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Evaluation of the Effective Emissivity of Reference Sources for the Radiometric Emissivity Measurements[1]

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The effective emissivity of cavities or interreflecting surfaces is formulated in terms of the effective absorptivity using Kirchhoff's law and the reciprocity of the bidirectional reflectivity distribution function. It is shown that, according to the formulation, the effective emissivity can be evaluated by analyzing absorption processes of radiation. Several types of reference sources are evaluated statistically and analytically: cylindro-cones, lateral holes formed on a sample tube, and opaque samples covered by a hemispherical mirror. The radiative properties of the associated surfaces are characterized by the isotropic specular-diffuse model.

KEY WORDS: effective emissivity; reference source; blackbody; evaluation; Monte Carlo method; specular-diffuse model.

1. INTRODUCTION

In radiometric emissivity measurements, the radiance ratio between a sample and a reference source provides the sample emissivity if two conditions are met. The first is the isothermal condition that the reference source must be at the same temperature as the sample. The second is the blackbody condition that the reference source should be a blackbody; otherwise, the effective emissivity must be known accurately, and the radiance ratio is corrected for the effective emissivity of the reference source.

There are three major methods for radiometric emissivity measurements: the separate blackbody method, the integral blackbody method, and the reflecting mirror method. In these methods reference sources are formed in a cavity or composed of interreflecting surfaces to

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approximate a blackbody. In this paper we describe an evaluation method for the effective emissivity of cavities and interreflecting surfaces. Evaluation results are presented for reference sources that are used in the respective methods.

2. METHOD OF EVALUATION

Figure 1a shows emission processes of radiation in an opaque enclosure having arbitrary surfaces and arbitrary temperature distributions. This enclosure represents a model for reference sources, where radiation is exchanged among surfaces. A radiometer views a surface element dA_1 on the enclosure.

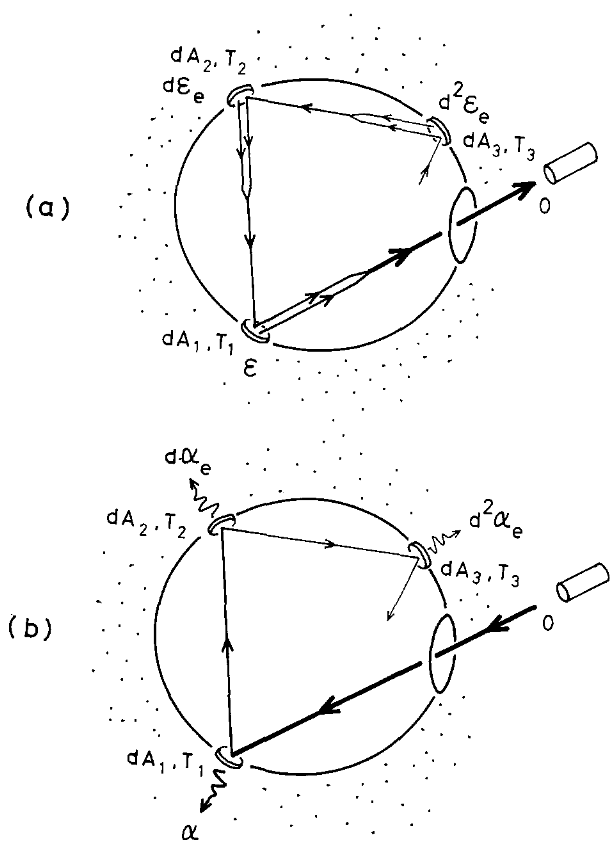


Fig. 1. Radiative processes in an opaque enclosure. (a) Emission processes; (b) absorption processes.

We now consider the exitent radiance of the surface element dA_1 in the direction of the radiometer. The exitent radiance is composed of many fractions of radiation. The first fraction is radiation emitted by the surface element dA_1. The second fraction is radiation originally emitted by a surface element dA_2 that is reflected by dA_1 in the direction of the radiometer. The third fraction is radiation originally emitted by dA_3 that is reflected by dA_2 and dA_1 successively in the direction of the radiometer. The sum of those fractions results in the exitent radiance.

