International Journal of Thermophysics, Vol. 16, No. 1, 1995

A Zirconia Near-Blackbody Radiation Source, 2500 K in Air[1]

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A near-blackbody radiation source was designed for operating in an oxidizing atmosphere up to 2500 K. As a small zirconia furnace, the radiation source has a blackbody cavity, provided by a lateral hole formed on an yttria-stabilized zirconia tube. A good transfer radiation source should have an emissivity independent of the wavelength. This condition depends on the emissivity of the material and on the thermal characteristics of the source. The emissivity of the cavity has been calculated for different experimental conditions. The influence of temperature gradients in the cavity has been outlined. The aperture of the source, which is given by the sizes of the holes in the radiation shields, should not be too large, to avoid a large temperature gradient, even though some compensation occurs. For special applications, the aperture can be as large as 60°. The stability of the source has been studied.

KEY WORDS: blackbody; emissivity; high temperature; infrared; pyrometry; radiation.

1. INTRODUCTION

Blackbody radiation sources are indispensable to calibrate infrared pyrometers, radiometers, and spectrometers, especially broad-band infrared instruments. The present paper describes the design, operation, and salient features of a new radiation source.

At high temperatures, one of the first kind of blackbody sources used in the past was a metallic tube electrically heated, with a lateral hole formed on it [1, 2]. This device was used to make the light intensity standard and to define the candela [3]. In this new radiation source, the blackbody

[1] Paper presented at the Twelfth Symposium on Thermophysical Properties, June 19–24, 1994, Boulder, Colorado, U.S.A.

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cavity is provided by a hole formed on an yttria-stabilized zirconia tube heated by the passage of electrical current. It operates in an oxidizing atmosphere up to 2500 K; thus it does not need any window, which would affect its apparant emissivity.[5]

To evaluate the quality of the blackbody source, we calculated the apparent emissivity, which depends on the properties of the material, the geometry of the cavity, and the thermal characteristics of the source.

Mostly, only a *transfer radiation source* is needed, the emissivity of which may be different from one, but should be independent of the wavelength. We examined how this condition is satisfied.

Two methods allow the calculation: the series-reflectivity method for diffusely reflecting cavities and the integral equation method.

The former method was applied for many years [4–6]. Approximate values were obtained, for simple geometries. The latter method has been the best since computers are in use. The most general problems can be solved by the integral equation method, but this method is also of great interest even for rather simple problems.

We extended Peavy's formulation [7] to nonisothermal cavities, for different geometries and different temperature distributions. The influence of the size of the lateral hole and of the temperature gradients was especially emphasized.

2. BLACKBODY SYSTEM

The blackbody system, designed to operate between 1500 and 2500 K, is shown in Fig. 1 [8]. The zirconia conductor (1, 3) is preheated to 1373 K in a kanthal furnace (5). The zirconia blackbody is surrounded by a zirconia radiation shield (2). The electrical contacts on the zirconia conductor are made by means of a lanthanum–chromite ceramic (4). The temperature gradients along the ceramic conductor should be such that the temperature of the electrical contacts does not exceed 1700–1800 K. The kanthal furnace is protected by an alumina thermal insulation (6), and its temperature is stabilized at 1373 K. The electrical power in the zirconia heater is about 1400 W at the maximum working temperature.

3. ANALYTICAL FORMULATION

Analytical formulation for the apparent emissivity of the surfaces of cylindrical enclosures has been derived by Sparrow et al. [9]. The equations are presented here in the form used by Peavy, except we added terms to take account of the fact that the cylindrical cavity may be closed at both

[5] Furnace manufactured by Pyrox, 78120 Rambouillet, France.

