A Calculating Method for Thermal Radiation Property of Multi-layer Film from Optical Constants[1]

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

[1] Paper presented at the Thirteenth Symposium on Thermophysical Properties, June 22-27, 1997, Boulder, Colorado, USA.

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

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

[4] To whom correspondence should be addressed.

ABSTRACT

A calculation method for incident angle dependence of solar absorptance α_S and temperature dependence of total hemispherical emittance ε_H of multi-layer films is proposed. The method is based on calculation of α_S and ε_H from optical constants in the wavelength region from 0.26 μm to 100 μm for thin polymer film and deposited metal. This paper is described values of α_S in the incident angle region from 0 degree to 90 degree and ε_H in the temperature range from 173.15 K to 373.15 K for two-layer sample, aluminum deposited polyimide film. The results obtained α_S and ε_H by the present method are compared with the experimental results measured by both spectroscopic and calorimetric methods. The calculated results of α_S and ε_H agree well with the experimental results.

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

1. INTRODUCTION

Thermal radiation properties (solar absorptance α_S and total hemispherical emittance ε_H) of thermal control multi-layer films used to thermal control of spacecrafts have been obtained by experimental measurements in our laboratory development. Solar absorptance was measured spectroscopically and total hemispherical emittance was measured calorimetrically [1]. It is possible to produce demanded α_S and ε_H of multi-layer films by selecting appropriate thickness of base films and deposited materials

This paper describes the calculation method for thermal radiation properties by optical constants of component films, especially thermal control malti-layer film deposited aluminum on one side of polyimide film which is UPILEX-R as shown in Fig. 1, concerning incident angle dependence of α_S and a sample temperature dependence of ε_H. By using this calculation method, it is possible to suitably design thermal control multi-layer films which have demanded α_S and ε_H, and to calculate values of α_S and ε_H in the region where it is difficult to measure experimentally.

2. CALCULATION METHOD [2, 3]

The calculation of thermal radiation properties are performed according to the following procedures, using data of optical constants of polyimide film and aluminum [4] and values of solar radiation intensity [5]. When a single phase film is in vacuum and incident angle of electromagnetic waves is 0 degree, spectral reflectance $R(\lambda,\theta)$ and transmittance $T(\lambda,\theta)$ of this film is expressed by

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

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

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 reflactive index, k is the extinction coefficient, λ is the wavelength, θ is the incident angle of electromagnetic waves, and d is the thickness. The optical constants of UPILEX-R film used for the calculation are obtained from a measurement of its normal spectral reflectance and transmittance from the following Eqs. (1) and (2) as shown in Fig. 2.

Amplitude reflectances are calculated from optical constants of component films, and then spectral reflectance is calculated with amplitude reflectances. The calculation is made in two cases : with and without considering an interference phenomenon. When an interference phenomenon is not considered, amplitude reflectances accounted for multiplex reflectance at the boundary surface between m-th and (m+1)-th layer from the bottom is expressed by

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

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

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

where, *ma* is the layer number.

On the other hand, when an interference phenomenon is considered, amplitude reflectances which takes into account multiplex reflectance at the boundary surface between *m*-th and (*m*+1)-th layer from the bottom is 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 reflactive index of *m*-th layer. Thus, spectral reflectance of the surface of multi-layer film as a function of the incident angle and the wavelength is expressed by

$$R(\lambda,\theta) = \frac{\left|R''_{Sma}(\lambda,\theta)\right|^2 + \left|R''_{Pma}(\lambda,\theta)\right|^2}{2}, \tag{6}$$

where, $R'_{Sma}(\lambda,\theta)$ and $R'_{Pma}(\lambda,\theta)$ are the spectral reflectance of S-polarization and P-polarization of the surface of multi-layer film given by Eq. (5). Thermal radiation properties are calculated from $R(\lambda,\theta)$ given by Eqs. (4) and (6).

A sample temperature dependence of ε_H is calculated by integration of the spectral reflectance in the wavelength region from 0.26 μm to 100 μm, expressed by

$$\varepsilon_H = \frac{\int_0^{\pi/2}\int_{0.26}^{100}\{1-R(\lambda,\theta)\}i_b(\lambda,T)\cos\theta\sin\theta d\lambda\, d\theta}{\int_0^{\pi/2}\int_{0.26}^{100} i_b(\lambda,T)\cos\theta\sin\theta d\lambda\, d\theta}, \tag{7}$$

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

power of blackbody is contained at 173.15 K and 99.8 % at 373.15 K in this wavelength region.