Figure 1b shows absorption processes of radiation in the same enclosure as Fig. 1a, but radiation is incident from the direction of the radiometer on the surface element dA_1. It should be noted that the direction of radiation is opposite to that in Fig. 1a. Now we consider absorption processes of incident radiation. The fraction of radiation that is absorbed by dA_1 is α, the surface absorptivity of dA_1. Radiation reflected by dA_1 reaches another surface element dA_2, where a fraction is absorbed by dA_2 and the rest is reflected. In this way incident radiation is reflected successively and finally absorbed somewhere on the surfaces of the enclosure or escapes through the aperture to the outside. We define the effective absorptivity of the enclosure, α_e, by the total fraction of incident radiation that is absorbed by the enclosure and also the differentials of the effective absorptivity, $d\alpha_e$, $d^2\alpha_e$, etc., by the fractions of incident radiation that are absorbed by dA_2, dA_3, etc., respectively.

The absorption processes and emission processes are related closely. Using Kirchhoff's law and the reciprocity of the bidirectional reflectivity distribution function, we can relate these two processes; the relation is expressed as

$$L_{\lambda,\mathrm{ex}} = L_{\lambda,\mathrm{b}}(\lambda, T_1) \cdot \alpha + \int_{2\pi} L_{\lambda,\mathrm{b}}(\lambda, T_2) \cdot d\alpha_e + \int_{2\pi} \int_{2\pi} L_{\lambda,\mathrm{b}}(\lambda, T_3) \cdot d^2\alpha_e + \cdots \quad (1)$$

where $L_{\lambda,\mathrm{ex}}$ is the spectral exitent radiance of the surface element dA_1 in the direction of the radiometer at the wavelength λ, $L_{\lambda,\mathrm{b}}(\lambda, T)$ is the blackbody spectral radiance of the temperature T, and T_k is the local temperature of the surface element dA_k. Thus, Eq. (1) expresses the spectral exitent radiance in terms of the effective absorptivity.

The effective (spectral directional) emissivity is defined by the ratio of the spectral exitent radiance to the blackbody spectral radiance of a reference temperature. We usually take the temperature of the surface at which a radiometer looks (i.e., T_1 in Fig. 1) as a reference temperature. Thus,

$$\varepsilon_e = L_{\lambda,\mathrm{ex}} / L_{\lambda,\mathrm{b}}(\lambda, T_1) \quad (2)$$

Using Eqs. (1) and (2), we can evaluate the spectral exitent radiance and the effective emissivity by analyzing absorption processes when radiation is incident from the direction of observation.

It should be pointed out that absorption processes can be considered as stochastic processes where incident radiation is regarded to consist of many ray bundles. When a ray bundle reaches an opaque surface, it is either absorbed or reflected. The occurring event, absorption or reflection, is determined statistically by using random numbers. Thus we can simulate absorption processes by the Monte Carlo method.

3. EVALUATION RESULTS

Real surfaces are usually neither specular nor diffuse but are intermediate ones. The specular-diffuse model for the radiative properties of a surface represents intermediate surfaces between specular and diffuse. In the model, when radiation is incident on a surface from a certain direction, reflected radiation consists of two components; a diffuse component and a specular one. By changing the ratio of the specular component to the diffuse one, one can characterize different surfaces from specular to diffuse through intermediate. We apply the specular-diffuse model throughout the following evaluations, assuming that the specular and diffuse reflectivities, ρ_s and ρ_d, respectively, are independent of the angle of incidence (isotropic specular-diffuse model).

3.1. Cylindro-cones

Problems on a reference source of the separate blackbody method are what shape of cavity should be chosen, how deep it should be, and what the effective emissivity is. One of the cavities most frequently used as a reference source is a cylindrical cavity having a conical bottom (cylindro-cone).

Figures 2a to d illustrate specular reflection processes in cylindro-cones. According to the discussion in the previous section, suppose that radiation is incident from the outside into the cavity, and analyze absorption processes of radiation in the cavities. When a cavity bottom is flat, a specular reflection results in the escape of radiation through the aperture to the outside. There is no cavity effect for such specularly reflected radiation. For apex angles of 90 and 60°, two and three successive specular reflections result in escape of radiation, respectively. In contrast with those, for an apex angle of 120°, successive specular reflections keep incident radiation within the cavity. So, there is a cavity effect.

