Research of a blackbody cavity for effective integrated emissivity with finite volume method

Bo Liu¹, Chong-yuan Wang¹, Jun-long Xu¹, Zhi-yuan Wang², Peng-fei Zhu¹

¹Shanghai Institute of Measurement and Testing Technology, Shanghai, 201203, China
²School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai, 200093, China

*Corresponding author’s e-mail: liubo021@126.com

Abstract. Temperature is a critical parameter for energy efficiency measurement evaluation. High-performance blackbody radiation source is the key equipment for highly precise reproduction of radiation temperature. The effects of blackbody geometric parameters, cavity material emissivity, and temperature distribution on integrated effective emissivity \( \varepsilon_e \) and normalized spatial integrated effective emissivity variation were studied by finite volume method. The numerical simulation has a good agreement with the result computed by Monte-Carlo method. The results show that the isothermal cavity has a higher \( \varepsilon_e \) and a smaller than the non-isothermal. A smaller aperture diameter \( D_a \) and a higher material emissivity are benefit for a higher \( \varepsilon_e \) and a more uniform distribution on detector of \( \varepsilon_e \). The results provide references for the design and study on high-performance blackbody radiation source.

1. Introduction

Temperature is a critical parameter for energy efficiency measurement evaluation. Blackbody cavities are commonly used as standard radiation sources for the calibration of radiation thermometers, thermal imagers, and radiometers. Radiation reaching the detector from points at the inner surface of the cavities has two different components. One is due to direct emission from the point where the optical system is focused (depending on the local temperature and spectral-directional intrinsic emissivity \( \varepsilon \)). The other contribution is due to multiple reflections of the radiation originated at any other point inside the cavity, which finally reaches the detector by reflection in the focus point (depending on the reflectance: diffuse or specular) [1]. The effective emissivity \( \varepsilon_e \) which is central to blackbody designs accounts for both emitted and reflected radiation. In general, \( \varepsilon_e \) depends on the intrinsic surface emissivity, cavity geometry, and local temperature at the point of interest (and the cavity thermal gradient as a whole). However, a different reference temperature (instead of the local) can be used in the definition of \( \varepsilon_e \), such as that of the bottom cavity.

Computational methods are needed to accurately predict \( \varepsilon_e \) since experimental determination of \( \varepsilon_e \) is limited to restricted geometries, spectral ranges, and cavity temperature distributions. The theoretical methods for calculating \( \varepsilon_e \) in blackbody cavities generally include the resolution (analytically or numerically) of complex integral equations [1].

The Monte-Carlo back ray tracing technique is nowadays the most common method used for solving radiative transfer problems. This statistical technique basically consists (when it is applied to the calculation of effective emissivity) in throwing a large number of photons from the detector toward...
the point of interest inside the cavity and subsequently counting those exiting the cavity after multiple reflections [2]. The Monte-Carlo method, though effective, is time-consuming for large numbers of traced rays [3]. Other computational methods need to be developed and verified to assure their computational accuracy.

Due to advance in numerical simulation technology, Liu et al. [4] reported on integrated effective emissivity computations for nonisothermal nonaxisymmetric cavities using the finite volume method. The governing equations were solved by Ansys Fluent, with the results agreeing well with the Monte-Carlo method.

The axisymmetric cavities, including conical, cylindrical, and cylindro-conical cavities with and without grooved walls, are widely used and their $\varepsilon_e$ have been calculated by many methods [5,6]. However, very few studies have calculated the $\varepsilon_e$ by numerical simulation method. This paper studied the effect of geometric parameters, cavity material emissivity, and temperature distribution on $\varepsilon_e$. This study is useful to validate other method results for integrated effective emissivity computations.

2. Physical and numerical models

The cylinder cavity geometry configuration and temperature distribution are shown in Figure 1. $D$ is the cylinder diameter, $D_a$ is the cavity aperture diameter, $H$ is the cavity length, $\varepsilon$ is the cavity material emissivity. $D$ was set to one throughout because of the scaling properties. The temperature along $z$ axis was linear distributed. $\Delta T_e$ ($\Delta T_e = (T_a - T_b) / T_a$) is defined to describe the non-isothermal distribution. $\Delta T_e$ equals to zero for isothermal cavity. The material for the entire inner wall of the cavity was assumed to be uniform and grey so that the radiating cavity surfaces were spatially uniform and independent of the wavelength and to ensure that the surfaces exhibit diffused emissions and reflections.

