A novel radiant source for infrared calibration by using a grooved surface

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A radiant source with a large aperture at 5—95 °C in the wavelength bands of 8—12 μm for calibrating infrared imaging systems has been designed. The effective emissivity of its flat bottom with concentric V-grooves was evaluated by the Monte-Carlo method whose correctness was tested and accuracy was discussed. The structure of the source was completed by incorporating the simulation results with the blackbody cavity effect. The source was certificated via an optical measurement system. The source can provide a consistent radiant flux with temperature uniformity of ±0.1 °C over an area of diameter of ϕ80 mm.

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As the fundamental to the definition of the international practical temperature scale (IPTS), blackbody cavities are used for the calibration of every kind of radiation thermometers[1]. The accuracy of radiation measurements of temperature is affected by blackbody calibrations[2]. National research council of Canada (NRC) established a calibration facility comprising both variable-temperature and fixed-point blackbody cavities covering the range from −50 to 2500 °C[3]. In 1995, Fowlder built the third generation water bath blackbody with high stability[4]. In 2001, Rice investigated five blackbody sources which reached the consistency within ±0.1 °C by measuring their brightness temperature using thermal-infrared transfer radiometer (TXR)[5]. With the developments of infrared (IR) technologies such as radiation thermometry, IR imaging, and IR detecting increasing significantly, the need to establish standard radiant sources with high quality becomes more important. The source is used for calibrating IR imaging at 5—95 °C in the wavelength bands of 8—12 μm. Minimum resolvable temperature difference (MRTD) sensitivity of the IR imaging system requires that the source has high uniformity, stability, and resolution. The shape of a cavity which is chosen for a particular application is determined by physical suitability and ease of construction[1]. Blackbody cavities with simple shapes and small apertures are often suitable for the case of high temperature range, but not for IR imaging. Some radiant sources with complex structures such as blackbody cavities with groove cylinders[6] have been developed for applications in low temperature ranges and far IR wavelength bands. The flat bottom of the source was processed into concentric V-grooves to increase its intrinsic emissivity.

Bedford method[7] which is available for analyzing many kinds of structures has become one of the most effective precise methods in blackbody cavity theory. In 2001, Caola applied it to study a non-isothermal spherical cavity[8]. Because the precise method involves calculating angle factors[1] between surfaces, it is difficult to adopt it to investigate the V-groove surface. Monte-Carlo techniques have been widely used in optical radiometry and blackbody cavity analysis[6,9]. Therefore, the Monte-Carlo method was used to analyze the bottom of the source. Analysis of the ray tracing is shown in Fig. 1 within which is the section through the source. For groove k which is formed by two cones, concave con1 and convex con2, the radiation either incident on or emitted by groove k is taken to consist of a very large number of discrete rays of energy. The trajectory of each ray within groove k due to multiple reflections is taken to be governed by the laws of probability. The history of each ray is then traced until the ray either is absorbed or leaves groove k. The angle of emission, whether absorption or reflection occurs at each contact point, and the angle of each reflection are all chosen at random with cognizance being taken of the proper weighting for each event. The effective emissivity of groove $k(\varepsilon_a(k))$ will converge to the true value as the number of traced rays increases.

When we consider the reflectance of an incident ray by the spectral-bidirectional reflectance distribution function (BRDF)[10], the complexity of BRDF is evident. However, the condition can be simplified by noting that surfaces may be idealized as isotropically diffuse or

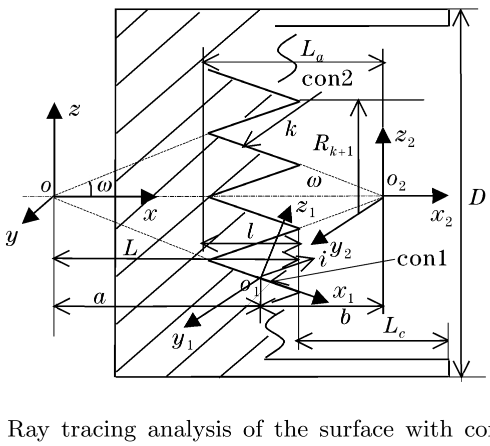

Fig. 1. Ray tracing analysis of the surface with concentric V-grooves.

perfectly specular[1]. If the surface is diffuse, the probability of zenith angle θ of an emitted ray (or a reflected) is

$$P(\theta) = \int_0^\theta 2\sin\theta\cos\theta \mathrm{d}\theta = \sin^2\theta. \quad (1)$$

Since the function rand( ) from Visual C++ has a better uniformity in comparison with the common modulo method[11], it is chosen as the random generator in the Monte-Carlo simulation. The procedures of Monte-Carlo simulation for V-groove k are as follows.

The first procedure is to choose either con1 or con2 on which ray i is emitted, to calculate the position (a) of the ray according to the random sampling, and to determine the angles (θ, φ) of the ray. If the ray is on con1, the simulation flow goes to the second procedure, otherwise, to the third procedure.