Incident angle dependence of α_S is obtained similarly for the visual and near IR region with an assumption of vertical incidence of electromagnetic waves expressed by

$$\alpha_S = \frac{\int_{0.26}^{2.5} \{1 - R(\lambda, \theta)\} I_S(\lambda) d\lambda}{\int_{0.26}^{2.5} I_S(\lambda) d\lambda}, \tag{8}$$

where, I_S is the solar radiation intensity. It is possible to ignore the difference between the calculated result and the theoretical value in a restriction of wavelength region, as about 96 % of solar radiation intensity is contained in the wavelength region from 0.26 μm to 2.5 μm.

3. ACCURACY OF THE CALCULATION METHOD

The accuracy of the calculated results is believed mainly due to the uncertainty of optical constants, and thickness of UPILEX-R. The uncertainty contributed to the accuracy of the calculated results are shown in Table I. The uncertainty of optical constants is estimated to be less than ± 2 % which corresponds to the experimental results, which are spectral reflectance and transmittance of UPILEX-R, of uncertainty of ± 2 %. The uncertainty of the thickness of UPILEX-R is estimated to be ± 5 %. Consequently, overall accuracy of the calculated results of ε_H is ± 4 % and that of α_S is ± 3 %.

4. RESULTS AND DISCUSSIONS

experimental results. Solar absorptance was measured spectroscopically with an integrating sphere in the wavelength region from 0.26 μm to 2.5 μm and in the incident angle range from 5 degree to 60 degree, and total hemispherical emittatnce was measured calorimetrically in the sample temperature range from 173.15 K to 373.15 K for aluminum deposited UPILEX-R film. UPILEX-R of these films were assumed to be 12, 25, 50, and 75 μm in thickness. Aluminum was deposited in vacuum with the thickness of 1500 Å on one side of each film.

4.1. Calculated results for e_H

Figure 3 shows comparison of the calculated and the experimental results for temperature dependence of e_H for the sample (25 μm). The maximum deviation of the calculated results from the experimental results is ± 4 %. Figure 4 shows comparison of the calculated and the experimental results for thickness dependence of e_H at 293.15 K. The maximum deviation of the calculated results from the experimental results is ± 7 %. But the accuracy of the calculated results of e_H is ± 4 % as mentioned above. On the other hand, the accuracy of the experimental results measured by calorimetric method is ± 2 %. Therefore, the calculated results agree very well with the experimental results.

4.2. Calculated results for a_S

Figure 5 shows comparison of the calculated and the experimental results for incident angle dependence of a_S for the sample (25 μm). The maximum deviation of the calculated results from the experimental results is ± 5 %. Figure 6 shows

dependence of a_S. The maximum deviation of the calculated results from the experimental results is ± 10 %. However, the accuracy of the calculated results of a_S is ± 3 % and the accuracy of the experimental results measured by spectroscopic method is ± 2 %. Therefore, the calculated results agree well with the experimental results.

The efficiency of the present method is confirmed by the discussions above. Besides, Fig. 7 shows the calculated results in the angle region which is larger than 60 degree. It indicates that the calculated results suddenly decrease in the region which is difficult to measure experimentally. This is due to incident angle dependence of the spectral reflectance calculated by using this calculation method shown in Fig. 7. Therefore, by using this calculation method, it is possible to estimate the thermal radiation properties in the region where it is difficult to measure experimentally.

REFERENCES

1. A. Ohnishi, and R. Sato, *Trans. IEE of Japan*, **116-A**, No.2, Feb. : 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 Edition (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.

Table I. The uncertainty contributed to the accuracy of the calculated results.

Thermal radiation property	The uncertainty of optical constants (%)	The uncertainty of thickness of UPILEX-R (%)	Overall accuracy of the calculated results (%)
a_S	± 2	± 5	± 3
e_H	± 2	± 5	± 4

List of Figure Captions

Fig. 1. Thermal control malti-layer film.

Fig. 2. Optical constants of UPILEX-R.

