxidized by heating 1200 K.

According to Fig.7, when solid angle is set to $d\Omega$=0,01π sr, temperature error ΔT caused by background radiation noise $N_r E_b(T_3)/\varepsilon_p(\theta)$ is maintained to about 1 K under the condition $T_1=T_3$=1273 K regardless of emissivity value of the specimen for λ=0,9 and 1,55 μm. In case of λ=3,9 μm, however, ΔT displays more than 4 K due to low spectral emissivity and long wavelength effect.

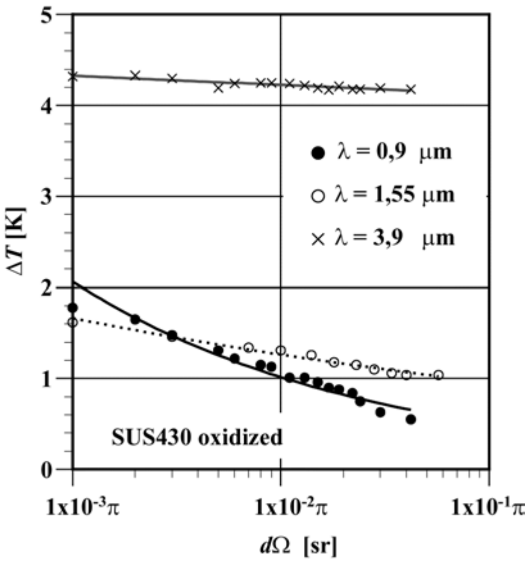


Fig.7 Relation between ΔT and $d\Omega$ for oxidized stainless steel (SUS430), which is calculated by use of Fig.6 and (19). Both T_1 and T_3 are 1273 K.

Fig.8 shows a relation between ΔT and $d\Omega$ for p-polarized emissivity compensation, where both T_1 is 1273 K and T_3 is 1373 K, that is, the wall temperature T_3 is higher than the specimen temperature T_1 by 100 K. The specimen is stainless steel (SUS430) which is oxidized by heating 1200 K.

Similarly, Fig.9 and Fig.10 show relations between ΔT and $d\Omega$ for s-polarized emissivity and for unpolarized emissivity compensation, respectively under the same conditions with Fig.8.

From Figs.8~10, we can see that ΔT becomes large when the wall temperature T_3 is higher than the specimen temperature T_1 by 100 K. For example, under the condition of $d\Omega$=0.01π sr when p-polarized emissivity compensation is used, ΔT=3 K for λ=0,9 μm, ΔT=4 K for λ=1,55 μm and 25 K for λ=3,9 μm as shown in Fig.8; by use of s-polarized emissivity compensation, ΔT=4 K for λ=0,9 μm, ΔT=9 K for λ=1,55 μm and 62 K for λ=3,9 μm as shown in Fig.9; and by use of unpolarized emissivity compensation, ΔT=4 K for λ=0,9 μm, ΔT=6 K for λ=1,55 μm and 35 K for λ=3,9 μm as shown in Fig.10, respectively.

Judging from quantitative analysis described above, the best choice is to use the relation between p-polarized emissivity at 0,9 μm and R_{ps} at 3.9 μm. Solid angle of $d\Omega$=0.02π sr (that corresponds to 8º of field view angle) is quite good design to avoid background radiation noise.

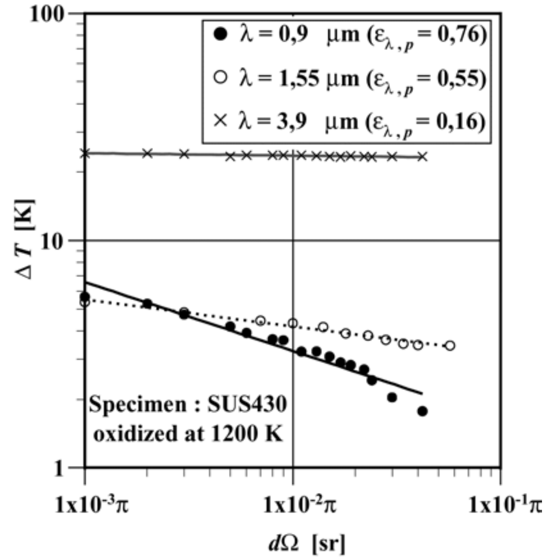


Fig.8 Relation between ΔT and $d\Omega$ for p-polarized emissivity compensation, where both T_1 is 1273 K and T_3 is 1373 K. The specimen is stainless steel (SUS430) which is oxidized by heating 1200 K.