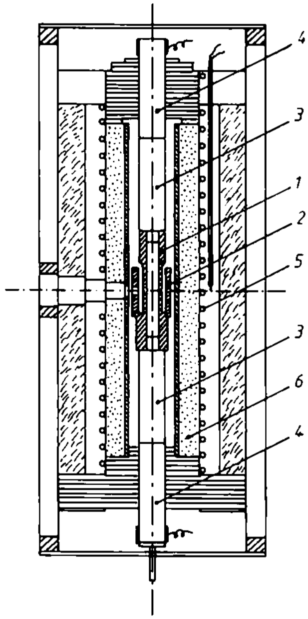

Fig. 1. Internal structure of the near-blackbody radiation source. (1) Zirconia blackbody; (2) zirconia radiation shield; (3) zirconia conductor; (4) lanthanum-chromite conductor; (5) kanthal resistor; (6) alumina thermal insulation to protect the kanthal resistor.

ends and that a lateral hole may be formed on the cylindrical surface. Bedford et al. [10–12] have studied cavities with a base and a lid, using another formulation.

As in the previous works, the discussion is limited to cavities with walls that emit and reflect diffusely. The wall emissivity e_w is assumed to be uniform, but we do admit the possibility of different values for the different surfaces of the cavity: e_x for the cylinder and e_L and e_0 for the bases.

The radiant exitances are given by Eqs. (1):

$$\begin{aligned} M(x_0) = e_{ax}(x_0)\, B_{ref} = e_x B_x(x_0) &+ (1 - e_x) \int e_{ax}(x)\, B_{ref} K_1(x_0, x)\, dx \\ &+ (1/4)(1 - e_x) \left\{ \int e_{aL}(r)\, B_{ref} z_0 K_2(x_0, r)\, r\, dr \right. \\ &\left. + \int e_{a0}(r')\, B_{ref} x_0 K_2'(x_0, r')\, r'\, dr' \right\} \end{aligned} \tag{1a}$$

$$M(r) = e_{aL}(r)\, B_{ref} = e_L B_L(r) + (1 - e_L)$$

$$\times \left\{ (1/2) \int e_{ax}(x)\, B_{ref} K_2(x, r)(L - x)\, dx \right.$$

$$\left. + 8 \int e_{a0}(r')\, B_{ref} L^2 K_3(r, r')\, r'\, dr' \right\} \tag{1b}$$

$$M(r') = e_{a0}(r')\, B_{ref} = e_0 B_0(r') + (1 - e_0) \left\{ (1/2) \int e_{ax}(x)\, B_{ref} K_2'(x, r')\, x\, dx \right.$$

$$\left. + 8 \int e_{aL}(r)\, B_{ref} L^2 K_3(r, r')\, r\, dr \right\} \tag{1c}$$

$e_{ax}(x_0)$, $e_{aL}(r)$, and $e_{a0}(r')$ are, respectively, the apparent emissivity on the cylindrical surface, the base at $x = L$, and the base at $x = 0$. The apparent emissivity $e_{ax}(x_0)$ is defined as the ratio of the radiant exitance $M(x_0)$ of coordinate x_0 to the blackbody radiance at temperature T_{ref}, and B_{ref}, $B_x(x_0)$, etc., are the Planck formula for blackbody radiance at temperature T_{ref}, $T(x_0)$, etc.

The kernels K_1, K_2, etc., are given by Eqs. (2), which are deduced from the angle factors between two elementary surfaces:

$$K_1(x_0, x) = 1 - (D/2)(2D^2 + 3)/(D^2 + 1)^{3/2} \tag{2a}$$

$$K_2(x, r) = (z + w)/[z^2 + z(1 - 2w) + w^2]^{3/2} \tag{2b}$$

$$K_2'(x, r') = (x^2 + w')/[x^4 + x^2(1 - 2w') + w'^2]^{3/2} \tag{2c}$$

$$K_3(r, r') = (4L^2 + r^2 + r'^2)/[(4L^2 + r^2 + r'^2)^2 - 4r^2r'^2]^{3/2} \tag{2d}$$

where $D = |x_0 - x|$, $z = (L - x)^2$, $w = (1 - r^2)/4$, L is the dimensionless length of the cavity (the length-to-diameter ratio), and x and r (and r') are the dimensionless coordinates (the distance along the cylinder-to-diameter ratio and the distance from the axis-to-radius ratio).

