International Journal of Thermophysics, Vol. 19, No. 2, 1998

# A Method for Calculating Thermal Radiation Properties of Multilayer Films from Optical Constants[1]

R. Horikoshi,[2] Y. Nagasaka,[2,3] and A. Ohnishi[4]

A calculation method for the incident angle dependence of the solar absorptance $\alpha_S$ and the temperature dependence of the total hemispherical emittance $\varepsilon_H$ of multilayer films is proposed. The method is based on calculation of $\alpha_S$ and $\varepsilon_H$ from optical constants in the wavelength region from 0.25 to 100 $\mu$m for thin polymer films and deposited metal. In this paper we provide values of $\alpha_S$ in the incident angle region from 0 to 90° and $\varepsilon_H$ in the temperature range from 173.15 to 373.15 K for two-layer samples of aluminum-deposited polyimide film. The results obtained for $\alpha_S$ and $\varepsilon_H$ by the present method are compared with experimental results measured by both spectroscopic and calorimetric methods. The calculated results of $\alpha_S$ and $\varepsilon_H$ agree well with the experimental results

**KEY WORDS:** multilayer films; optical constants; reflectance; total hemispherical emittance; solar absorptance

## 1. INTRODUCTION

Thermal radiation properties (solar absorptance $\alpha_S$ and total hemispherical emittance $\varepsilon_H$) of thermal control multilayer films used for thermal control of spacecrafts have been obtained by experimental measurements in our laboratory. Solar absorptance was measured spectroscopically, and total hemispherical emittance was measured calorimetrically [1]. It is possible to produce multilayer films with the required values of $\alpha_S$ and $\varepsilon_H$ by selecting the appropriate thickness of base films and deposited materials.

[1] Paper presented at the Thirteenth Symposium on Thermophysical Properties, June 22–27, 1997, Boulder, Colorado, U.S.A.

[2] Department of Mechanical Engineering, Keio University, 3-14-1, Hiyoshi, Yokohama 223, Japan.

[3] To whom correspondence should be addressed.

[4] Institute of Space and Astronomical Science, 3-3-1, Yoshinodai, Sagamihara 229, Japan

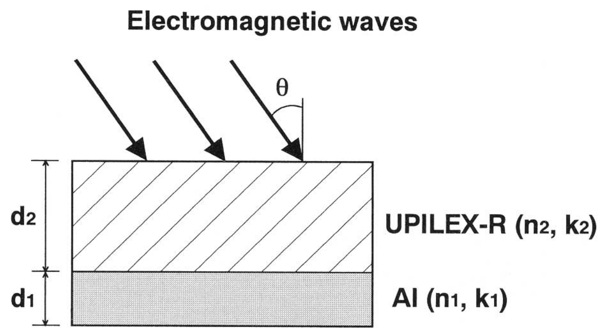


**Fig. 1.** Thermal control multilayer film.

This paper describes the calculation method for thermal radiation properties using optical constants of component films, especially for thermal control multilayer films of deposited aluminum on one side of a UPILEX-R polyimide film as shown in Fig. 1. The incident angle dependence of $\alpha_S$ and the sample temperature dependence of $\varepsilon_H$ are determined. Using this calculation method, it is possible to design suitable thermal control multilayer films which satisfy the target values of $\alpha_S$ and $\varepsilon_H$ and to calculate the values of $\alpha_S$ and $\varepsilon_H$ in the region where they are difficult to measure experimentally.

## 2. CALCULATION METHOD [2, 3]

Calculations of thermal radiation properties are performed according to the following procedures, using data for the optical constants of polyimide film and aluminum [4] and values of solar radiation intensity [5]. As thin films are discussed in this calculation, assumptions are smooth surfaces and homogeneous, nonscattering materials. When the incident angle of electromagnetic waves for a single-phase film in vacuum is 0°, the spectral reflectance $R(\lambda, \theta)$ and transmittance $T(\lambda, \theta)$ of this film is expressed by

$$R(\lambda, \theta) = \rho \frac{\{1 - \exp(-\beta d)\}^2 + 4\exp(-\beta d)\sin^2\delta}{\{1 - \rho\exp(-\beta d)\}^2 + 4\rho\exp(-\beta d)\sin^2(\delta + \phi)} \tag{1}$$

and

$$T(\lambda, \theta) = \frac{(1-\rho)^2\exp(-\beta d)\} + 4\rho\exp(-\beta d)\sin^2\delta}{\{1 - \rho\exp(-\beta d)\}^2 + 4\rho\exp(-\beta d)\sin^2(\delta + \phi)} \tag{2}$$

where $\rho = \{(n-1)^2 + k^2\}/\{(n+1)^2 + k^2\}$, $\beta = 4\pi nk/\lambda$, $\delta = 2\pi nd/\lambda$, $\tan\phi = 2k/(n^2 + k^2 - 1)$, $n$ is the refractive index, $k$ is the extinction coefficient, $\lambda$ is