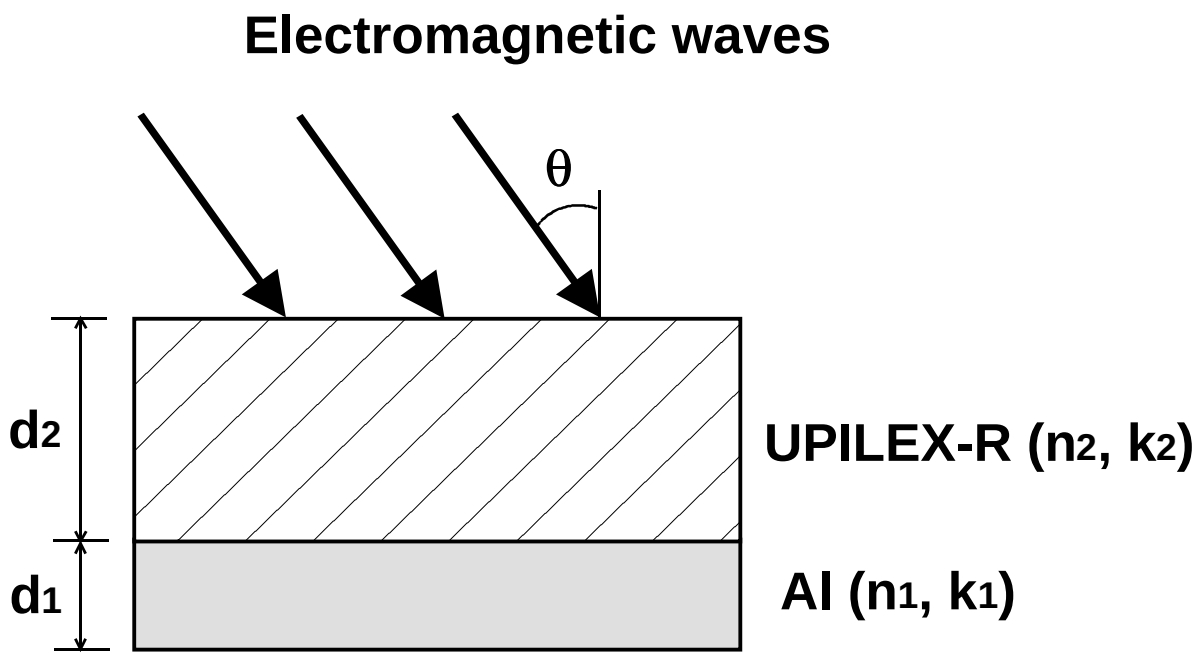
Fig. 3. Comparison of the calculated and the experimental results for a sample temperature dependence of total hemispherical emittance of UPILEX-R(25 μm)/Al.

