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TEMPERATURE COEFFICIENTS OF TOPCON RADIATION THERMOMETERS

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Abstract − The ambient or instrument temperature affects the outputs of a standard radiation thermometer through various parts such as a detector, a feedback resistance and an interference filter. Usually the output was corrected by one coefficient assuming the linear dependence. If the filter wavelength changes, the dependence is different at each target temperature. We measured the temperature coefficients of Topcon radiation thermometers at different target temperatures and found the target temperature dependence as well as the feed back resistance dependence. Therefore a high stability radiation thermometer requires controlling the detector, filter and amplifier temperatures.

Keywords: ambient temperature effect, radiation thermometer, wavelength shift

1. INTRODUCTION

Topcon radiation thermometers are used in the traceability system of radiation thermometers in Japan, 0.65 μm from 960 ºC to 2800 ºC and 0.9 μm from 400 ºC to 2000 ºC. Stability is one of the important factors for the uncertainty of radiation thermometers. We reported the long term stability of 0.65 μm Topcon radiation thermometers and found that the output change was mainly caused by the shift of the center wavelength of the interference filter [1]. We also reported that the range ratios of most Topcon radiation thermometers were stable within ±0.01%/year [2].

This paper describes the effect of ambient temperature on the thermometer output. The ambient or instrument temperature change causes the change in response through many factors. The response of the silicon detector has a large temperature coefficient at the longer wavelength than 1 μm. The amplifier gain changes by the change of the feedback resistance. The filter changes its transmittance and center wavelength. It has been very difficult to measure the shift of the filter center wavelength therefore its effect was assumed small, the temperature coefficient was measured at one target temperature and the value was applied for the whole temperature range. We studied the temperature coefficients about the target temperature dependence as well as the detector dependence, the wavelength dependence, the filter dependence and their stability.

2. EXPERIMENTAL

2.1. Radiation thermometers

The characterization of 0.9 μm and 0.65 μm radiation thermometers are described in references 3 and 4 [3,4]. Eight thermometers, R1 to R8 were used for 0.65 μm, six, S1 to S6 for 0.9 μm and two, T1 and T2 for 1 μm.

Most 0.65 μm thermometers used S1336-5BK of the Hamamatsu Photonics as a detector, and DIF-BPF-2 of the Optical Coating of Japan (OCJ) or hard coating one of the Barr Associates as an interference filter. Thermometer R5 had a different detector S1226-5BK and a different filter TO-399. The band width was about 15 nm.

The early made 0.9 μm thermometers S1 and S6 had S874-5K of the Hamamatsu Photonics as a detector. They were changed to S1336-5BK. Other thermometers had S1336-5BK except for S2 thermometer which had S2386-5K as a detector. All 0.9 μm thermometers had DIF-BPF-4 of OCJ as a filter with a band width of about 80 nm.

All 1 μm thermometers had S1336-5BK as a detector and DIF-BPF-4 of the OCJ as a filter with a band width of about 90 nm.

For monitoring the instrument temperature, Topcon radiation thermometers used an IC temperature sensor, μPC616 placed close to the detector. The output of the sensor was multiplied ten times and monitored by a voltmeter, K2000 of the Keithley. The output signal of the silicon photodiode was amplified by an operational amplifier, OPA111BM with a feed back resistance from 10 kΩ, 100 kΩ, 1 MΩ, 10 MΩ and 100 MΩ. The amplified output was monitored by a voltmeter, 3458A of the Agilent.

2.2. Measurement of temperature coefficient

Four kinds of fixed-point blackbodies were used, copper (1084.62 ºC), silver (961.78 ºC), aluminium (660.323 ºC) and zinc (419.527 ºC) [5]. The temperature coefficients of 0.65 μm thermometers were measured only at copper and silver. Usually the coefficients of 0.9 μm thermometers were measured any of the first three fixed points and the zinc point coefficient was measured especially for this research.

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In measuring the temperature coefficient, the laboratory temperature had been set at 21 °C from the previous evening. Next morning two freezing curves of the fixed point were measured. Then the laboratory temperature was increased to 25 °C. After waiting for three hours two freezing curves were measured again.