Figure 2e shows effective emissivities of cylindro-cones against the apex angle, θ, calculated by the Monte Carlo method [1]. The length-to-

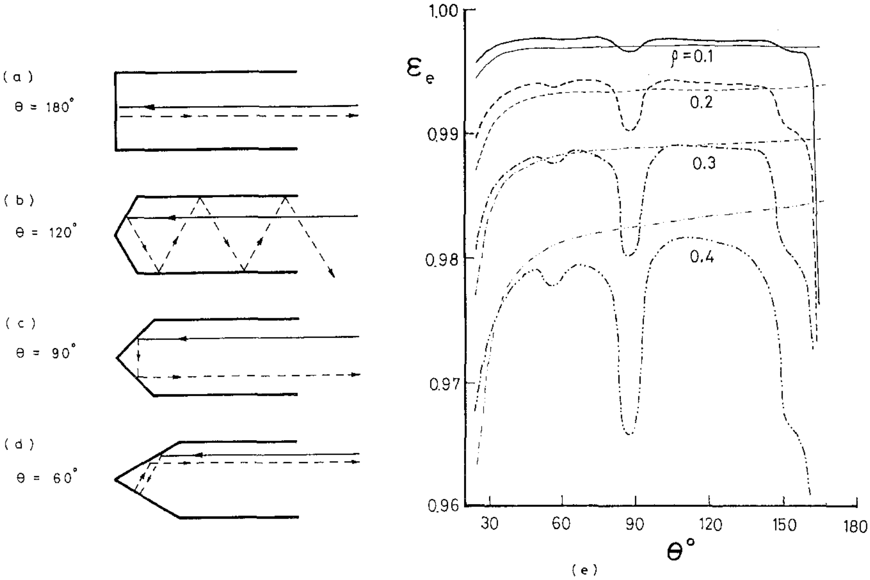


Fig. 2. (a–d) Specular reflection processes in cylindro-cones having different apex angles. (e) Effective emissivities of cylindro-cones at the conical bottoms. Thick and thin curves are for $\rho_s/\rho = 0.3$ and 0.0, respectively.

diameter ratio of cavity, L/D, is 3 and the degree of specularity of surfaces, ρ_s/ρ, is 0.3, where ρ is the directional-hemispherical reflectivity ($\rho = \rho_s + \rho_d$). The effective emissivity has minima around 180, 90, and 60° due to specular reflection effects as described before. In contrast with those, the effective emissivity has broad maxima around 120°. It is recommended that an apex angle of about 120° be chosen for highest emissivity when a cavity surface has a specular reflection component.

Figure 3 shows effective emissivities of cylindro-cones having an apex angle of 120° and different length-to-diameter ratios, $L/D = 3$, 6, and 10. The calculation has been done by the Monte Carlo method using 10^4 to 5×10^4 incident ray bundles. The cone surfaces are characterized by the isotropic specular-diffuse model, but the cylinder surfaces are assumed to be isotropically diffuse reflectors (i.e., there is no specular reflection component), considering that cylinder surfaces are often spirally grooved or baffled. The degree of specularity of the cone surface, ρ_s/ρ, is varied parametrically from 0.0 to 1.0 at an interval of 0.2 that corresponds to the curves in Fig. 3 from the top to the bottom in that order. It should be noted that the ordinates indicate the difference between unity and effective emissivity. The abscissas indicate the surface emissivities of the cylinder and