![Figure 1. Cylinder cavity geometry and temperature distribution](image)

The key factors influencing integrated effective emissivity of the cylinder cavity are summarized in Table 1. The factors range is selected based on blackbody cavities manufacturers. The effects of $D_a$, $H$, and $\varepsilon_e$ are studied in Runs 1-2, 3-4, and 5-6, respectively. Isothermal and non-isothermal cavities are studied with $\Delta T_e = 0$ and 0.3 in Runs 1-6, respectively.

| Runs | $D_a$ | $H$ | $\Delta T_e$ / % |
|------|-------|-----|-----------------|
| 1    | 0.6 – 1.0 | 4   | 0.95            | 0     |
| 2    | 0.6 – 1.0 | 4   | 0.95            | 0.3   |
| 3    | 0.8     | 3 – 7| 0.95            | 0     |
| 4    | 0.8     | 3 – 7| 0.95            | 0.3   |
| 5    | 0.8     | 4   | 0.91-0.95       | 0     |
| 6    | 0.8     | 4   | 0.91-0.95       | 0.3   |

The local directional effective emissivity of a non-isothermal cavity in a non-refractive environment is
\[ \varepsilon_{e,i}(\xi, \omega) = \frac{L(T, \xi, \omega)}{L_b(T_0)} \]  

(1)

where \( L \) is the radiance emitted from a point \( \xi \) with a local temperature \( T \) on the cavity wall in the direction of \( \omega \); \( L_b \) is the radiance of a perfect blackbody at a reference temperature \( T_0 \) in the same direction. The bottom center temperature of the cavity was used as the reference temperature.

The integrated effective emissivity is defined as

\[ \varepsilon_e(D_a, H_a) = \frac{\Phi(D_a, H_a)}{\Phi_b(T_0, D_a, H_a)} \]  

(2)

where \( \Phi(R_b H_0) \) is the radiant flux falling onto the black detector that is irradiated by the radiating cavity surfaces, and \( \Phi_b(T_0, R_b H_0) \) is the radiant flux falling onto the same detector that is irradiated by a cavity with perfectly black walls. The integrated effective emissivity can be derived from Eq. (1) via integration over the appropriate areas and solid angles.

The outgoing flux from the radiating cavity surface consists of the flux that is intrinsically emitted and that reflected after incidence from the other radiating cavity surfaces. Therefore, the outgoing radiant flux of a radiating cavity surface element is expressed as

\[ J_k = E_k + (1 - \varepsilon_k) \sum_{j=1}^{N} F_{k,j} J_j \]  

(3)

where \( E_k \) is the radiant flux emitted by a radiating surfaces element, \( \varepsilon_k \) is the emissivity of the radiating cavity surface, \( F_{k,j} \) is the configuration factor for two surface elements, and \( N \) is the number of surface elements. The local radiant flux is calculated by iteratively solving Eq. (3). The radiant flux that falls onto the black detector irradiated by the radiating cavity surfaces is

\[ \Phi(D_a, H_a) = \sum_{k=1}^{N} F_{k,a} J_k \]  

(4)

where \( F_{k,a} \) is the configuration factor for one surface element and the detector. The radiant flux falling onto the same detector that is irradiated by the cavity with perfectly black radiating surface is given by

\[ \Phi_b(T_0, D_a, H_a) = \sum_{k=1}^{N} F_{k,a} J_{k,b} \]  

(5)

where \( J_{k,b} \) is the outgoing radiant flux of a perfect black surface element. Thus, the integrated effective emissivity is calculated as

\[ \varepsilon_e(T_0, D_a, H_a) = \frac{\Phi(D_a, H_a)}{\Phi_b(T_0, D_a, H_a)} = \frac{\sum_{k=1}^{N} F_{k,a} J_k}{\sum_{k=1}^{N} F_{k,a} J_{k,b}} \]  

(6)

The configuration factors were calculated using the surface-to-surface model in Ansys Fluent according to the geometry and the grid. The radiating cavity surface temperature distribution was defined using a UDF.

The detector does not affect the radiative transfer. Therefore, the detector emissivity was set to 1, and the temperature was set to 0 K.

3. Mesh independence test and model verification

The integrated effective emissivity of non-isothermal axisymmetric cylindrical cavities were calculated at \( D = 1, D_a = 0.8, H = 4, \varepsilon = 0.91, T_a = 500 \text{ K}, \) and \( T_b = 498.5 \text{ K} \). A fictitious detector was set at the cavity aperture. In other words, the detector diameter equals to \( D_a \) and the distance from the detector to the aperture is zero. Figure 2 shows the computational results for various numbers of elements. As demonstrated, the difference is less with the increase of elements. Therefore, in order to save computational time, similar meshing method and grid size to the \( 2.3 \times 10^3 \) elements were employed for the subsequent runs.
Comparison with Monte-Carlo results [7] had been made to verify the model setup in our previous study [8],[9]. The maximum relative difference is less than 0.005%, indicating that the present method is accurate.

