Journal of Mechanical Engineering Research and Developments
ISSN: 1024-1752
CODEN: JERDFO
Vol. 43, No. 1, pp. 351-357
Published Year 2020

Numerical Evaluation About Spectral Reflection Properties of Solar Collector With Microstructure

S. Kinoshita[†*], K. Kageyama[†] & A. Yoshida[†]

[†]Department of Mechanical Engineering, Osaka Prefecture University 1-1 Gakuen-cho, Naka-Ku, Sakai, Osaka 599-8531, Japan
*Corresponding Author Email: kinosita@me.osakafu-u.ac.jp

ABSTRACT: In recent years, attention is increasingly focused on renewable energy. In order to increase the efficiency of solar thermal power generation which is one of renewable energy, it is important to improve the power generation efficiency by increasing the absorption rate of the solar energy collector while reducing the radiation loss. It is known that spectral characteristics control is possible by applying a microstructure to the surface. In this study, the effect of surface periodic microstructure on solar reflectance characteristics is evaluated. FDTD method is applied for electromagnetic field analysis. As the spectrum of solar radiation is distributed in the visible region and the near-infrared region, reflectance of uneven surface is calculated in the region of wavelength from 0.3 mm to 2.5 mm. Evaluation is performed by giving a plane wave to the dielectric with a periodic microstructure of the depth L_x, the opening length L_y, and the pitch length L, respectively. Poynting vector is used for calculating the reflectance. For the analysis of solar reflectance, calculations were made with reference to JIS K 5602: 2008. It can be seen that when the ratio of the concave portion to the convex portion is 1: 1, the solar reflectance becomes lower than in the other proportions. Also, when the depth was 0.1 mm, the reflectance was the lowest, 0.0350, which was about 31.5% of the solar reflectance of the flat plate.

INTRODUCTION

Recently, emission reduction of carbon dioxide which occupies most of the global warming greenhouse gas is urgent issue for climate change, and utilization of renewable energy increases in the importance of countermeasure to the global warming. In the solar thermal power generation using the solar radiation, which is one of the renewable energy, it is necessary to improve the heat collection efficiency not only by increasing the solar absorptance of solar collector but also by reducing heat loss due to infrared emission from the surface. It is expected that the efficiency of heat collector surface can be improved by realizing the absorption properties which is most suitable for a spectrum of solar radiation. In addition, because surface temperature of heat collector exceeds 1100°C in maximum and spectrum of infrared radiation emitted from the surface is distributed around the near-infrared region of solar radiation, it is necessary for the reduction of heat loss to decrease the spectral emittance of the wavelength region. Thus, it is considered that heat collector surface with lower reflectance from 0.3 to 2.5mm in wavelength and higher reflectance in longer wavelength region from 2.0mm is most suitable. Control of the spectrum properties of solid surface is known to be realized by constructing the surface microstructure[1-2]. In this study, it is numerically evaluated the effect of periodic microstructure on solar reflection properties of solid surface by means of FDTD method.

FUNDAMENTAL EQUATIONS AND NUMERICAL CONDITIONS

The behavior of electromagnetic fields in space is expressed by Maxwell's equations as shown in the following equations.

$$\nabla \times \boldsymbol{E}(\boldsymbol{r},t) = -\frac{\partial \boldsymbol{B}(\boldsymbol{r},t)}{\partial t} \tag{1}$$

$$\nabla \times \boldsymbol{H}(\boldsymbol{r},t) = \frac{\partial \boldsymbol{D}(\boldsymbol{r},t)}{\partial t} + \boldsymbol{J}(\boldsymbol{r},t) \tag{2}$$

where E, electric field; B, magnetic flux density; H, magnetic field; D, electric flux density; J, electric current density; r, position; t, time. This electromagnetic field is numerically evaluated with FDTD method. Discretization of fields and numerical procedure are based on Yee algorithm.

Incident wave is TM wave composed of three components of E_x, E_y and H_z. As the spectrum of solar radiation is distributed from visible to near-infrared region, wavelength region for analysis is set from 0.3 to 2.5mm and the spectral reflectance in the region of solid surface is evaluated. Computation domain is shown in Fig.1. As shown in the figure, computations are performed to the dielectric substance with a periodic microstructure where a plane TM wave is incident. It assumed that the other domain is a vacuum for simplification. Surface structure of dielectric consists of rectangular groove with the depth L_x, aperture width L_y and aperture pitch L, and is uniform in z direction, as shown in Fig. 1. Periodic boundary condition is set for the surfaces of z = 0 and L, and PML boundary condition is set for the surfaces parallel to the yz plane. For the wave source for plane wave incidence, sine wave of an electric field is set as expressed in Eq. (3) and set at a cross section enough far from a solid surface for analysis.