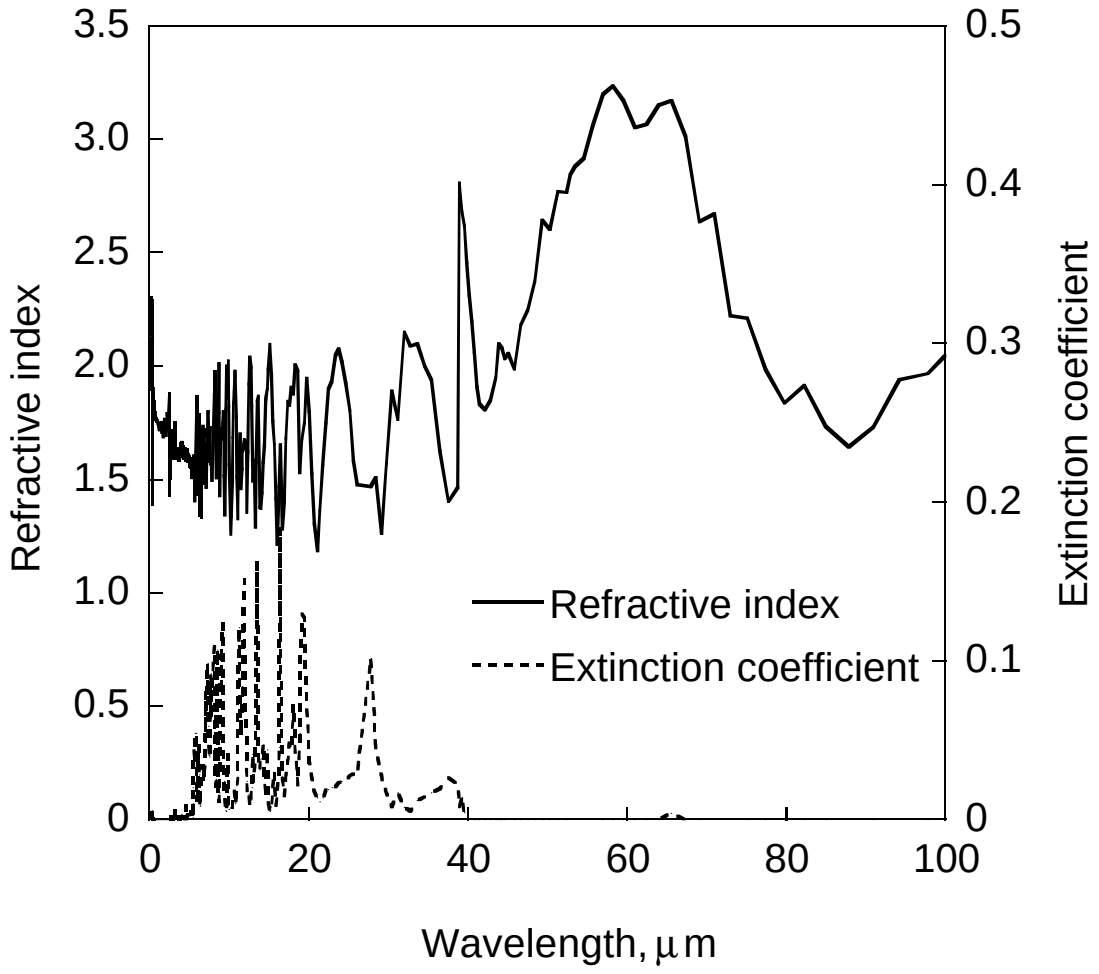
Fig. 4. Comparison of the calculated and the experimental results for thickness dependence of total hemispherical emittance at 293.15 K.

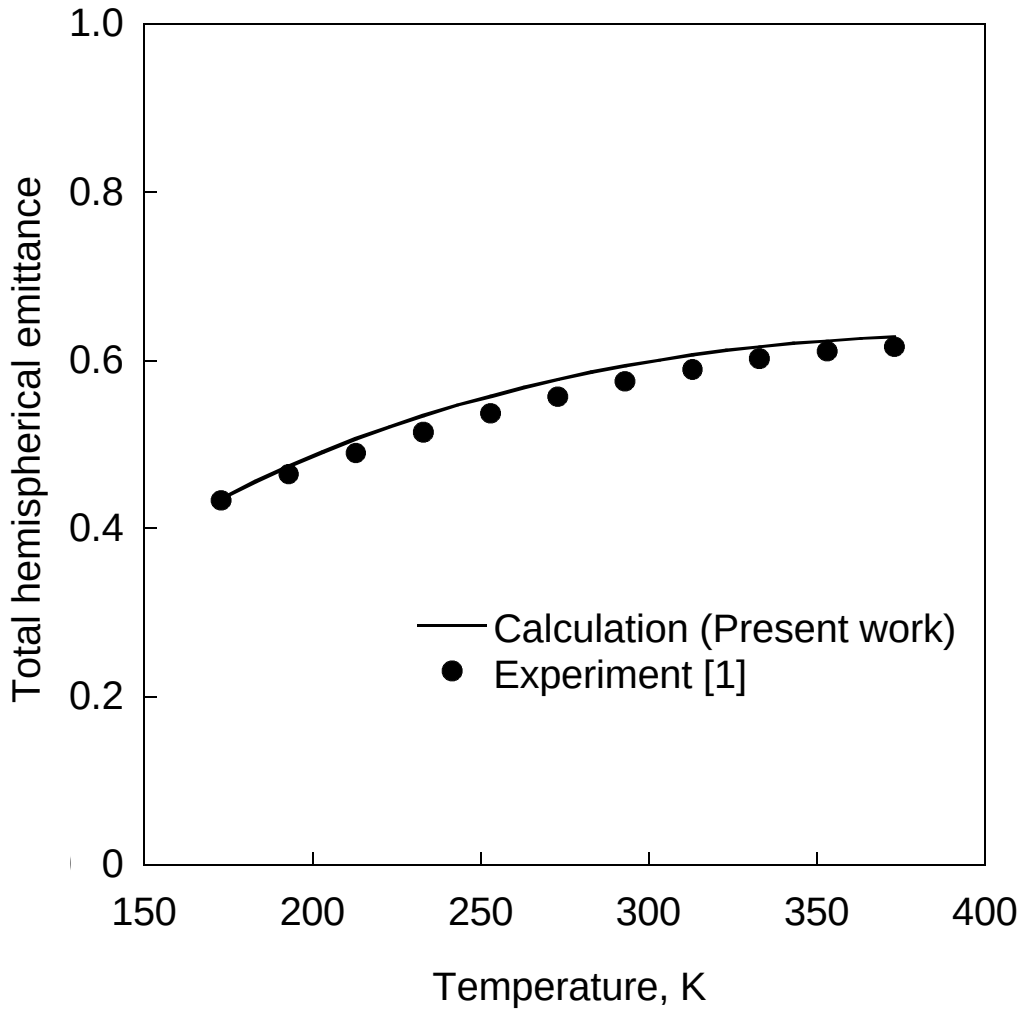
Fig. 5. Comparison of the calculated and the experimental results for incident angle dependence of solar absorptance of UPILEX-R(25μm)/Al.