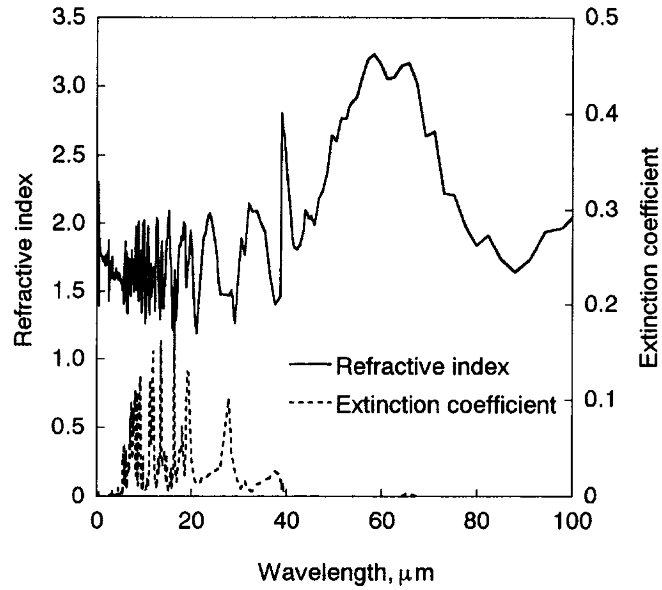


Fig. 2. Optical constants of UPILEX-R.

the wavelength, $\theta$ is the incident angle of electromagnetic waves, and $d$ is the thickness. The optical constants of the UPILEX-R film used for the calculation are obtained from a measurement of its normal spectral reflectance and transmittance from Eqs. (1) and (2) as shown in Fig. 2. The spectral reflectance and transmittance are measured by spectroscopy with an integrating sphere in the wavelength region from 0.25 to 2.5 $\mu$m and FT-IR in the wavelength region from 2.5 to 100 $\mu$m.

Amplitude reflectances are calculated from the optical constants of component films, and then the spectral reflectance is calculated with amplitude reflectances. The calculation is made for two cases: with and without considering an interference phenomenon. The maximum resolution of the spectral reflectances is 10 nm in the wavelength region from 0.25 to 2.5 $\mu$m. The spectral reflectances for which the interference phenomenon does not occur were measured with spectroscopy in this wavelength region. Thus, it is necessary to calculate the spectral reflectances without considering an interference phenomenon.

When an interference phenomenon is not considered, amplitude reflectances accounted for multiplex reflectance at the boundary surface between the $m$th and the $(m+1)$th layers from the bottom as expressed by

$$R'_m(\lambda, \theta) = r_m + \frac{(1-r_m)^2 R'_{m-1}(\lambda, \theta) \exp(-2\gamma_m d_m)}{1 - r_m R'_{m-1}(\lambda, \theta) \exp(-2\gamma_m d_m)} \tag{3}$$

where $\gamma_m = 4\pi k_m/\lambda \cos\theta_m$, $r_m = (|r_{S_m}|^2 + |r_{P_m}|^2)/2$, $r_{S_m}$ and $r_{P_m}$ are the Fresnel coefficients, $k_m$ is the extinction coefficient of the $m$th layer, $\theta_m$ is the incident angle of electromagnetic waves of the $m$th layer, and $d_m$ is the thickness of the $m$th layer. Thus, the spectral reflectance of the surface of the multilayer film as a function of the incident angle and the wavelength is expressed by

$$R(\lambda, \theta) = r_{ma} + \frac{(1 - r_{ma})^2 R'_{ma-1}(\lambda, \theta) \exp(-2\gamma_{ma} d_{ma})}{1 - r_{ma} R'_{ma-1}(\lambda, \theta) \exp(-2\gamma_{ma} d_{ma})} \tag{4}$$

where the subscript $ma$ indicates the layer number

On the other hand, when an interference phenomenon is considered, amplitude reflectances which take into account multiplex reflectance at the boundary surface between the $m$th and the $(m+1)$th layers from the bottom are expressed by

$$R''_m(\lambda, \theta) = \frac{r_m + R''_{m-1}(\lambda, \theta) \exp(-i\eta_m)}{1 + r_m R''_{m-1}(\lambda, \theta) \exp(-i\eta_m)} \tag{5}$$