3. MEASURED RESULTS

3.1. Filter wavelength 0.65 μm

Fig. 1 shows an example of the temperature coefficient measurement of the 0.65 μm radiation thermometer R1. The laboratory temperature was 21 °C and 25 °C and the instrument temperature was about 22.4 °C and 27 °C, respectively. The output signal of the thermometer decreased from 44.58 mV to 44.53 mV. From the slope of the linear fitting, the temperature coefficient of the thermometer was obtained as -0.027 %/°C.

Fig. 2 shows temperature coefficients of eight 0.65 μm radiation thermometers from 1994 to 2008. In the legend after R*n* (*n*=1 to 8), A denotes that the detector is S2386-5BK and B denotes that the filter is a hard coating type of the Barr Associates, respectively.

R1: The temperature coefficient of R1 using a Barr filter was measured six times from 2000 and the average and the standard deviation were -0.027 %/°C and 0.004 %/°C, respectively.

R2: The temperature coefficient of R2 using an OCJ filter was measured four times from 1999 and the average and the standard deviation were +0.015 %/°C and 0.002 %/°C, respectively. The filter of R2 was changed to a Barr filter in early 2006. The temperature coefficient was -0.02 %/°C in 2006 and 2008.

R3: The temperature coefficient of R3 using an OCJ filter was +0.016 %/°C in 2000 and +0.018 %/°C in 2001 then it increased to +0.042 %/°C in 2003 and +0.088 %/°C in 2005. This change corresponded to the filter center wavelength shift to longer wavelength, 0.5 nm from 2001 to 2003 and 4 nm from 2003 to 2005 [1]. The filter of R3 was changed to a Barr filter in early 2006. The temperature coefficient became negative, -0.01 %/°C in 2006 and 2008.

R4: The temperature coefficient of R4 using a Topcon filter was measured three times from 1994 and the average and the standard deviation were -0.045 %/°C and 0.001 %/°C, respectively.

R5: The temperature coefficient of R5 using a Barr filter was -0.08 %/°C in 1999 and after changing the detector and the amplifier, it was -0.02 %/°C.

R6: The temperature coefficient of R6 using an OCJ filter was +0.01 %/°C in 1994. After changing the filter to a Barr filter, it became -0.02 %/°C in 1998 and 2008.

R7, R8: The temperature coefficients of R7 and R8 using OCJ filters, were +0.02 %/°C.

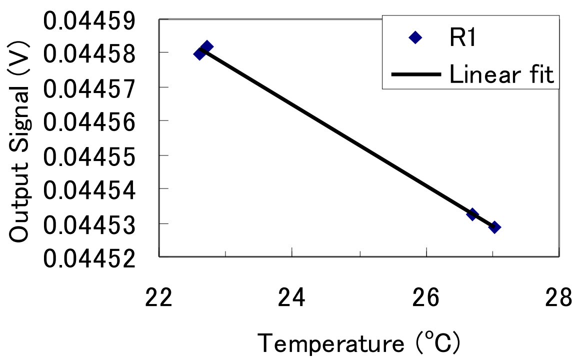

Fig. 1. Instrument temperature dependence of the output signal of the 0.65 μm radiation thermometer R1 at the copper point.

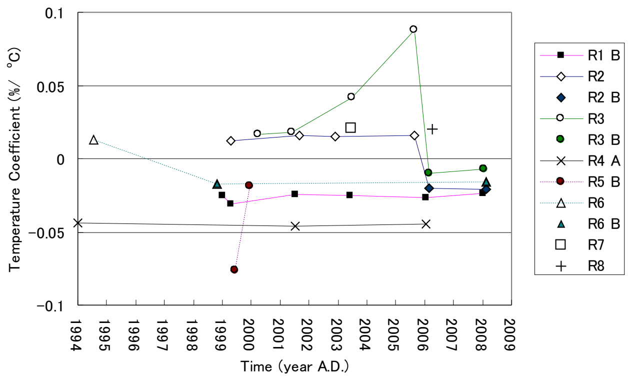

Fig. 2. Temperature coefficients of 0.65 μm radiation thermometers. B in the legend box means a Barr filter.

3.2. Filter wavelength 0.9 μm

Temperature coefficient stability

Fig. 3 shows temperature coefficients of six 0.9 μm radiation thermometers from 1983 to 2008 AD.