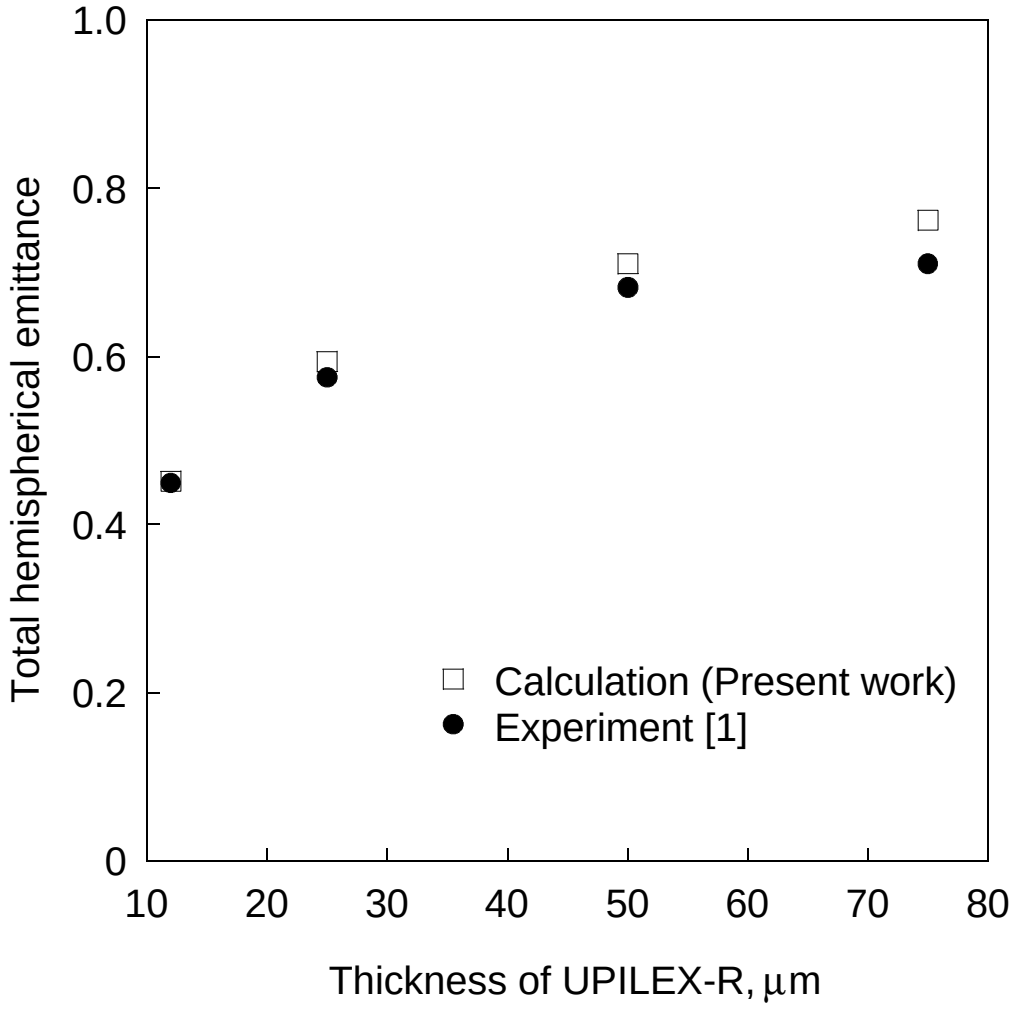
Fig. 6. Comparison of the calculated and the experimental results for thickness dependence of solar absorptance at 293.15 K.