where $\eta_m = 4\pi \hat{n}_m d_m \cos\theta_m/\lambda$, and $\hat{n}_m$ is the complex refractive index of the $m$th layer. Thus, the spectral reflectance of the surface of the multilayer film as a function of the incident angle and the wavelength is expressed by

$$R(\lambda, \theta) = \frac{|R''_{S_{ma}}(\lambda, \theta)|^2 + |R''_{P_{ma}}(\lambda, \theta)|^2}{2} \tag{6}$$

where $R''_{S_{ma}}(\lambda, \theta)$ and $R''_{P_{ma}}(\lambda, \theta)$ are the spectral reflectances of S-polarization and P-polarization of the surface of the multilayer film from Eq. (5). Thermal radiation properties are calculated from $R(\lambda, \theta)$ in Eqs. (4) and (6).

A sample temperature dependence of $\varepsilon_H$ is calculated by integration of the spectral reflectance in the wavelength region from 0.25 to 100 $\mu$m, expressed by

$$\varepsilon_H = \frac{\int_0^{\pi/2} \int_{0.25}^{100} \{1 - R(\lambda, \theta)\}\, i_b(\lambda, T) \cos\theta \sin\theta \, d\lambda \, d\theta}{\int_0^{\pi/2} \int_{0.25}^{100} i_b(\lambda, T) \cos\theta \sin\theta \, d\lambda \, d\theta} \tag{7}$$

where $T$ is the sample temperature and $i_b(\lambda, T)$ is the Planck's spectral distribution of emissive power. It is possible to ignore the difference between the calculated result and the theoretical value over a restricted wavelength region, as about 97.9% of the emissive power of the blackbody is contained at 173.15 K, and 99.8% at 373.15 K, in this wavelength region.

The incident angle dependence of $\alpha_S$ is obtained similarly in the wavelength region from 0.25 to 2.5 $\mu$m with the assumption of vertical incidence of electromagnetic waves expressed by

$$\alpha_S = \frac{\int_{0.25}^{2.5} \{1 - R(\lambda, \theta)\} I_S(\lambda)\, d\lambda}{\int_{0.25}^{2.5} I_S(\lambda)\, d\lambda} \tag{8}$$

where $I_S$ is the solar radiation intensity. It is possible to ignore the difference between the calculated result and the theoretical value over a restricted wavelength region, as about 96% of the solar radiation intensity is contained in this wavelength region

## 3. ACCURACY OF THE CALCULATION METHOD

The accuracy of the calculated results is believed to be due mainly to the uncertainty in the optical constants and the thickness of UPILEX-R. The uncertainty contributing to the accuracy of the calculated results is shown in Table I. The uncertainty in the optical constants is estimated to be less than 2%, which corresponds to the experimental results for the spectral reflectance and transmittance of UPILEX-R. The uncertainty of the thickness of UPILEX-R is estimated to be $\pm 5$%. Consequently, the overall accuracy of the calculated results of $\varepsilon_H$ is $\pm 4$% and that of $\alpha_S$ is $\pm 3$%

## 4. RESULTS AND DISCUSSIONS

To evaluate the present method, the calculated results are compared with the experimental results. The solar absorptance was measured spectroscopically with an integrating sphere in the wavelength region from 0.25 to 2.5 $\mu$m and in the incident angle range from 5 to 60°, and the total hemispherical emittance was measured calorimetrically in the sample temperature range from 173.15 to 373.15 K for aluminum-deposited UPILEX-R

**Table I.** Uncertainties of the Calculated Results

| Thermal radiation property | Uncertainty (%) of | | Overall uncertainty of calculated results (%) |
|---|---|---|---|
| | Optical constants (%) | Thickness of UPILEX-R (%) | |
| $\alpha_S$ | $\pm 2$ | $\pm 5$ | $\pm 3$ |
| $\varepsilon_H$ | $\pm 2$ | $\pm 5$ | $\pm 4$ |

films. These films were assumed to be 12, 25, 50, and 75 $\mu$m in thickness. Aluminum was deposited in vacuum to a thickness of 1500 Å on one side of each film.

### 4.1. Calculated Results for $\varepsilon_H$

Figure 3 shows a comparison of the calculated and experimental results for the temperature dependence of $\varepsilon_H$ for a sample of 25-$\mu$m thickness. The maximum deviation of the calculated results from the experimental results is $\pm 4\%$. Figure 4 shows a comparison of the calculated and experimental results for the thickness dependence of $\varepsilon_H$ at 293.15 K. The maximum deviation of the calculated results from the experimental results is $\pm 7\%$. But the uncertainty of the calculated results of $\varepsilon_H$ is $\pm 4\%$ as mentioned above. On the other hand, the accuracy of the experimental results measured by the calorimetric method is $\pm 2\%$. Therefore, the calculated results agree very well with the experimental results. It is clear that the sample temperature dependence of $\varepsilon_H$ is estimated by using this calculation method.