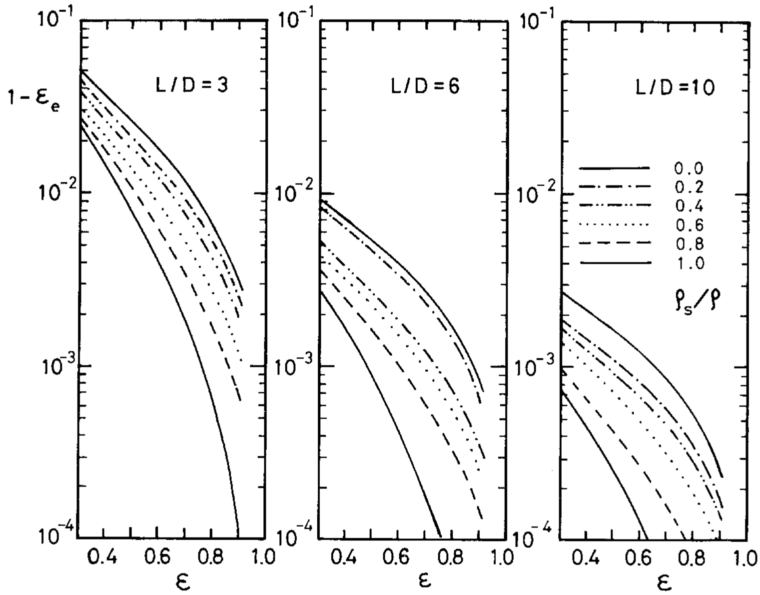


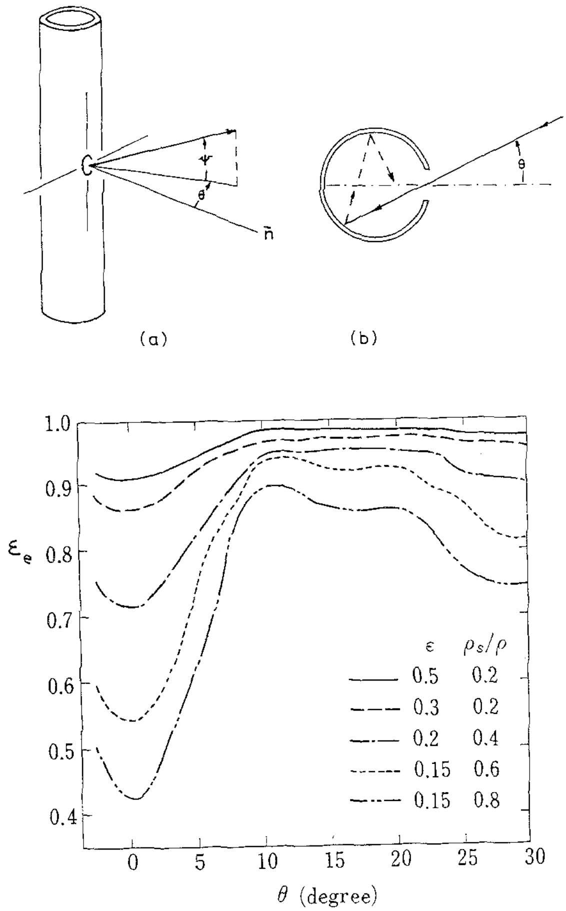
Fig. 3. Effective emissivities of cylindro-cones, having an apex angle of 120°, at the conical bottoms. The ordinates represent the deviation of the effective emissivity from unity. L/D is the depth-to-diameter ratio of a cylindro-cone. ρ_s/ρ is the degree of specularity of the cone surfaces, and the cylinder surfaces are assumed to be isotropically diffuse reflectors.

cone, which are assumed to be the same value, ε. Detailed calculation procedures have been described in Ref. 2.

3.2. Lateral Holes Formed on a Sample Tube

Figure 4a shows an example of the integral blackbody method, wherein a reference source is composed of a lateral hole formed on a sample tube and the hollow space of the sample tube. The sample tube is heated by direct current passage up to high temperatures, and a sample target is a tube surface near the lateral hole. Figure 4b is the horizontal cross section of the sample tube at the level of the lateral hole. Incident radiation is reflected by the inner surface of the sample tube and finally absorbed somewhere or escapes through the lateral hole to the outside.

One of the problems of this reference source is the determination of the viewing angle for the highest emissivity. Figure 4c shows calculation results by the Monte Carlo method. The effective emissivity is plotted against the horizontal angle of incidence, θ, keeping vertically normal, $\psi = 0^\circ$. The degree of specularity and the sample emissivity are varied



(c)

Fig. 4. (a) Lateral hole formed on a sample tube. (b) Horizontal cross section of the sample tube at the level of the lateral hole. (c) Effective emissivities of a lateral hole against the horizontal angle of viewing while keeping vertically normal, $\psi = 0°$.

parametrically. The geometrical dimensions are such that the tube is 5.54 mm in inner diameter and 140mm long, and the lateral hole is 1.7mm in diameter. The effective emissivity has deep minima around 0° (normal incidence) due to a specular reflection effect resulting in the escape of radiation through the lateral hole. We can see shallow minima around 30°. For this angle of incidence, two successive specular reflections result in the escape of radiation. The effective emissivity has nearly constant maxima from 10 to 20°. In this region, there is a cavity effect. So it is recommended that, for highest emissivity, a lateral hole be viewed horizontally about 15° off normal.