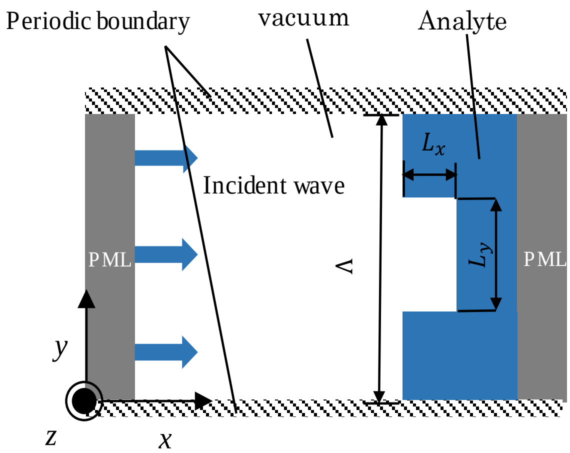

Figure 1. Computation domain and boundary condition.

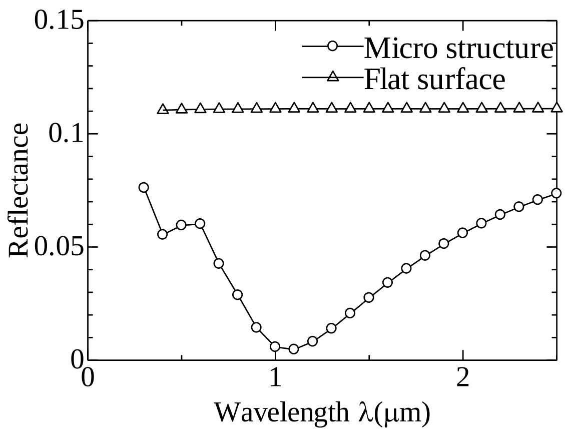

Figure 2. Spectral reflectance of micro-structured and flat surfaces.

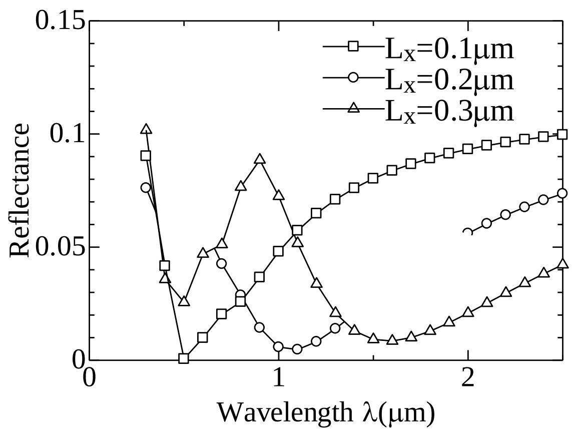

Figure 3. Effect of groove depth on spectral hemispherical reflectance.

$$E_y = E_{amp} \sin(2\pi ft) \quad (3)$$

where E_{amp} is arbitrary constant, and is set 10V/m in common condition, and f is frequency.

Spectral reflectance is evaluated by the ratio energy flux of scattered wave to that of incident wave through the cross section enough far from solid surface. Energy flux is evaluated by time average of Poynting vector integrated on the cross section.

NUMERICAL RESULTS OF NORMAL INCIDENCE

Evaluation of reflection characteristics for flat surface and micro-structured surface

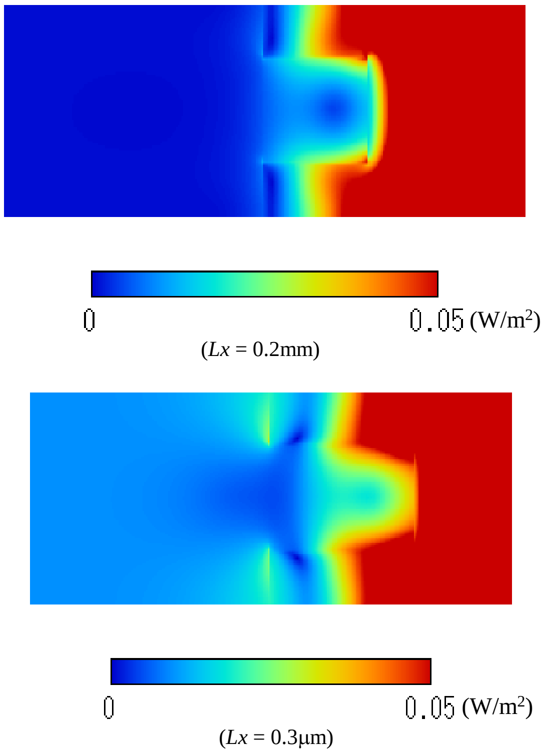

Figure 4. Distribution of scattering energy flux.