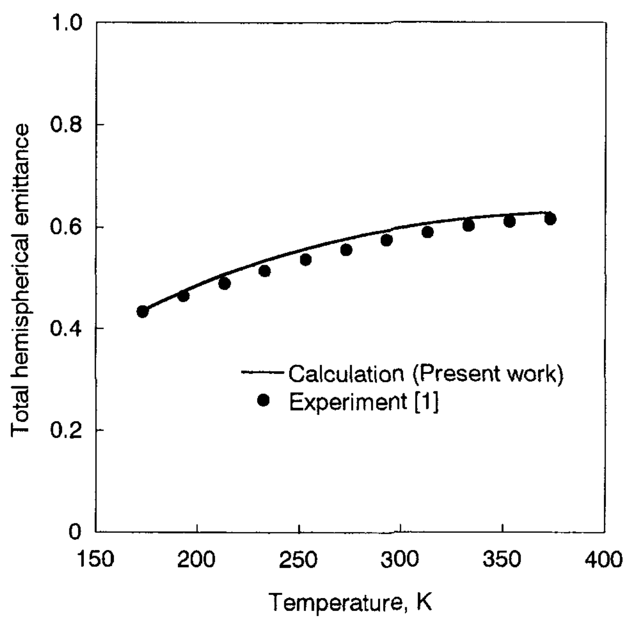


**Fig. 3.** Comparison of the calculated and experimental results for a sample temperature dependence of the total hemispherical emittance of UPILEX-R (25 $\mu$m)/Al.

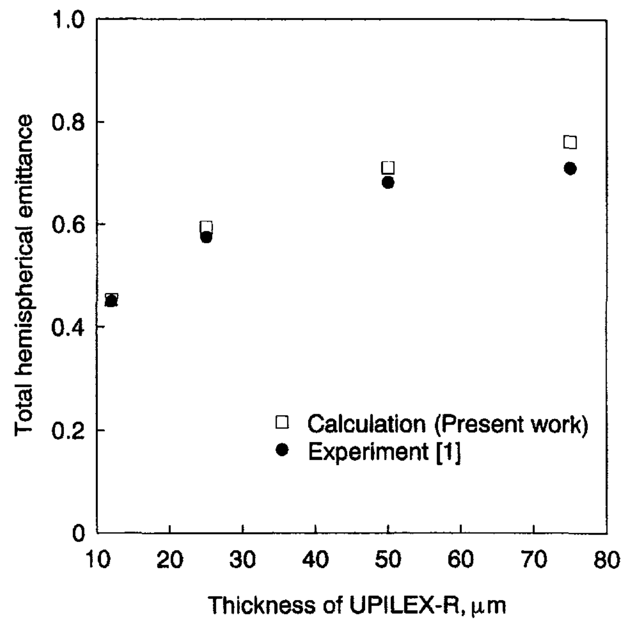


Fig. 4. Comparison of the calculated and experimental results for the thickness dependence of the total hemispherical emittance at 293.15 K.

### 4.2. Calculated Results for $\alpha_S$

Figure 5 shows a comparison of the calculated and experimental results for the incident angle dependence of $\alpha_S$ for a sample of 25-$\mu$m thickness. The maximum deviation of the calculated results from the experimental results is $\pm 5\%$. Figure 6 shows a comparison of the calculated and experimental results for the thickness dependence of $\alpha_S$. The maximum deviation of the calculated results from the experimental results is $\pm 10\%$. However, the uncertainty of the calculated results of $\alpha_S$ is $\pm 3\%$ and the uncertainty of the experimental results measured by the spectroscopic method is $\pm 2\%$. Therefore, the calculated results agree well with the experimental results.

Also, Fig. 7 shows the calculated results in the region for angles larger than 60°. It indicates that the calculated results suddenly decrease in the region which is difficult to measure experimentally. This is due to the incident angle dependence of the spectral reflectance as shown in Fig. 7. Therefore, using this calculation method, it is possible to estimate the incident angle dependence of $\alpha_S$ in the region where it is difficult to measure experimentally.