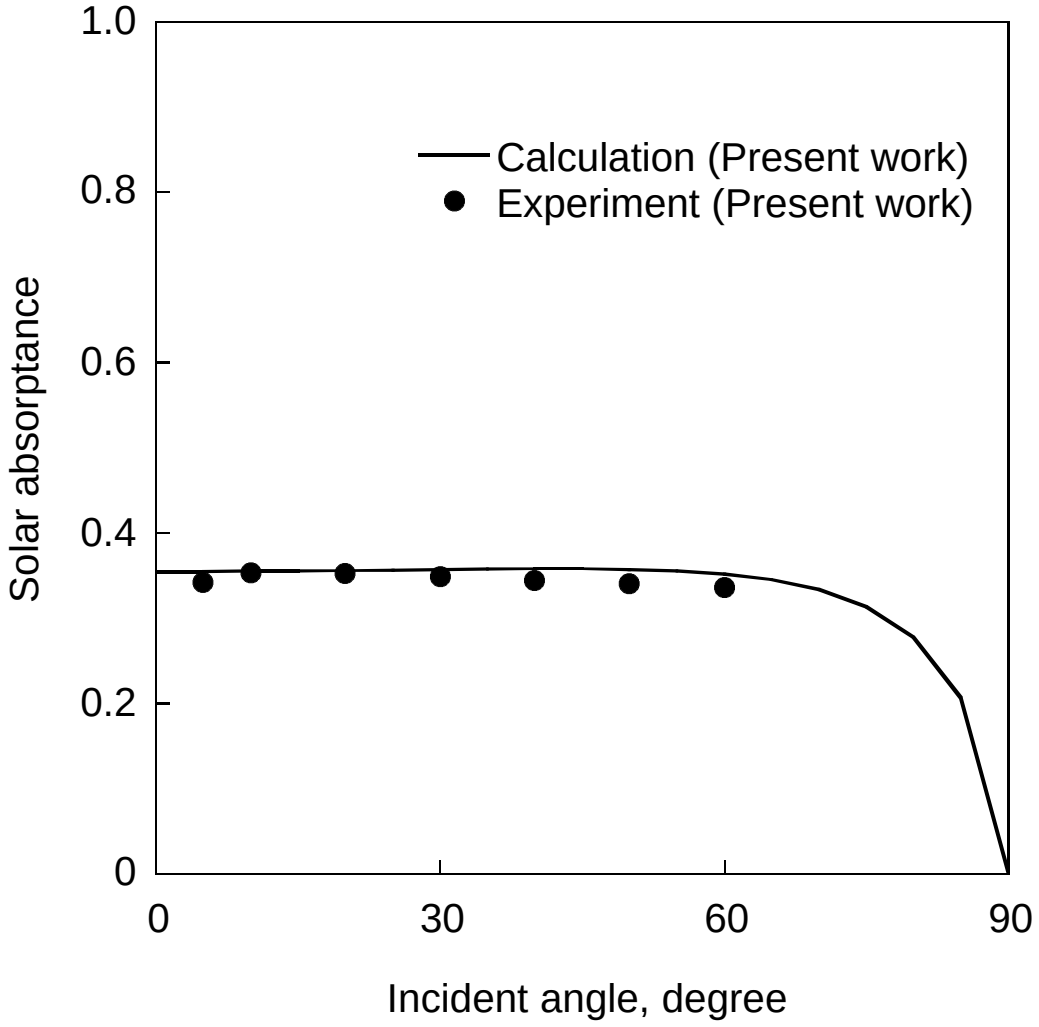
Fig. 7. Calculation results of incident angle dependence of spectral reflectance.