Figure 2. Effect of elements numbers on the integrated effective emissivity

4. Results and discussion

Figure 3 shows the effect of aperture diameter $D_a$ on integrated effective emissivity $e$ and normalized spatial integrated effective emissivity variation with $H = 4$ and $\eta = 0.95$. $e$ is defined to describe the $e$ distribution on detector, as $\eta = \frac{e}{e_{\text{mean}}}$, in which $e_{\text{mean}} = \int e dA / \int dA$ and $e^2 = \int (e - e_{\text{mean}})^2 dA / \int dA$. With the increase of $D_a$, the $e$ decrease and the increase in both isothermal and non-isothermal conditions. A smaller $D_a$ indicates that the cylinder cavity is closer to an ideal blackbody. An inverse trend is observed between $e$ and $\eta$. In other words, a higher $e$ indicates its distribution is more uniform. The cavity bottom temperature is set as reference temperature for the calculation of $e$. The isothermal cylinder cavity emits more radiation flux than the non-isothermal one. Therefore, the isothermal cavity has a higher $e$ and a smaller $\eta$ than the non-isothermal.

Figure 3. Effect of $D_a$ on $e$ and $\eta$ with $H = 4$ and $\eta = 0.95$

Figure 4 shows the effect of cavity length $H$ on $e$ and with $D_a = 0.8$ and $\eta = 0.95$. The influence of $H$ is less significant in isothermal condition. The $e$ decreases and the $\eta$ increases with the increase of $H$ in non-isothermal conditions. For the blackbody source manufacturer, a method to improve cavity thermal homogeneity is more useful than extend the cavity length. Figure 5 shows the significant effect of cavity material emissivity on $e$ and with $D_a = 0.8$ and $H = 4$. With the increase of $e$, the $e$ increases and the $\eta$ decreases in both conditions. A linear relationship is observed between the $e$ and the $\eta$ in all the studied Runs, not shown in figure for brevity. Generally
speaking, the blackbody source with a higher $e$ will have a uniform distribution of $e$ on the detector. This performance is benefit for thermometer calibration.

![Figure 5. Effect of $\alpha$ on $e$ and $\epsilon$ with $D_a = 0.8$ and $H = 4$.](image)

5. Conclusions

High-performance blackbody radiation source is the key equipment for highly precision reproduction of radiation temperature. This paper studied the effect of geometric parameters, cavity material emissivity, and temperature distribution on integrated effective emissivity $e$ and normalized spatial integrated effective emissivity variation by finite volume method. The numerical simulation has a good agreement with the result computed by Monte-Carlo method. The results show that the isothermal cavity has a higher $e$ and a smaller $\alpha$ than the non-isothermal. A smaller aperture diameter $D_a$ and a higher material emissivity are benefit for a higher $e$ and a more uniform distribution on detector of $e$. The results provide references for the design and study on high-performance blackbody radiation source.

Acknowledgements

This work was supported by the Research Program of Shanghai Municipal Bureau of Quality and Technical Supervision (No. 2018-17).

References

[1] Bedford, R.E. (1988) Calculation of effective emissivities of cavity sources of thermal radiation. In: DeWitt, D.P. and Nutter, Gene D. (Eds.), Theory and practice of radiation thermometry. Wiley Inc., New York. pp. 653-772.

[2] Prokhorov, A.V. (1998) Monte Carlo method in optical radiometry. Metrologia, 35: 465-472.

[3] Liu, D. Duan, Y.Y. Yang, Z. (2013) Calculations of the average normal effective emissivity for nonaxisymmetric cavities using the modified finite volume method. Opt. Eng., 52: 039702.

[4] Liu, D. Duan, Y.Y. Yang, Z. (2013) Integrated effective emissivity computation for non-isothermal non-axisymmetric cavities. Chin. Opt. Lett., 11: 022001.

[5] Prokhorov, A. V. (2012) Effective emissivities of isothermal blackbody cavities calculated by the Monte Carlo method using the three-component bidirectional reflectance distribution function model. Appl. Opt., 51: 2322–2332.

[6] Prokhorov, A. V. (2012) Application of the three-component bidirectional reflectance distribution function model to Monte Carlo calculation of spectral effective emissivities of nonisothermal blackbody cavities. Appl. Opt., 51: 8003–8012.

[7] Prokhorov, A. V., Hanssen, L. M. (2004) Effective emissivity of a cylindrical cavity with an inclined bottom: I. Isothermal cavity. Metrologia, 41: 421-431.

[8] Liu, B., Zheng, W., Li, H.-Y., et al. (2018) Research of an isothermal blackbody cavity for effective integrated emissivity. In: 1st Chinese thermophysical properties conference, Hanzhong, China. TP2018050. (in Chinese)
[9] Liu B., Zheng W., Li H.-Y., et al. (2019) Study on integrated emissivity of an isothermal blackbody cavity with response surface methodology. Acta Metrologic Sinica, 40(4): 625-630. (in Chinese)