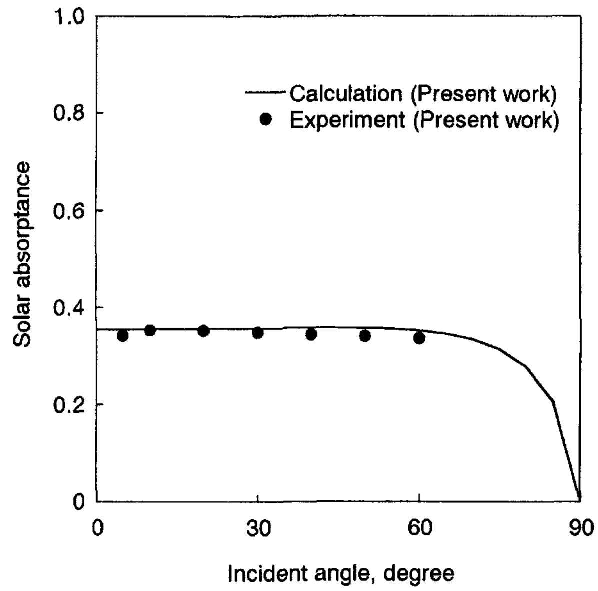


**Fig. 5.** Comparison of the calculated and experimental results for the incident angle dependence of the solar absorptance of UPILEX-R (25 μm)/Al.

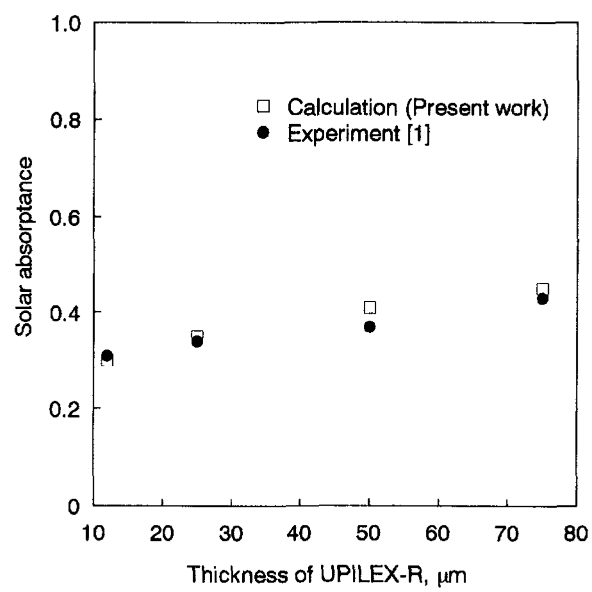


**Fig. 6.** Comparison of the calculated and experimental results for the thickness dependence of the solar absorptance at 293.15 K.

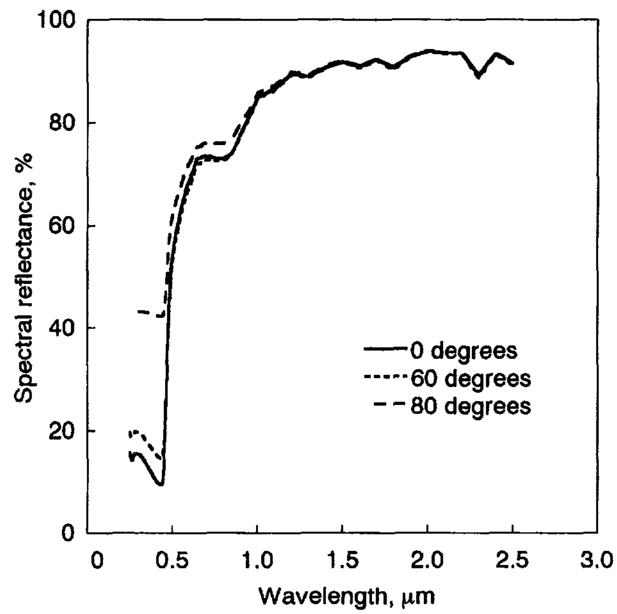


**Fig. 7.** Calculation results of the incident angle dependence of the spectral reflectance.

## REFERENCES


1. A. Ohnishi and R. Sato, *Trans. IEE Japan* **116-A**(2):136 (1996) (in Japanese).
2. O. S. Heavens, *Optical Properties of Thin Solid Films* (Dover, New York, 1965), pp. 159–275.
3. R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer* (McGraw-Hill, New York, 1972), pp. 42–78.
4. *American Institute of Physics Handbook*, 3rd ed. (McGraw-Hill, New York, 1972), pp. 6–124.
5. M. P. Thekaekara, *The Solar Constant and the Solar Spectrum Measured from A Research Aircraft*, NASA TR R-351 (1970), pp. 71–80