This formulation allows us to calculate the emissivity everywhere on the surfaces of all the cavities, which may be opened or closed at one or two ends, with or without a lateral hole, isothermal or not, and with different wall emissivity on the cylinder and on the bases.

The integral equations, Eq. (1), should be solved by iteration. The kernels $K_2(x, r)$ and $K_2'(x, r')$ become singular at the junctions of any two surfaces, so that we have used substitutions similar to those proposed by Peavy. Equations (1a) to (1c) become

$$e_{ax}(x_0) = e_x B_x(x_0) + (1 - e_x) \int e_{ax}(x)\, K_1(x_0, x)\, dx$$

$$+ (1/4)(1 - e_x)(b_0 I_{11} + b_1 I_{12} + S_{xr} + b_0' J_{11} + b_1' J_{12} + S_{xr'}) \qquad (3a)$$

$$e_{aL}(r) = e_L B_L(r) + (1 - e_L) \Big\{ (1/2)(a_0 I_{21} + a_1 I_{22} + S_{rx})$$

$$+ 8(1 - e_L) \int e_{a0}(r')\, L^2 K_3(r, r')\, r'\, dr' \Big\} \qquad (3b)$$

$$e_{a0}(r') = e_0 B_0(r') + (1 - e_0) \Big\{ (1/2)(a_0 J_{12} + a_1 J_{22} + S_{r'x})$$

$$+ 8(1 - e_0) \int e_{aL}(r)\, L^2 K_3(r, r')\, r\, dr \Big\} \qquad (3c)$$

where

$$a_0 = e_{ax}(L), \qquad a_1 = [e_{ax}(0) - e_{ax}(L)]/L^2$$

$$b_0 = e_{aL}(1), \qquad b_0' = e_{a0}(1), \qquad b_1 = 4[e_{aL}(0) - e_{aL}(1)]$$

and

$$b_1' = 4[e_{a0}(0) - a_{a0}(1)]$$

and B_x, B_L, and B_0 are dimensionless radiances assuming $B_{ref} = 1$.

The integrals are, for instance,

$$S_{xr} = \int e_{aL}(r)\, z_0 K_2(x_0, r)\, r\, dr \qquad (4a)$$

and

$$I_{11} = (L - x_0) \int K_2(x_0, r)\, r\, dr \qquad (4b)$$

Integrals I and J do not depend on the apparent emessivities, so that they may be calculated before the iterations.

A good agreement (better than $6 * 10^{-4}$) was obtained compared to Sparrow's and Peavy's results for cylinders closed at one end (wall emmissivity, $e_w = 0.5$; criterion for the last iteration, $|[e_{ax}(x)]_n - [e_{ax}(x)]_{n-1}| < 0.0001$; increment, 1/64). The smaller the increment (and the larger the wall emissivity), the better the agreement, but the longer the calculation.

3.1. Cavity with a Lateral Hole

The main aim of this work is to study the influence of a lateral hole on the apparent emissivity of nonisothermal closed cavities.

Despite the efficiency of the Monte Carlo method, a simpler method (even with rather rough assumptions) is of great interest to get the influence of some factors, such as the length-to-diameter ratio, temperature gradients, and the size of the lateral hole.

The following assumptions have been used: (i) The hole does not appreciably disturb the axial symmetry; (ii) the temperature (so the radiance) and the apparent emissivity depend only on the coordinate x, r, or r'; and (iii) the hole is assumed to be square, with a dimensionless side H (the side-to-cavity diameter ratio). Thus for $(L - H)/2 < x < (L + H)/2$ the angle factors are reduced, and the kernels K and K' are multiplied by $M = 1 - (\sin^{-1} H)/\pi$.