S1: The temperature coefficient of S1 with an S874-5K detector and a 0.88 μm filter was +0.23 %/°C. The detector and filter were changed and the coefficient became +0.02 %/°C and was stable from 1994 to 2008.

S2: The temperature coefficient of S2 with an S2386 detector was measured seven times from 1999 and the average and the standard deviation were +0.016 %/°C and 0.004 %/°C, respectively.

S3: The temperature coefficient of S3 with an S1336-5BK detector was measured five times from 1999 and the average and the standard deviation were +0.029 %/°C and 0.006 %/°C, respectively.

S4: The temperature coefficient of S4 with an S1336-5BK detector was +0.025 %/°C.

S5: The temperature coefficient of S5 with an S1336-5BK detector was +0.01 %/°C in 1999 and in 2006.

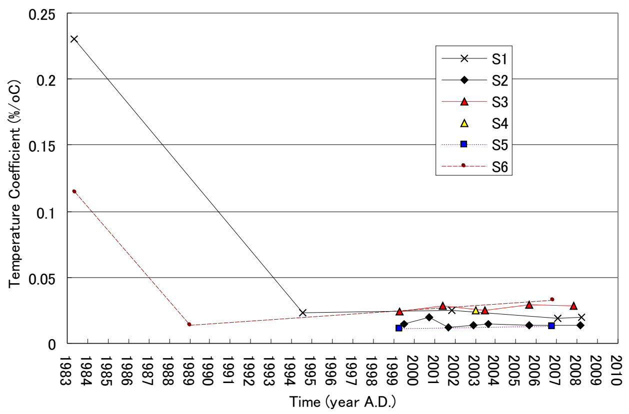

Fig. 3. Temperature coefficients of 0.9 µm radiation thermometers

S6: The temperature coefficient of S6 with an S874-5K detector was +0.11 %/°C. After changing the detector to S1336-5BK the coefficient became smaller, 0.014 %/°C in 1989 and 0.03 %/°C in 2004.

Dependence on target temperature

Fig. 4 shows the target temperature dependence of the temperature coefficient of S1 at the four fixed points. Gain 10 was used at the Zn and Al points, gain 1 at the Ag point, and gain 0.1 at the Cu point. The solid line shows the temperature coefficient when the center wavelength shifts 0.026 nm/°C to longer wavelength. This was calculated by the following equation

$$\frac{dV}{V} = (-5 + \frac{c_2}{\lambda T}) \cdot \frac{d\lambda}{\lambda}, \qquad (1)$$

derived from the Wien's equation. Here dV is the change of the output V, c_2 is the second radiation constant, λ is the center wavelength, $d\lambda$ is the wavelength shift and T is the target temperature. The error bar shows the standard deviation of the coefficient calculated from the four measured data as in Fig. 1. The standard deviation at 420 °C was large because the 0.9 µm thermometer output was small. At other points the error bars were too small to see.

Fig. 5 shows the target temperature dependence of the temperature coefficient of S2 at the four fixed points. Different gains were used at the Al, Ag and Cu points to study the gain dependence of the coefficient. The solid line shows the temperature coefficient when the center wavelength shifts 0.026 nm/°C to longer wavelength.

The target temperature dependence of the temperature coefficients of five 0.9 µm radiation thermometers were measured at the four fixed points. Most data were measured at the Ag and Cu points. Most measured coefficients are matched as the center wavelength shifts to longer wavelength between 0.015 nm/°C and 0.035 nm/°C.

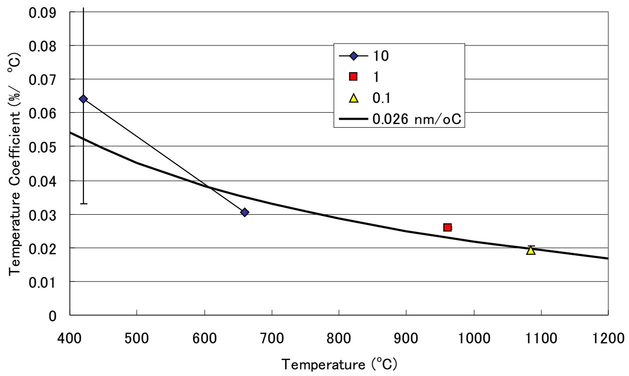

Fig. 4 Target temperature dependence of the temperature coefficient of S1 at the four fixed points. Different gains 10 to 0.1 were used. The line shows the effect of wavelength shift by 0.026 nm/°C.

