Research on a Radiant Source for Infrared Image Calibration

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Abstract. The theory, concepts and applications of blackbody cavities were introduced in this paper. Characteristics of a new kind blackbody cavity with large aperture which can be used as standard radiant source in infrared imaging system were discussed. The bottom of blackbody cavities was grooved with homocentric cycles in order to increase its intrinsic emissivity. The effective emissivity \( \varepsilon_a(r) \) of the bottom of the cavity were analyzed and calculated by combing the integrated equation method and the Monte Carlo method. For large number of Monte Carlo simulation, rejection Sample method was used to simulate the Monte Carlo probability model constructed in order to reduce the calculating time. The cavity characteristics have been further proved via testing the consistency and stability of the temperature field. The characteristics of this kind of heat pipe blackbody cavities with large aperture have been authenticated.

1. Introduction
Blackbodies are used for the calibration of every kind of radiation thermometer such as pyrometers, and also are fundamental to the definition of the International Practical Temperature Scale (IPTS). Blackbody has the greatest radiant power, which can be used as radiant standard to calibrate other objects’ radiation. To maintain the blackbody at the known freezing point of a metal; when the metal surrounding the cavity melts or freezes, not only is the temperature known without auxiliary measurement, but also the cavity is likely to be more nearly isothermal. Cavities used for calibrations need not to be black; to within the needs of the calibration, they will almost certainly be gray, in which case it is only necessary to know the values of their emissivities. These values are more readily calculated than measured [1].

NRC (National Research Council of Canada) has established a calibration facility comprising both variable-temperature and fixed-point blackbody cavities spanning the range from -50°C to 2500°C [2].

ASTER (a high-spatial-resolution multi-spectral imager on the Terra—the first platform of NASA’s Earth Observing System) needed a blackbody onboard for its calibration [3].

The design of a new type of heat pipe blackbody radiant source with a large aperture as a standard source for calibrating the infrared imaging system has been implemented. The radiant source whose radiant characteristics have been evaluated by the Monte Carlo method is suitable for infrared thermometry and imaging.
2. Methodology

Many people have worked on calculating emissivities of blackbody cavities and formed the theory of blackbody cavity. The main parameters often adopted for cavity characteristics are \( I_a \) and \( I_c \) [4]. The term effective emissivity with reference to a cavity. We define the effective spectral-directional emissivity of \( dA(x, y) \) on the cavity wall, written as \( \epsilon_a(\lambda, \theta', \phi', T, x, y) \), to be the ratio of the spectral exitance of \( dA(x, y) \) to the spectral exitance of if it were black at the same temperature.

\[
\epsilon_a(\lambda, \theta', \phi', T, x, y) = \frac{M_{\lambda}(\lambda, \theta', \phi', T, x, y)}{M_{\lambda,b}(\lambda, T)}
\]  

(1)

Because the precise method involves calculating angle factors 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 [5,6]. Lu Yiping used it to analyze the radiant distribution of a cylinder surface [7]. Therefore, the Monte Carlo method was adopted to analyze the bottom of the source. The Monte-Carlo model used here is to simulate the real physical model, in which radiant flux are considered coming from light points distributing identically along the surface, each ray possessing the same energy, that is \( E = \epsilon_0 T^4 \) (\( \epsilon \) is the staff emissivity; \( T, ds \) are the point temperature and its infinitesimal area respectively, \( \sigma \) is Boltzmann’s constant). The analysis of the ray tracing is shown in figure 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 is either 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 \( k \) (\( \epsilon_a(k) \)) will converge to the true value as the number of rays traced increases.

Monte-Carlo simulation: There are different sampling methods according to different distributions. When random variables are discrete, their distribution is as \( F(x) = \sum_{x_i < x} P_i \), where \( x_1, x_2, ..., x_i \) are the discrete points, \( p_1, p_2, ..., p_i \) are the corresponding probabilities and its’ sampling method is as the direct:

\[
\zeta_F = x_n, \quad \text{when} \quad \sum_{i=1}^{n-1} P_i < r \leq \sum_{i=1}^{n} P_i .
\]

As to a continuous distribution: \( F(x) = \int_{-\infty}^{x} f(t) dt \), where \( f(x) \) is its’ probability frequency function, the direct sampling method: \( \zeta_F = F^{-1}(r) \). But for large number of samples, rejection method is often adopted [8].
If \( f(x) \) is defined over \([a,b]\) interval, and has a limit \( M \), see figure 2, so \( f(x) \leq M \), its’ rejection sampling method is as below:

\[
M \cdot r_2 \leq f[a + (b-a) \cdot r_1] \\
Y \\
\bar{\xi} = a + (b-a) \cdot r_2
\]

To generate a point position: when \( r_2 \leq r_1 \), \( x = L \cdot r_1 \). To generate direction angles \( \theta, \psi \): when \( r_1 \leq \sin \pi r_1, \theta = (\pi/2) r_1 \). After \( \theta \) is got, then to determine \( \psi \) whose scope should be the part excluding the ray under \( \theta \) running out. The equation of the ray under half conical angel \( \theta \), is as below:

\[
\begin{align*}
\bar{z}_1^2 &= \cot^2(\bar{x}_1^2 + \bar{y}_1^2) \\
\bar{y}_1 &= \bar{x}_1 \tan \psi
\end{align*}
\]

The equation of the curve of the ring on the plane is as below:

\[
\begin{align*}
\left[(z_1 \sin \omega - x_1 \cos \omega) - R_{k+1}\right]^2 + y_1^2 &= R_{k+1}^2 \\
x_1 &= L - x \\
y_1 &= x_1 \tan \psi
\end{align*}
\]