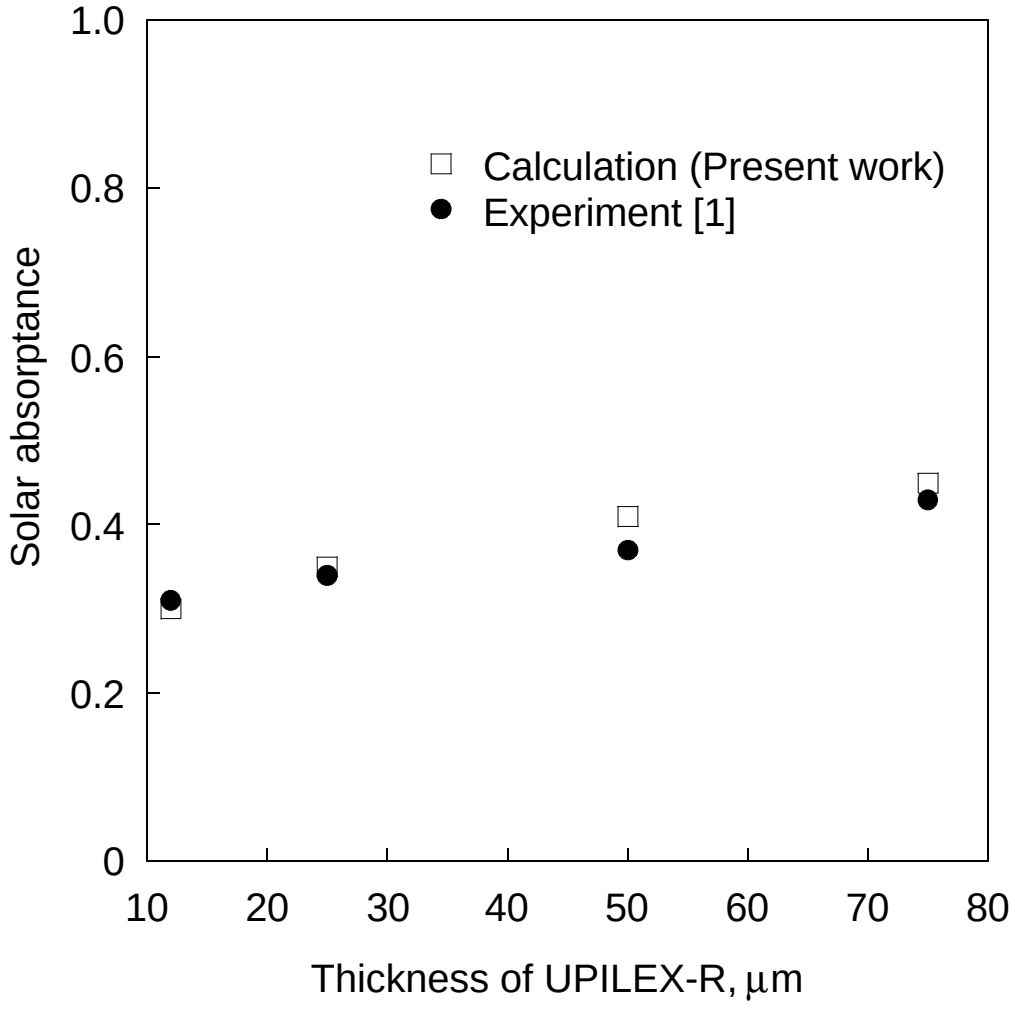

Electromagnetic waves
θ
d2
UPILEX-R (n2, k2)
d1
Al (n1, k1)