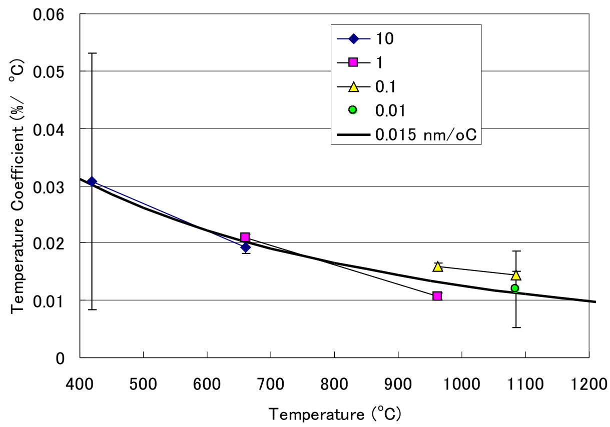

Fig. 5 Target temperature dependence of temperature coefficient of S2 at the four fixed points. Different gains 10 to 0.01 were used. The line shows the effect of wavelength shift by 0.015 nm/°C.

3.3. Filter wavelength 1 *µm*

The temperature coefficients of two 1 µm radiation thermometers were measured. Figure 6 shows the temperature coefficient of T1 at the four fixed points. The coefficient was much larger than 0.9 µm and was from +0.33 %/°C to +0.41 %/°C. The standard deviation at the Zn point was much smaller than that of 0.9 µm. The measured data can be explained by the sum of two effects. One is a center wavelength shift of the filter by 0.065 nm/°C to longer wavelength side (dashed line) and the other is a constant shift of 0.28 %/°C due to the detector (dotted line). The sum is shown by a solid line.

The temperature coefficient of T2 was from +0.23 %/°C to +0.30 %/°C. Figure 7 shows the target temperature dependence of the temperature coefficient of T2 at four fixed points. The standard deviation was about 0.002 %/°C so the deviation cannot be seen in the figure. The solid line and dotted line show the effect of wavelength shift by 0.057 nm/°C and constant offset 0.182 %/°C, respectively and the

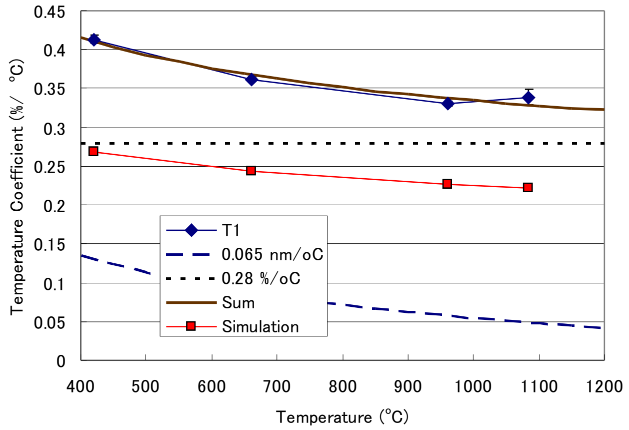

Fig. 6 Target temperature dependence of temperature coefficient of T1 at the four fixed points (diamond). The dashed line and dotted line show the effect of wavelength shift by 0.065 nm/°C and constant offset 0.28 %/°C, respectively and the thick solid line shows the sum of the two. A square shows the simulation result based on the spectral responsivity and detector temperature coefficient.

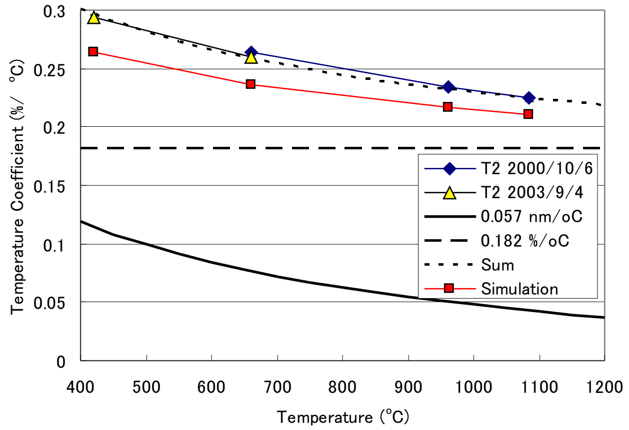

Fig. 7 Target temperature dependence of temperature coefficient of T2 at the four fixed points. Diamonds and triangles show data of different date. The solid line and dashed line show the effect of wavelength shift by 0.057 nm/°C and constant offset of 0.18 %/°C, respectively and the dotted line shows the sum of the two. A square shows a simulation result based on the spectral responsivity and detector temperature coefficient.

solid line shows the sum of the two. The tendency is the same as T1 but the coefficient was a little less.