Figure 5 shows the effective emissivity plotted against the emissivity of the tube inner surface for the same sample tube as the above, keeping the horizontal angle of incidence 15° off normal. It can be seen that, if an accuracy of a few percent is required for a radiometric emissivity measurement, it is necessary to correct an experimentally measured radiance ratio for the deviation of the effective emissivity from unity. Detailed calculations has been described in Ref. 3.

3.3. Opaque Samples Covered by a Hemispherical Mirror

Figure 6 illustrates an example of the reflecting mirror method for radiometric emissivity measurements. A hemispherical mirror is placed on a sample in such a way that the center of the sphere is coincident with the sample surface. The hemispherical mirror has an aperture on it for observing the sample by a radiometer. Radiation emitted by the sample is mostly returned to the sample itself by mirror reflection. Radiation

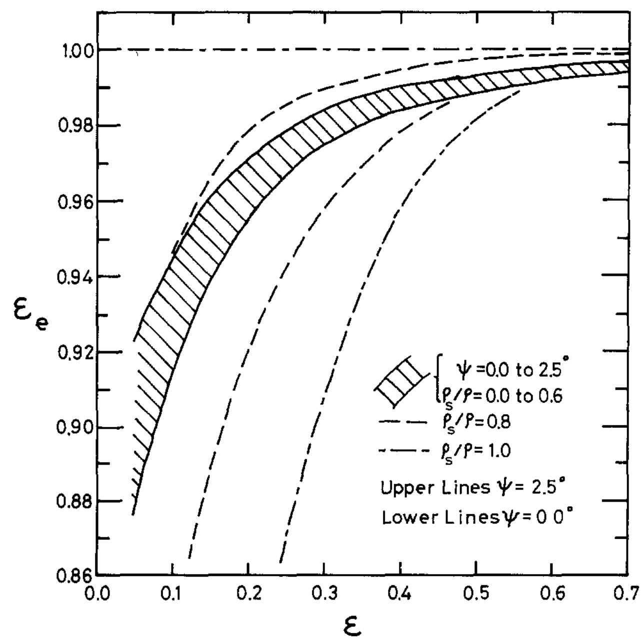


Fig. 5. Effective emissivities of a lateral hole viewed horizontally 15° off normal against the emissivity of the tube inner surface.

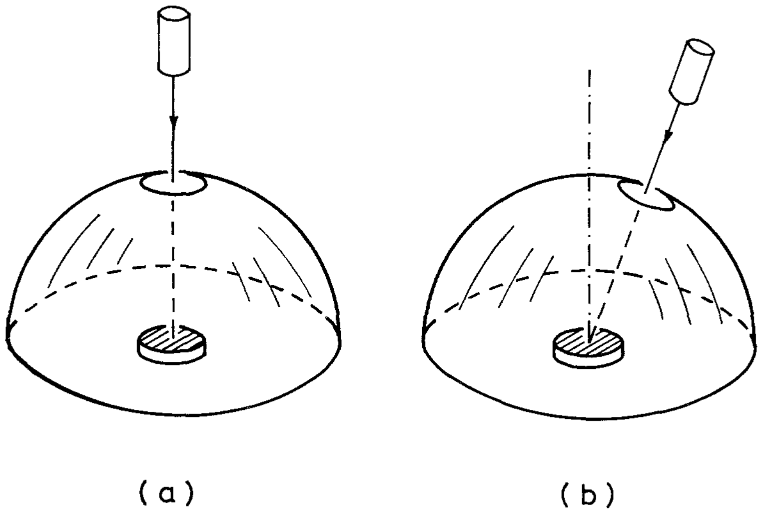


Fig. 6. Configurations of an opaque sample and a hemispherical mirror. (a) Normal aperture; (b) inclided aperture.

returned is either absorbed or reflected by the sample. Reflected radiation is mostly returned to the sample again. In this case, multiple reflections of radiation between the sample and the mirror occur.