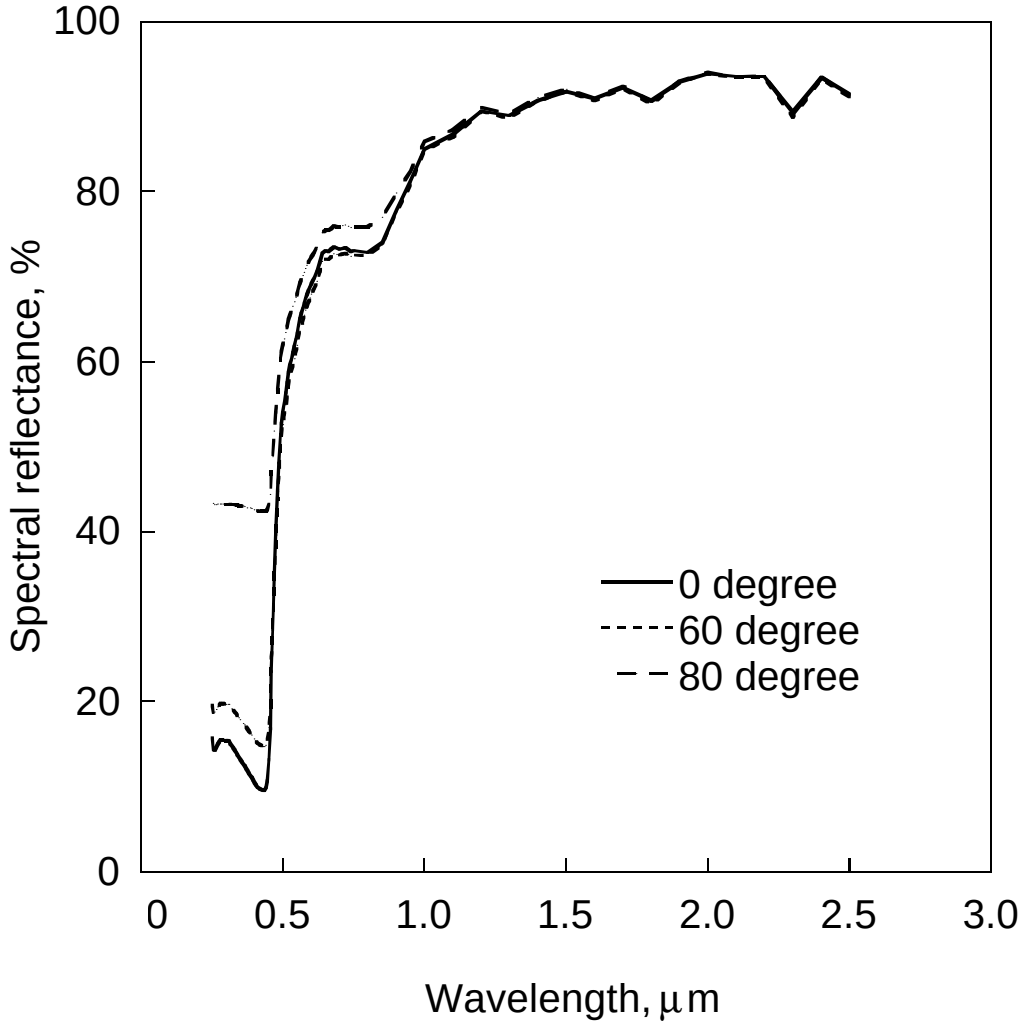

3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Refractive index
0.5
0.4
0.3
0.2
0.1
0
Extinction coefficient
0
20
40
60
80
100
Wavelength, μm
Refractive index
Extinction coefficient


1.0
0.8
0.6
0.4
0.2
0
Total hemispherical emittance
150
200
250
300
350
400
Temperature, K
Calculation (Present work)
Experiment [1]


1.0
0.8
0.6
0.4
0.2
0
10
20
30
40
50
60
70
80
Total hemispherical emittance
Thickness of UPILEX-R, μm
Calculation (Present work)
Experiment [1]


1.0
0.8
0.6
0.4
0.2
0
Solar absorptance
Calculation (Present work)
Experiment (Present work)
0
30
60
90
Incident angle, degree


1.0
0.8
0.6
0.4
0.2
0
Solar absorptance
Calculation (Present work)
Experiment [1]
10
20
30
40
50
60
70
80
Thickness of UPILEX-R, μm


100
80
60
40
20
0
Spectral reflectance, %
0
0.5
1.0
1.5
2.0
2.5
3.0
Wavelength, μm
0 degree
60 degree
80 degree