3.2. Nonisothermal Cavities

To express the dimensionless radiances, B_x, B_L, and B_0, one point has been chosen as reference. In the case of a cavity opened at one end, T_{ref} is the temperature at the center of the closed base, but in the case of a closed cavity with a lateral hole, T_{ref} is the temperature at the point of the cylinder opposite the lateral hole.

To calculate the total emissivity, we have to write

$$B_x(x) = [T(x)/T_{ref}]^4 \tag{5a}$$

and for the spectral emissivity,

$$B_x(x) = [\exp(c_2/\lambda T_{ref}) - 1]/[\exp(c_2/\lambda T(x)) - 1] \tag{5b}$$

Equation (5b), for monochromatic radiation, involves a correction smaller than the one given by Eq. (5a), except if the wavelength is smaller than 1.8 μm. We carried out all calculations with Eq. (5a).

The results have been given for two temperature profiles:

$$T(x') = T_0 - DT_x(2x'/L)^2 \tag{6a}$$

$$T(x') = T_0 - DT_x(2x'/L)^2 - DT_0 \exp(-4x'^2/H^2) \tag{6b}$$

where x' is the dimensionless distance from the center of the lateral hole along the x axis. The temperature is assumed to be constant on the bases. The first distribution, Eq. (6a), is such that the temperature at the center of the cavity is T_0, and the temperature on the bases is $T_0 - DT_x$. The last term in Eq. (6b) is introduced to take account of some cooling (DT_0) of the tube in front of the lateral hole. Owing to the size of the zirconia conductor, the electrical input, and the heat losses, the values of DT_x and DT_0 were roughly estimated, in order to have an idea of the influence of the temperature gradient on the apparent emissivity. The following values were used:

$$T_0 = 2300 \text{ K}, \qquad DT_x = 100 \text{ K}, \qquad DT_0 = 0\text{-}10\text{-}20 \text{ K}$$

4. RESULTS

Yttria-stabilized and calcia-stabilized zirconia have the same spectral emissivities in the infrared range [13]. This emissivity varies from 0.3 to 1 versus the wavelength [14, 15].

To discuss the results, we first present the emissivities for isothermal cavities and then show the influence of temperature gradients.

4.1. Isothermal Cavity with a Lateral Hole

As expected, the presence of a lateral hole decreases the apparent emissivity everywhere on the surface of the cavity, especially in front of the lateral hole. Figure 2 shows typical results of the apparent emissivity $e_{ax}(x)$ along the cylindrical surface of an isothermal cavity. The emissivity of

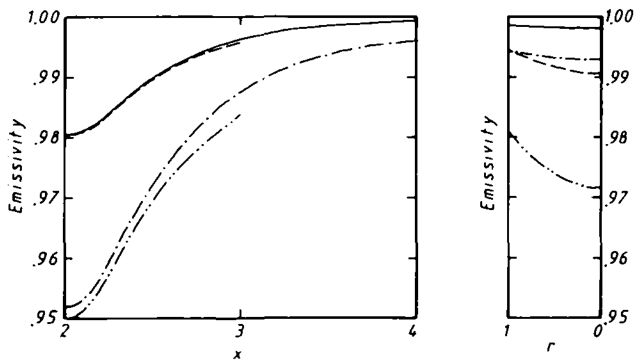

Fig. 2. Apparent emissivity $e_{ax}(x)$ and $e_L(r)$ in isothermal closed cavities with a lateral hole ($H = 0.5$; see explanation in the text). $e_w = 0.75$: ( ) $L = 4$; ( ) $L = 2$. $e_w = 0.5$: (· ·) $L = 4$; (·· ··-) $L = 2$.

cavity e_c, in front of the hole, remains rather large, even when the wall emissivity is as small as 0.5 and H as large as 0.5. Furthermore, the length of the cavity, over $L = 2$, does not change e_c significantly. In Fig. 3 we can see e_c decreasing when the hole size increases. Some results for nonisothermal cavities are also given in Fig. 3. Before concluding we have to look at how the temperature gradient affects e_c.