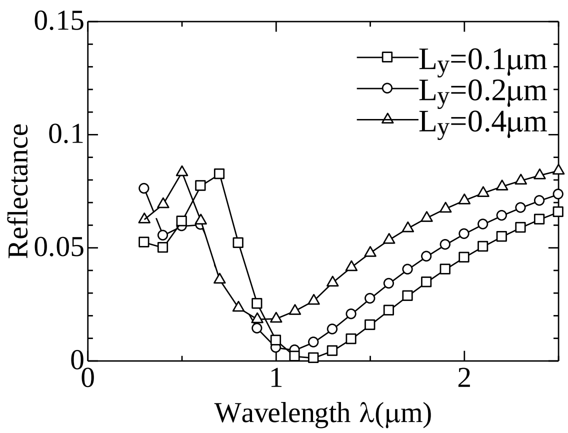

Figure 5. Effect of apperture width on spectral reflectance.

In order to evaluate the effect of micro structure installed on flat surface on reflection characteristics, the spectral reflectance of the micro-structured surface with depth L_x = 0.2mm, aperture width L_y = 0.2mm and aperture pitch L

= 0.4 mm is analyzed, and the results is compared with that of flat surface. Relative permittivity of dielectric is assumed to be constant in 4.0. In this case, the theoretical reflectance is estimated as 0.111 according to Fresnel's formula. Figure 2 shows the results. As shown in the figure, it is found that the spectral characteristics in reflection of micro-structured surface differ from that of flat surface. This result is confirmed to agree with the result analyzed by RCWA method [3-4]. It is found that the spectral reflectance becomes the local minimum near the wavelength 1.0mm, and becomes larger with increase of wavelength, which is caused by reduction of the effect of micro structure with increase of wavelength and is approached to the principle of the reflection of flat surface.

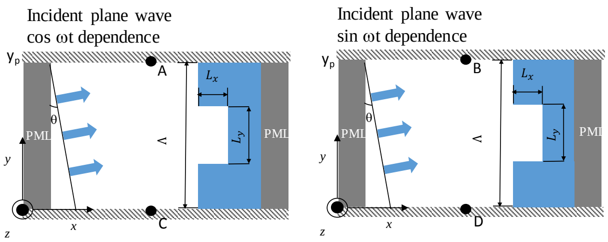

Figure 6. Concept of the sine-cosine method.

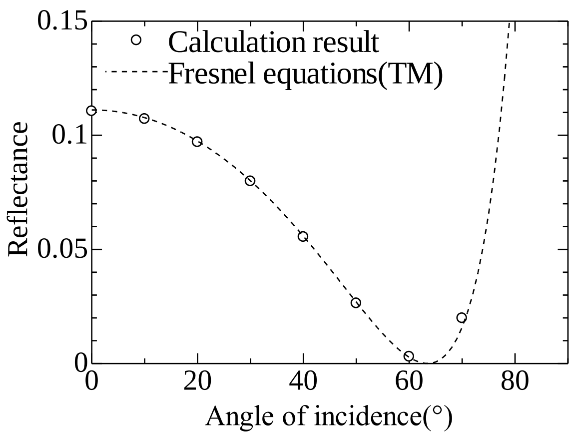

Figure 7. Effect of incident angle on spectral reflectance for flat surface.

Effect of depth of groove structure

In order to evaluate the effect of depth of groove on reflection characteristics, numerical analyses in the condition that depth of groove is changed and aperture width and pitch are constant are performed. Figure 3 shows the results of spectral reflectance in changing depth condition. As shown in the figure, position of the local minimum of spectral reflectance shifts with changing the depth, and it is confirmed that the effect of depth of groove to reflection characteristics is significant. Figure 4 shows the profile of time averaged scattering energy at wavelength 1.0mm. As shown in the figure, intensity of scattering energy in the case of L_x = 0.3mm is stronger than that in L_x = 0.2mm, which is related to higher reflectance. The wavelength to interfere the groove structure varies with the depth of groove. And the reflectance becomes larger with increase of wavelength, which is caused by the reduction of the effect of micro structure as the results in section 3.1.