The second procedure is to judge whether the ray crosses con2 or con1. If it crosses neither con2 nor con1, the ray flies out of the groove, then the general energy radiates out (E_{out}) accumulates, the flow goes to the fourth procedure.

The equation of the ray is (in coordinates $O_1X_1Y_1Z_1$)

$$\begin{cases} z_1^2 = \mathrm{ctg}^2\theta(x_1^2 + y_1^2) \\ y_1 = x_1\mathrm{tg}\varphi \end{cases}. \quad (2)$$

The con2 equation is

$$x_2^2\mathrm{tg}^2\omega = y_2^2 + z_2^2. \quad (3)$$

The transformation between $O_2X_2Y_2Z_2$ and $O_1X_1Y_1Z_1$ is

$$\begin{cases} x_2 = x_1\cos\omega + z_1\sin\omega - b \\ z_2 = -x_1\sin\omega + z_1\cos\omega - a\mathrm{tg}\omega \end{cases}. \quad (4)$$

From Eqs. (2) and (3), we obtain

$$Ax_1^2 + Bx_1 + C = 0. \quad (5)$$

The cross point x_1 is the root of it.

Pursuant to Eq. (4), x_1 is transformed into x_2. If $L - a - b \geq x_2 \geq L - l - a - b$, the ray crosses con2, otherwise it may cross con1. If the ray is reflected at the cross point, the position is taken down and the angles (θ, φ) of the reflected ray are generated, the flow goes to the third procedure or the second procedure according to the cross point is on either con2 or con1 respectively.

The third procedure is to judge whether the ray on con2 crosses con1, if the ray crosses con1 at x ($x = x_1\cos\omega + z_1\sin\omega + a$), then $L \geq x \geq L - l$. If it is reflected at the cross point, its position is taken down, the reflected angles (θ, φ) are generated, the flow goes back to the second procedure, otherwise, it is absorbed, then goes to the fourth procedure. If it does not cross con1, E_{out} accumulates, the flow goes on to the fourth procedure.

The fourth procedure is to increase the ray number, if it has not reached the total sampling number N_{s}, the flow returns back to the first procedure; otherwise the simulation stops to calculate the effective emissivity of groove k

$$\varepsilon_a(k) = \varepsilon \cdot E_{\text{out}} \cdot (A_{\text{con1}} + A_{\text{con2}})/(A_{\text{r}}(k) \cdot N_{\text{s}}), \quad (6)$$

where $A_{\text{r}}(k) = \pi(R_{k+1}^2 - R_k^2)$.

Because $\varepsilon_a(k)$ is determined statistically after tracing all the rays, the simulated results are affected significantly by factors such as the Monte-Carlo model, ray tracing, sampling numbers, random sampling methods, the uniformity of random number generator etc. Only if the correctness is proved can the Monte-Carlo method be applied to perform the simulation. The correctness test was completed by comparing the result of the Monte-Carlo method with that of Bedford method for the same center cone of the surface. The errors between the two methods in every case are limited in 0.0004, usually around 0.0001 or 0.0002. Table 1 shows the correctness test calculation, $N_{\text{s}} = 2 \times 10^7$, ε is stuff emissivity.

The Monte-Carlo program was compiled and run under Visual Studio.net2003 environment. 30 grooves of a round piece surface were simulated, as shown in Fig. 2 ($\varepsilon = 0.95$, $\omega = 30°$, $l = 3$ mm). The simulation results fluctuate severely when N_{s} is small, and smooth gradually with N_{s} increasing. Since the results converge very slowly, the sampling number should be more than 2×10^7 to keep the deviation within 0.0001. In order to reduce the computing time, angle θ can be determined by the rejection sampling[11], $\theta = r_1\pi/2$ when $r_2 < \sin\pi r_1$ (r_1, r_2 are random numbers).

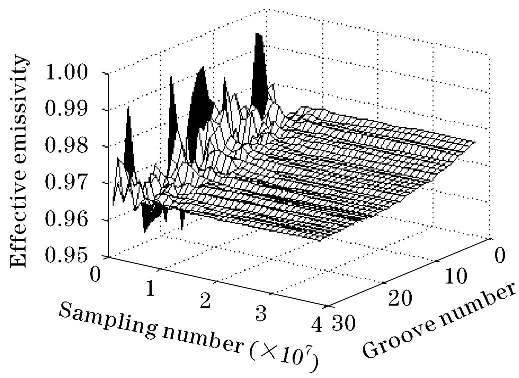

Fig. 2. Results of Monte-Carlo simulation.