The compound equation is got as below:

\[
A \cos^2 \psi + B \cos \psi + C = 0
\]

when no real root for \( |\cos \Psi| \leq 1 \), \( \Psi = 2\pi r \),

only one real root for \( |\cos \Psi| \leq 1 \), \( \Psi = 2(\pi - \Psi_2) r + \Psi_2 \),

two real roots for \( |\cos \Psi| \leq 1 \), \( \Psi = [2\pi - 2(\Psi_2 - \Psi_1)] r + \Psi_2 - 2\Psi_1 \)

The result of equivalent emissivity \( \varepsilon(r) \) from Monte-Carlo is higher than material intrinsic emissivity, but reduced along the radium. Substitute \( \varepsilon(r) \) into equation (5) to obtain the effective emissivity \( \varepsilon_a(r) \) on the bottom, because the second cavity effect, \( \varepsilon_a(r) \) getting higher and increase along the radium, which balance the trend of \( \varepsilon(r) \), and \( \varepsilon_a(r) \) become consistent on the bottom. See table 1.

\[
\varepsilon_a(r) = \varepsilon(r) + (1 - \varepsilon(r)) \int_{\rho}^{\rho'} \varepsilon_a(x) d^2 F_{\rho-\rho'}
\]
Table 1. Effective emissivity $e_a(r)$ on the bottom.

| Material intrinsic emissivity $e$ | 0.7 | 0.8 | 0.9 |
|----------------------------------|-----|-----|-----|
| $e_a(r)$                         | 0.991 | 0.995 | 0.999 |

3. Experiment Test

The radiant source was designed into the structure which is composed of the concentric V-groove surface plus cylinder shield. When it is isothermal, the radiant source possesses large surface with consistent radiant flux. Heat pipe technique which has high heat conductivity, reliability, temperature consistency and is proper for heating surface radiant sources was adopted as heating system. 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 (As shown in figure 3).

![Figure 3. The radiant source for infrared image calibration.](image)

The radiant source was tested by an optical system which converts the radiant light into 8~12μm bandwidth far infrared light. The incoming radiation is scanned by a mechanically rotating mirror, and it passes a chopper which eliminates the ambient disturbance then on to a parabolic mirror, which focuses the modulated alternate beam upon a detector of mercury-cadmium-telluride (HgCdTe) photoconductor [9] which is sensitive to far IR radiation (3~14μm). The standard deviation of temperature ($S_δ$) is within ±0.04°C. Thus we should expect that 95% of the data would be within 1.96 $S_δ$. The results show that the radiant temperature uniformity and stability are within ±0.1°C. See table 2. The results show that the effective emissivity $e_a(r)$ on the bottom is consistent.

Table 2. Temperature consistency of the cavity bottom.

| Setting temperature $T_S$(°C) | Scanning scope $\Phi(\%)$ | Radiant Temperature $T$(°C) | $\Delta T_{max}$(°C) | Consistency $T_b$(°C) |
|-------------------------------|-------------------------|---------------------------|----------------------|----------------------|
| 30.00                         | $\Phi 160 (\Phi 114 - 71\%)$ | 0.16                      | ±0.08                |
| 40.00                         | $\Phi 160 (\Phi 112 - 70\%)$ | 0.15                      | ±0.08                |
| 50.00                         | $\Phi 160 (\Phi 110 - 69\%)$ | 0.17                      | ±0.08                |
| 60.00                         | $\Phi 160 (\Phi 110 - 69\%)$ | 0.21                      | ±0.10                |
| 70.00                         | $\Phi 160 (\Phi 109 - 68\%)$ | 0.21                      | ±0.10                |
4. Conclusion
In order to obtain reliable calculation, correct Monte Carlo model should be set up and large sampling number is also a guarantee. From the convergence of the results the sampling number should be larger than $2 \times 10^7$. In addition, the homogeneity of the random number, correct sample methods are important factors to the correct results [10]. From the results calculated the effective emissivity of this kind cavity with large aperture can easily reach 0.99 for several intrinsic material emissivities. This is significant in applications. The results show the features of this kind of radiant sources satisfying the requirement well. The high sensibility, portability, convenient operation make the source being appropriate for calibrating online. The experiment shows that the results tested fit the theoretical analysis well. In the practical application, the source can provide homogenous and stable radiation and be an ideal standard source in IR imaging such as the visualization in dark environment and satisfy the requirement.

References
[1] Detit D P and Nutter G D 1989 Theory and Practice of Radiation Thermometry (John Wiley & Sons, InC) 656
[2] Hill K D and Woods D J 2003 The NRC blackbody-based radiation thermometer calibration facility Temperature: Its Measurement and Control in Science and Industry 7 669
[3] Tonooka H, Sakuma F, Kudoh M and Iwafune K 2004 ASTER/TIR onboard calibration status and user-based recalibration Proc. SPIE 5234 191
[4] Bedford R E, Ma C K, Chu Z, et al. 1985 Emissivities of diffuse cavities. 4: isothermal and non-isothermal cylindro-inner-cones Applied Optics 24 2971
[5] Ishii J, Kobayashi M and Sakuma F 1998 Effective emissivities of blackbody cavities with grooved cylinders Metrologia 35 175
[6] Prokhorov A V 1998 Monte Carlo method in optical radiometry Metrologia 35 465
[7] Yiping Lu, Bingji Li, Baocheng Jiang, et al. 2004 Directional radiation properties of an isothermal cylindrical cavity Journal of Harbin Institute of Technology 36 714
[8] Zhongji Xu 1985 Monte-Carlo Method Shanghai Science and Technology Press 98–108
[9] Norton P 2002 HgCdTe infrared detectors Opto-Electron, Rev. 10 159
[10] Hong Zhang and Jingmin Dai 2005 Evaluation on effective emissivity of a surface with homocentric V-grooves by Monte-Carlo method System Simulation & Scientific Computing Proceedings 1 124