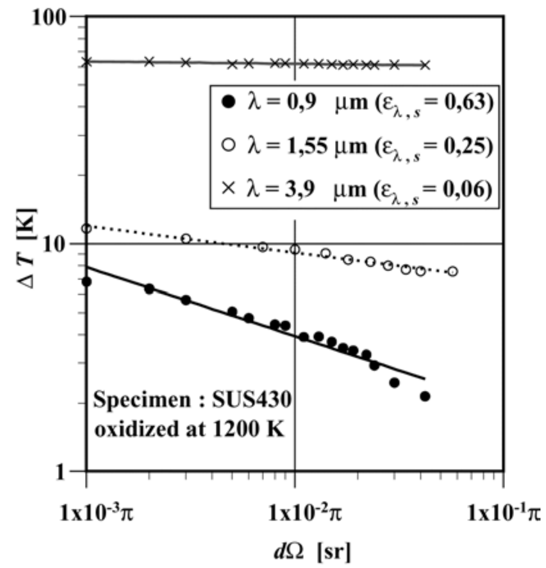


Fig.9 Relation between ΔT and $d\Omega$ for s-polarized emissivity compensation. The condition is the same with Fig.8.

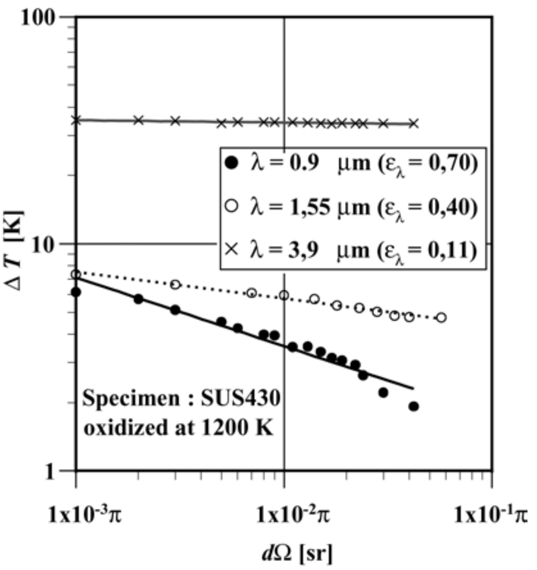


Fig.10 Relation between ΔT and $d\Omega$ for unpolarized emissivity compensation, where both T_1 is 1273 K and T_3 is 1373 K. The specimen is stainless steel (SUS430) which is oxidized by heating 1200 K.

3. CONSIDERATIONS FOR PRACTICAL USE

Fig.11 shows schematic of a practical radiation thermometry system intended to be installed in a high temperature furnace for annealing of stainless steel. Following requirements have been mentioned by feasibility study, which is based on experimental results,

(1) a pseudo blackbody installed in the furnace and radiometers 1 should be symmetrically set at an angle more than θ=70°,
(2) radiometers 1 should possess combined sensors that can detect p-polarized and s-polarized radiances at λ=3.9 μm to obtain R_{ps}, and radiance at 0,9 μm or 1,55 μm to compensate $\varepsilon_\lambda(\theta)$ as well,
(3) radiometer 2 equipped with a Si sensor sensitive at 0,9 μm detects the temperature T_2 of a pseudo-blackbody which is naturally heated by the radiation in the furnace.

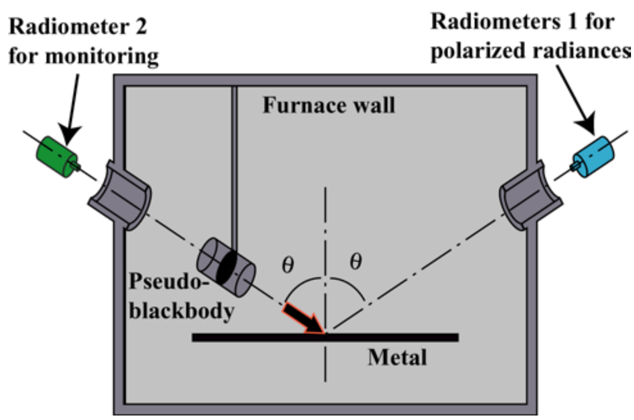


Fig.11 Schematic of a practical radiation thermometry system for stainless steel in a high temperature furnace.

4. CONCLUSION

A reliable and reproducible relation between R_{ps} and emissivity $\varepsilon_\lambda(\theta)$ has been obtained for emissivity-compensated radiation thermometry of stainless steel (SUS430) in laboratory experiments. The measurements of emissivity and temperature are possible with about 9,0 % and 1,3 % errors, respectively at temperature region over 1000 K.

In order to apply this method to specimens in a high temperature furnace, a quantitative relation between solid angle $d\Omega$ that represents size of a blackbody aperture, and temperature error ΔT caused by background radiation noise from surrounding wall of the furnace has been found.

Under the conditions of T_1=1273 K, T_3=1373 K (T_3-T_1=100 K) and $d\Omega$=0,02π sr, temperature error ΔT is suppressed within 4 K for both λ=0,9 μm and λ=1.55 μm.

Radiation thermometry system of stainless steel in a high temperature furnace has been designed, which is based on the above relation.

The pseudo-blackbody which is naturally heated inside the furnace possesses such features that it can remove background radiation noise filled in the furnace without cooling a specimen and also provide the reference radiation that is useful for signal processing to obtain emissivity of the specimen.

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