4. DISCUSSION

The detector, the filter and the amplifier contributed the temperature coefficient of radiation thermometers.

4.1. Detector dependence

In case of Topcon radiation thermometers four kinds of detectors were used. They were S874-5K, S1226-5BK, S2386-5K and S1336-5BK. Old S874 and S1226 had small temperature dependence at 0.65 µm and large temperature dependence of 0.3 %/°C at 0.9 µm and 0.7 %/°C at 1 µm. S2386 and S1336 had no temperature dependence from 0.6 µm to 0.9 µm and about 0.1 %/°C at 1 µm and increased rapidly in longer wavelength [6]. The main factor of the temperature coefficients of 1 µm thermometers is the detector.

In Fig. 3 all six 0.9 µm thermometers used OCJ filters. In 1983 the detectors of S1 and S6 were S874 and had large temperature coefficients. After changing the detectors to S2386 or S1336 the temperature coefficients were about +0.02 %/°C.

Simulation of 1 µm thermometer

The output V of a radiation thermometer with a relative spectral responsivity $R(\lambda)$ measuring a blackbody of temperature T is calculated as follows

$$V(T) = a\int R(\lambda)L(\lambda,T)d\lambda. \qquad (2)$$

Here a is a constant and L is the Planck's function at the wavelength λ. Using the temperature coefficient α at λ, the instrument temperature t_a dependence of the output is shown as follows.

$$\alpha(\lambda) = \frac{1}{R(\lambda)}\frac{dR(\lambda)}{dt_a}, \qquad (3)$$

$$\frac{dV}{dt_a} = a\int \alpha(\lambda)R(\lambda)L(\lambda,T)d\lambda. \qquad (4)$$

The measured spectral responsivity data of T1 and S2 are shown in Fig. 8 as a thick solid line and a dotted line, respectively. The temperature coefficient shown as a thin solid line started to increase from 940 nm. The responsivity of S2 was influenced negligibly in this case.

The integrands of eq. (2) at the copper point and zinc point are shown in Fig. 9 as a thick solid line and a dotted line, respectively. Because of the characteristics of the

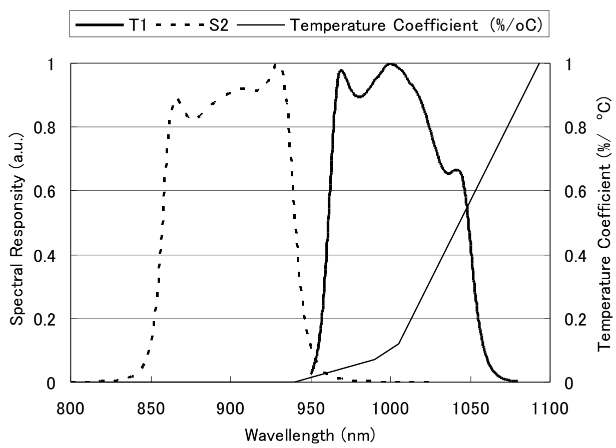

Fig . 8 Spectral responsivity of T1 (thick solid line) and S2 (dotted line). Temperature coefficient of S1336 (thin solid line) [5].

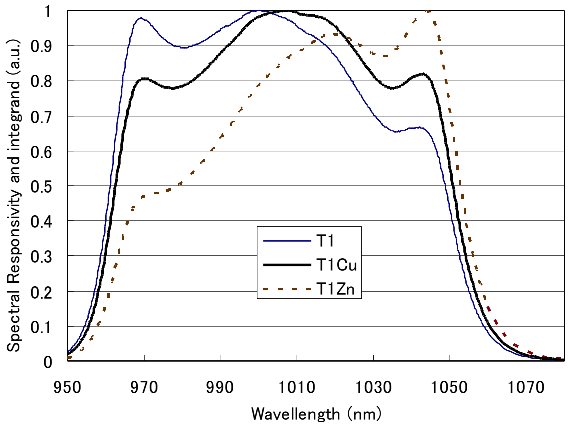

Fig. 9 Spectral responsivity of T1 (thin solid line) and normalized integrands at the copper point (thick solid line) and the zinc point (dotted line).