4.2. Nonisothermal Cavity with a Lateral Hole

Figure 4 presents typical results for nonisothermal cavities. Both temperature distributions Eq. (6a) and (6b) were considered, with $T_0 = 2300$ K, $DT_x = 100$ K, and $DT_0 = 0$, 10, and 20 K. The following conclusions can be drawn.

(1) The temperature distribution Eq. (6a), alone, lowers e_c from 1 to 0.986 in a fully closed cavity ($H = 0$, and $e_w = 0.5$). In an isothermal cavity, a lateral hole of size $H = 0.5$ has a larger effect: $e_c = 0.952$.

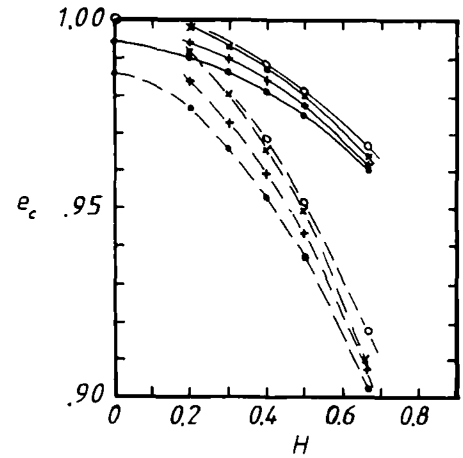

Fig. 3. Variation of the emissivity e_c of a cavity versus the size of the lateral hole. (——) $e_w = 0.75$; (- - - -) $e_w = 0.5$ ($L = 4$). (—○—) Isothermal cavity; (—•—) temperature distribution, Eq. (6a); (—+—) temperature distribution, Eq. (6b), with $DT_0 = 10$ K, $T_{ref} = 2290$ K; (—×—) temperature distribution, Eq. (6b), with $DT_0 = 20$ K, $T_{ref} = 2280$ K.