Effect of aperture width of groove structure

To evaluate the effect of aperture width on reflection characteristics, analyses of reflectance in the condition that the aperture width of groove L_y is changed and depth L_x and pitch L is set to be constant in 0.2mm and 0.4 mm are performed. Figure 5 shows the results. As shown in the figure, the position of wavelength which the spectral reflectance takes local minimum scarcely changes in the change of depth. It is found that the reflectance is larger with increase of the aperture width, which is caused by reducing the effect of groove structure and approaching the condition of flat surface.

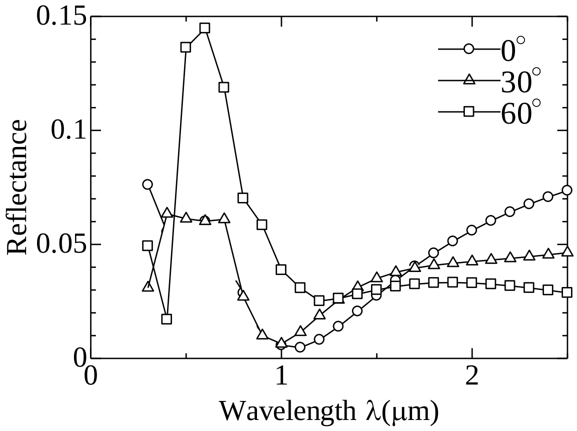

Figure 8. Effect of incident angle on spectral reflectance for surface microstructure.

NUMERICAL RESULTS OF OBLIQUE INCIDENCE

Periodic boundary condition for oblique incidence

In the case of oblique incidence, simply applying the periodic boundary condition leads to phase difference between upper and lower sides of boundaries. So, it is necessary for performing accurate simulation in oblique incidence condition to apply some approximate analysis in periodic boundary condition. In this study, sine-cosine method [5-6] is applied to the periodic boundary, and is one of solutions in modelling periodic boundary for specific frequency. Figure 6 shows the concept of sine-cosine method. In the method, both of the fields of incident wave depended on coswt and sinwt are simultaneously analyzed, and unknown magnetic or electric field on periodic boundary is predicted as following equations.

$$E_x(A) = \mathrm{Re}\left\{\left[E_x(C) + jE_x(D)\right]\exp\left(-jk_y y_p\right)\right\} \tag{4}$$

$$E_x(B) = \mathrm{Im}\left\{\left[E_x(C) + jE_x(D)\right]\exp\left(-jk_y y_p\right)\right\} \tag{5}$$

$$H_z(C) = \mathrm{Re}\left\{\left[H_z(A) + jH_z(B)\right]\exp\left(jk_y y_p\right)\right\} \tag{6}$$

$$H_z(D) = \mathrm{Im}\left\{\left[H_z(A) + jH_z(B)\right]\exp\left(jk_y y_p\right)\right\} \tag{7}$$

where j is the imaginary unit, k_y is wavenumber. Figure 7 shows the reflectance characteristics for each incident angle of plane wave to the flat surface. In the same figure, reflection characteristics calculated with Fresnel's formula is also shown. Numerical result agrees with solution Fresnel's formula, and the angle that reflectance becomes zero, which corresponds to brewster's angle, agrees with each other. From these results, applicability of the method is confirmed.

The effect of oblique incidence for micro-structured surface

In order to evaluate the effect of the incident angle on reflection characteristics of micro-structured surface, reflectance analysis is performed in the conditions that incident angle is changed under common rectangular groove structure surface with L_x = 0.2mm, L_y = 0.2mm and L = 0.4mm. Figure 8 shows the results. As the incident angle becomes larger, the maximum of spectral reflectance becomes larger, and spectral reflectance in longer wavelength region tends to be lower as same as the result of flat surface. It is confirmed that the reflectance characteristics is strongly affected by the micro structure of the dielectric surface in short wavelength region, and is influenced by the characteristics of flat surface in long wavelength region.