Table 1. Correctness Test Calculation

ω	ε	0.75	0.77	0.79	0.81	0.83	0.85	0.87	0.89	0.91	0.93
22.5°	Precise	0.86780	0.87963	0.89121	0.90256	0.91368	0.92458	0.93526	0.94574	0.95602	0.96611
	Monte-Carlo	0.86742	0.87935	0.89098	0.90224	0.91380	0.92453	0.93513	0.94577	0.95612	0.96605
30°	Precise	0.84580	0.85940	0.87275	0.88586	0.89875	0.91141	0.92386	0.93611	0.94815	0.95999
	Monte-Carlo	0.84554	0.85939	0.87262	0.88561	0.89881	0.91140	0.92353	0.93621	0.94800	0.96000

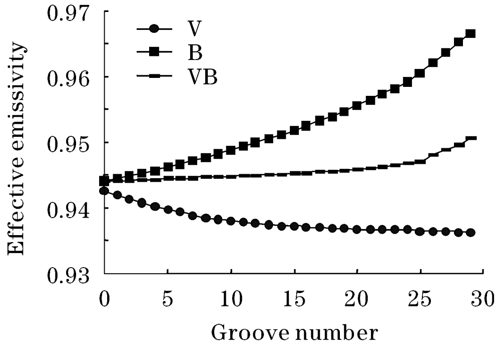

Fig. 3. Source effective emissivity distribution.

The values of $\varepsilon_a(k)$ become slightly lower from the center to the edge along radium direction. As shown in Fig. 3, curve V represents the emissivity distribution of the V-groove surface, and curve B is the emissivity distribution of the flat bottom of a cylinder cavity. A compensation for $\varepsilon_a(k)$ is made by combining the V-grooves surface with a short cylinder because of the blackbody cavity effect. The optimal design of the source structure was implemented by the calculation of the local effective emissivity of the bottom whose uniformity should be within 0.01 in the large scope. Therefore, the radiation of the source can be uniformly distributed over 80% of the bottom area when $Lc = D$, shown as curve VB.

Cesium and sodium filled heat pipes were used for large aperture sources[3]. The heating system of the source is realized by a heptane filled heat pipe, which keeps the temperature homogeneity of the bottom surface within ± 0.01 °C when the source is uprightly installed. There is a gold coated reflecting mirror arranged in 45° on the top to convert the radiation from the vertical direction into the horizontal direction[12].

The characteristics of the source were not only theoretically analyzed, but also tested by the scheme of the optical system, as shown in Fig. 4.

The source is laid on the focal plane of the parabolic mirror M1 (an off-axis parabola is used). The radiation coming out of the source is reflected by the mirror M2, changed into parallel rays by M1, and then it passes through the filter which limits the light within the band width of 8—12 μm. The incoming radiation is scanned by a mechanically rotating mirror, and it passes a chopper which eliminates the ambient disturbance then onto a parabolic mirror, which focuses the modulated alternate beam upon a detector of mercury-cadmium-telluride (HgCdTe) photoconductor[13] which is sensitive to far IR radiation (3—14 μm). The area of the bottom with

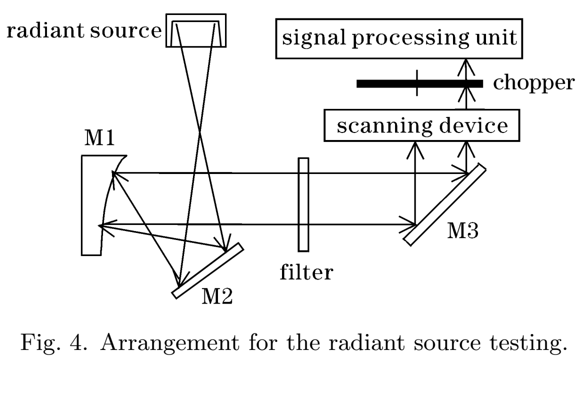

Fig. 4. Arrangement for the radiant source testing.

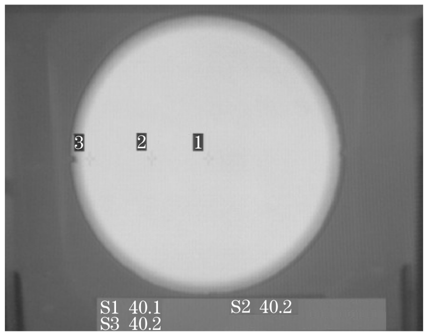

Fig. 5. Scanning image of the radiant source.

diameter of ϕ80 mm was scanned. The image of the radiant source is shown in Fig. 5, and the standard deviation of temperature distribution (S_{D}) is within ± 0.04 °C. Thus we should expect that 95% of the data would be within $1.96S_{\mathrm{D}}$. The results show that the radiant temperature uniformity and stability are within ± 0.1 °C.

In conclusion, design of the source is implemented by means of the Monte-Carlo analysis, the blackbody cavity theory, and the heat pipe technique etc.. The high sensibility, portability, and convenient operation make the source be appropriate for calibrating online. The experiment shows that the results tested fit the theoretical analysis well. In practical application, the source can provide homogenous and stable radiation and is an ideal standard source in IR imaging such as the visualization in dark environment and satisfies the requirement.

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