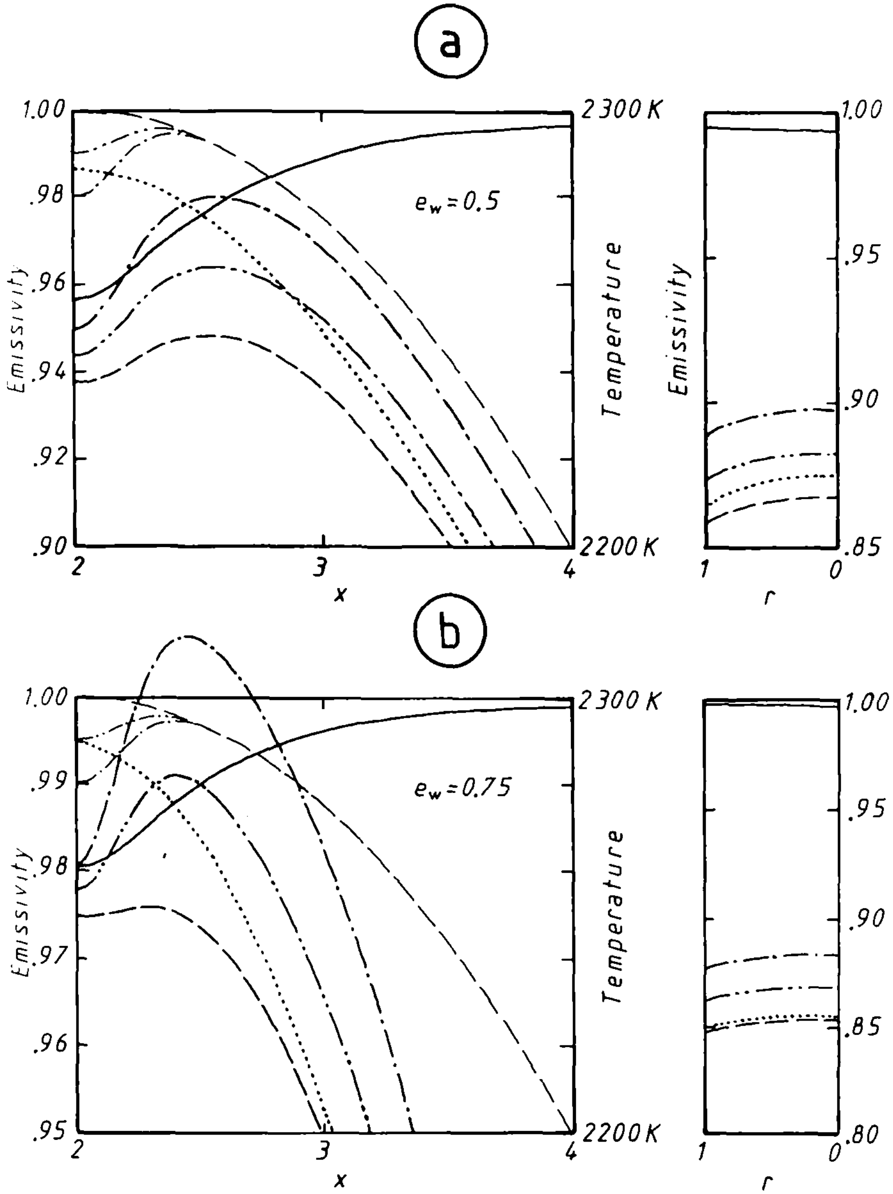

Fig. 4. Apparent emissivity of nonisothermal cavities ($H = 0.5$, $L = 4$; see explanation in the text). (a) $e_w = 0.5$; (b) $e_w = 0.75$. (– –) Temperature distribution, Eq. (6a), $DT_x = 100$ K; (·· ··–) temperature distribution, Eq. (6b), $DT_x = 100$ K, $DT_0 = 10$ K; (· · · ·) temperature distribution, Eq. (6b), $DT_x = 100$ K, $DT_0 = 20$ K; (–) isothermal cavity; (·········) full closed cavity ($H = 0$), temperature distribution, Eq. (6a).

(2) The effects of the lateral hole and of the temperature distribution are approximately additive; e_c is lowered to 0.938 in a non-isothermal cavity with a hole of size $H = 0.5$.

(3) The temperature distribution Eq. (6b), which takes account of some cooling in front of the lateral hole, provides some compensation, when $T_{ref} = T_0 - DT_0$, as shown in Fig. 4. For instance, the lowering of e_c is smaller ($e_c = 0.944$ when $DT_0 = 10$ K, and $e_c = 0.950$ when $DT_0 = 20$ K, instead of 0.938). This is because T_{ref} is not the highest temperature in the cavity. Such a compensation improves the quality of the blackbody. We should notice that $e_{a\lambda}(x)$ is given instead of radiance $B_\lambda(x)$, thus values larger than one mean that $T(x)$ is larger than T_{ref}. The emissivity e_c decreases similarly versus the size of the lateral hole, whether the cavity is isothermal or not.

5. CONCLUSIONS

A zirconia-tube blackbody can work in air up to 2500 K. The apparent emissivity has been calculated for a closed cylindrical cavity with a lateral hole formed on it. Typical results are presented for a few values of the wall emissivity, the size of the cavity (length-to-diameter ratio), and the size of the hole. The case of nonisothermal cavities has been emphasized. The temperature gradient and the lateral hole lead to additive decreasing of the emissivity of cavity. Some cooling in front of the hole provides an apparent compensation, improving the quality of the blackbody.

ACKNOWLEDGMENTS

The authors are grateful to the Bureau National de Métrologie for partial financial support and to the Laboratoire National d'Essais for its cooperation.

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