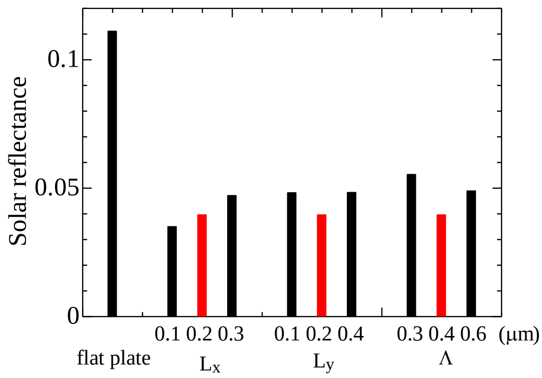

Figure 9. Effect of micro structure on solar reflectance of dielectric.

EVALUATION OF SOLAR REFLECTANCE

Solar reflectance is calculated according to JIS K5602: 2008[(4)]. Spectral reflectance for each wavelength through the object wavelength region is evaluated with FDTD method, and is multiplied by weighted factor corresponding to the spectral radiation intensity of standard solar light, and solar reflectance is evaluated by weight mean value as following equation.

$$\rho_e = \frac{\sum \rho_\lambda E_\lambda \Delta\lambda}{\sum E_\lambda \Delta\lambda} \qquad (8)$$

where r_e is solar reflectance, r_l is spectral solar reflectance and E_lDl is weight factor of standard solar light. Figure 9 shows the solar reflectances calculated by changing the structure parameter in the case of L_x = 0.2mm, L_y = 0.2mm , L = 0.4mm as the standard structure. Incident angle is normal. As shown in the figure, it can be seen that when the ratio of the concave portion to the convex portion is 1:1, the solar reflectance becomes lower than in the other proportions. Also, when the depth was 0.1 mm, the reflectance was the lowest, 0.0350, which was about 31.5% of the solar reflectance of the flat plate.

SUMMARY

The effect of surface periodic microstructure on solar reflectance characteristics of solar energy collector surface is numerically evaluated with FDTD method. Results are as following.

- In the control of spectral reflection characteristics, the depth of groove is most influenced.
- The reflectance characteristics is strongly affected by the micro structure of the dielectric surface in short wavelength region.
- When the ratio of the concave portion to the convex portion is 1: 1, the solar reflectance becomes lower than in the other proportions.
- When the depth was 0.1 mm, the reflectance was the lowest, 0.0350, which was about 31.5% of the solar reflectance of the flat plate.

Refer to each table and figure in the text. Place tables and figures in the order mentioned in the text as close as possible to text reference. Allow single spacing between the table or figure and the adjacent text, and no space between the table title and table (or between figure caption and figure). Tables and figures should not repeat data available elsewhere in the paper. Number them consecutively with single Arabic numerals (e.g., Figure 1, Table 1). Please fit figures, tables, and photographs in one column if possible. Do not reduce figures or tables to a size at which their labels will be difficult to read. Please make the length of both columns equal on the last page.

REFERENCES

[1] D. Hirashima, Y. Kameya. and K. Hanamura. “Normal Spectral Emittance of Nickel Metal Surface with Rectangular Microcavities”. *Netsu Bussei*, Vol. 22, No. 3, pp.167-171. 2008.

[2] M. Elmnifi, M. Alshilmany, M. Abdraba. "Potential of Municipal Solid Waste in Libya For Energy Utilization". *Acta Mechanica Malaysia*, vol. 2, no. 1, pp. 11-15. 2019

[3] M.G. Moharam, T.K. Gaylord. "Diffraction Analysis of Dielectric Surface-relief Gratings". *Journal of the Optical Society of America*, Vol.72-10, pp.1385-1392. 1982.

[4] H. Khan, Muhammad Arif, S.T. Mohyud-Din. "Numerical Solution Of Fractional Boundary Value Problems By Using Chebyshev Wavelet Method". *Matrix Science Mathematic*, vol. 3, no. 1, pp. 13-16. 2019.

[5] A. Taflove, and S.C. Hagness, *Computational Electrodynamics: The Finite Difference Time Domain Method*. Artech house. 2005.

[6] M. M. Hanafiah, K. M. Jansar. "MySTREAM: Empowering 21st Century Skills Through Transdisciplinary and Sustainability Techniques". *Engineering Heritage Journal*, vol. 3, no. 2, pp. 9-11. 2019.

[7] Japanese Industrial Standard Committee. "JIS K5602: Determination of Reflectance of Solar Radiaton by Painted Film". 2008.

[8] H.H. Jobaneh. "An Ultra-Low-Power and Ultra-Low –Voltage 5 GHz Low Noise Amplifier Design with Precise Calculation". *Acta Electronica Malaysia*, vol. 3, no. 2, pp. 23-30. 2019.