Planck's equation, the weight of the integrand shifts to the longer wavelength as the temperature decreases.

The simulated temperature coefficients of T1 and T2 are shown as squares in Figs. 6 and 7. The simulated coefficients were similar in tendency to and less than the measured ones, about 70 % for T1 and 90 % for T2, respectively. The target temperature dependences of the simulation were also smaller than the measured data. The difference might come from the detector temperature coefficient data because only typical values were shown in the manufacturer's data sheet.

4.2. Filter dependence

0.65 μm: In Fig.2 the temperature coefficients of 0.65 μm thermometers with Barr filters were negative and about -0.02%/°C while those with OCJ filters were positive and about +0.02%/°C. When the filter was changed from the OCJ to the Barr for R2, R3 and R6, the coefficient changed from positive to negative. This fact clearly shows that the filter contributes the temperature coefficients. The difference of the temperature coefficients between the Barr filters and the OCJ filters was about 0.04 %/°C which corresponded to 0.02 nm/°C at the copper point. This value is the same order of the temperature coefficients of interference filters in a manufacturer's catalogue [7].

0.9 μm: In Figs. 4 and 5 the temperature coefficients of 0.9 μm thermometers S1 and S2 had clear target temperature dependence. The temperature coefficient increased as the target temperature decreased. This dependence is very well explained by the center wavelength shift of 0.026 nm/°C for S1 and 0.015 nm/°C for S2 to the longer wavelength shown as a solid line in the Figs. 4 and 5. If the main contributions of the temperature coefficients of five 0.9 μm thermometers were filter center wavelength shift, the shifts were from 0.015 nm/°C to 0.035 nm/°C.

1 μm: The temperature coefficients of 1 μm thermometers T1 and T2 increased as the target temperature decreased. The amount of increase was estimated as 0.065 nm/°C for T1 and 0.057 nm/°C for T2 in shift of the center wavelength with a offset of 0.28 %/°C for T1 and 0.182 %/°C for T2. The main wavelength shift and offset comes from the detector. More detailed knowledge is necessary to discuss the filter change of 1 μm thermometers.

4.3. Thermometer S2 gain dependence

The target temperature dependence of the temperature coefficient of S2 was about 0.015 nm/°C. However the coefficient at the Cu point was higher by 0.005 %/°C. S3 had similar dependence. We checked the gain dependence of the coefficients in Fig. 4 and found that gain dependence exists and that the dependence was less than 0.005 %/°C

4.4. Stability

Figs. 2 and 3 show the stability of temperature coefficients. Unless the detector, filter and amplifier were changed, the temperature coefficients were usually stable for years; nine years for R1, seven years for R2, twelve years for R4, nine years for R6, twelve years for S1, six years for S2, nine years for S3 and seven years for S5. Therefore the coefficients are usually stable in time. When the filter center wavelength shifted in time as R3, the coefficient also changed.

4.5. Correction error

Usually the measured temperature coefficient was assumed to be a constant and independent of the target temperature. If the coefficient was mainly contributed from the shift of the filter center wavelength, the coefficient had the target temperature dependence. Here we consider the error in the mistreatment of the instrument temperature correction for 0.65 μm and 0.9 μm thermometers.

0.65 μm: The solid line in Fig. 10 shows the relative output change dV/V of a 0.65 μm radiation thermometer due to the center wavelength shift of 0.02 nm. The output change was 0.007 % at 2700 °C and 0.035 % at the copper point. If the temperature coefficient is corrected with the value at the copper point, 0.035 %, the error in the correction dt is calculated by the following equation,

$$dt = (0.035\% - \frac{dV}{V}) \cdot \frac{\lambda T^2}{c_2}. \quad (5)$$

The error is shown as a dotted line in Fig. 6 and is about 0.11 °C at 2700 °C.