Due to such multiple reflection effects those sample-and-mirror configurations give approximate blackbody radiation through the aperture, and they can be used as a reference source for radiometric emissivity measurements. The measurement procedure is such that a hemispherical mirror is operated on and off a sample, and the radiance ratio is radiometrically measured. This radiance ratio provides the sample emissivity by correcting for the effective emissivity of the sample-and-mirror configuration.

Considering specular reflection effects in absorption processes, it can be seen easily that the configuration in Fig.6b has an advantage over that in Fig.6a for higher emissivity. Assuming that the aperature area is small enough compared to the mirror surface area, the effective absorptivity of the sample (i.e., the total fraction of incident radiation that is absorbed by the sample), $\alpha_{e,s}$, is expressed analytically as

$$\alpha_{e,s} = \alpha \cdot (1 + \rho_s \cdot \rho_m) \cdot (1 - \rho_s \cdot \rho_m) / [1 - (\rho_s + \rho_d \cdot F_m) \cdot \rho_m] \qquad (3)$$

where F_m is the view factor of the hemispherical mirror at the sample position, and ρ_m is the reflectivity of the surface of the hemispherical mirror.

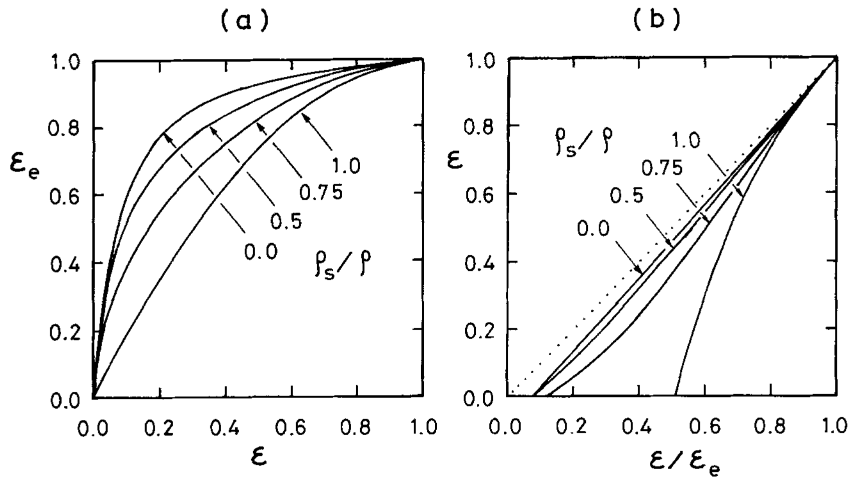


Fig. 7. Evaluation results of the sample-and-mirror configuration shown in Fig. 6b. (a) Effective emissivity vs sample emissivity; (b) sample emissivity vs emissivity ratio.

Assume that the sample temperature is high so that the emission of radiation by the hemispherical mirror and the surroundings is negligible compared with that of the sample. Then the effective emissivity of the sample-and-mirror configuration, ε_e, becomes equal to the effective absorptivity of the sample, $\alpha_{e,s}$, given by Eq. (3). Evaluated effective emissivities are shown in Fig. 7a against the sample emissivity based on the condition that the hemispherical mirror is 120 mm in diameter, the aperature is 20 mm in diameter and inclined by 20° off normal ($F_m = 0.972$), and the mirror reflectivity is 95% ($\rho_m = 0.95$).

Figure 7b replots the results in Fig. 7a on a different coordinate system, where the ordinate is the sample emissivity, ε, and the abscissa is the emissivity ratio between the sample and the sample-and-mirror configuration, $\varepsilon/\varepsilon_e$. The reason for taking the emissivity ratio as the abscissa is that the emissivity ratio can be experimentally measured as the radiance ratio when a hemispherical mirror is operated off and on the sample. The sample emissivity can be determined from an experimentally measured radiance ratio with the knowledge of the degree of specularity of the sample. An experimental arrangement using a hemispherical mirror has been described elsewhere [4].

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