0.9 μm: If the relative output change dV/V of a 0.9 μm radiation thermometer was due to the center wavelength shift of 0.03 nm, the output change was 0.007 % at 2000 °C, 0.022 % at the copper point and 0.062% at 400 °C as shown in Fig. 11. The temperature error in correcting with 0.022 % is +0.05 °C at 2000 °C and -0.01 °C at 400 °C.

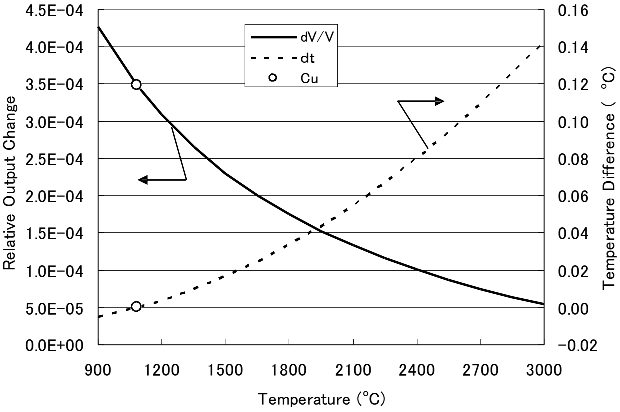

Fig. 10 Relative output change due to 0.02 nm change in center wavelength of a 0.65 mm radiation thermometer (solid line). Open circle shows the copper point. Broken line shows the temperature difference when the temperature coefficient is corrected with the value at the copper point (circle), 0.035 %.

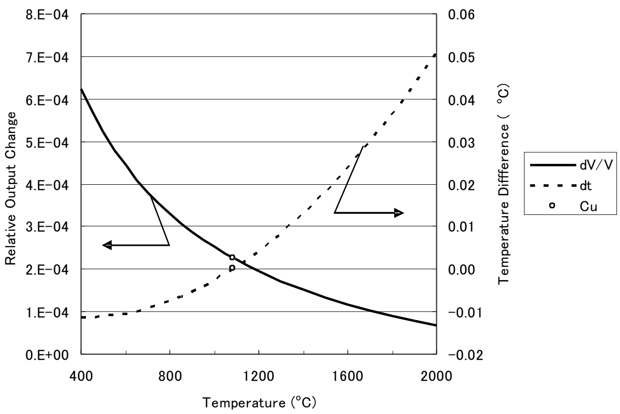

Fig. 11 Relative output change due to 0.03 nm change in center wavelength of a 0.65 mm radiation thermometer (solid line). Open circle shows the copper point. Broken line shows the temperature difference when the temperature coefficient is corrected with the value at the copper point (circle), 0.023 %.

5. CONCLUSIONS

The temperature coefficients of Topcon radiation thermometers were measured by calibrating the fixed-point blackbodies while changing the ambient temperature. The measured coefficients were from -0.05 %/°C to 0.02 %/°C, from 0.01 %/°C to 0.03 %/°C and about 0.3 %/°C for 0.65 μm, 0.9 μm and 1 μm, respectively. The temperature coefficients of 0.65 μm thermometers using OCJ filters were about 0.02 %/°C while those using Barr Associates filters were about -0.02 %/°C. Usually the temperature coefficients are stable in years unless the filter, detector and amplifier are changed. If the center wavelength shifted in time, the coefficient changed.

The target temperature dependences of the temperature coefficients of 0.9 μm radiation thermometers were measured at the copper, silver, aluminum and zinc points. The coefficients were larger at lower target temperatures and the result was well described by the shift of the filter center wavelength. The estimated shift was from 0.015 nm/°C to 0.035 nm/°C. Also a small temperature coefficient due to the gain difference was observed and the difference was within 0.005 %/°C. The target temperature dependences of 1 μm thermometers were also observed. This effect was caused by the large detector temperature coefficient which increased rapidly in a longer wavelength.

When the filter center wavelength shifts in the ambient temperature change, the correction of the instrument temperature should be different from other change, such as the detector response or the feedback resistance. The effect of the wrong correction on the temperature error was estimated.

The best way of suppressing the instrument temperature effect is to control the instrument temperature including the detector, the filter and the amplifier. Recently we developed with the Chino a new standard radiation thermometer with the instrument temperature controlled at 30 °C [8].

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