Systematic Numerical Experiments for Investigation of Urban Albedo Characteristics

Chimklai, Parichart
Department of Energy and Environmental Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Tanimoto, Jun
Department of Energy and Environmental Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

Hagishima, Aya
Department of Energy and Environmental Engineering, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University

https://doi.org/10.15017/16692

出版情報：九州大学大学院総合理工学報告. 25 (2), pp.207-214, 2003-09. 九州大学大学院総合理工学府

九州大学大学院総合理工学報告
第25巻 第2号 207-214 頁 平成15年9月

Engineering Sciences Reports, Kyushu University
(KYUSHU DAIGAKU SOGORIKOGAKU HOKOKU)
Vol. 25, No. 2 pp. 207-214 SEPT. 2003

Systematic Numerical Experiments for Investigation of Urban Albedo Characteristics

Parichart CHIMKLAI*1,† Aya HAGISHIMA*2 and Jun TANIMOTO*3
†E-mail of corresponding author: *parich@cm.kyushu-u.ac.jp*

(Received July 31, 2003)

One of the important parameters used to estimate Urban Heat Island that involved with mesoscale model is albedo. It is useful to reliably investigate the energy budget in an urban through the radiation exchange study within urban canopy. In order to systematically clarify the urban albedo characteristics coupling with that of factorial effects, we introduce an *Albedo Calculation Model*, which is simple and more reliable to provide the 3-dimensional urban albedo simulation. In addition, the numerical experiment based on the model was carried out for supplementary explanation of how the significant factors affect albedo characteristics. In this paper, the principle of Albedo Calculation Model and associated numerical experiment results are obviously described.

Keywords: *Mesoscale Model, Albedo, Albedo Calculation Model, Numerical Experiments*

1. Introduction

The improvement of mesoscale performance for more suitable with urban atmospheric model enable to estimate urban heat island effects is significant in recent years. Regarding the evaluation of energy budget in an urban canopy, it is basically considerable in line with the study of urban radiation exchange. Normally, mesoscale models assume the flat surface of any grid cell to be identical at a given altitude with a given group of surface characteristics. From an energy balance aspect, the reflectivity to the surface called Albedo is one of the important parameters of those characteristics.

It is generally agreed that urban geometry plays an important role in the urban net radiative balance (Arnfield, 1982). The roughness of urban surface causes the multiple reflections and reduction of the total solar energy reflected. Nevertheless, it is difficult to represent the detailed physics with in the urban canopy due to the complexity and diversity. At this stage, many studies have pushed effort to quantitatively specify the influence of urban configurations to albedo functional for implementation in a mesoscale model. Aida (1982) has observed the effect of urban surface structure on albedo by employing both the scale blocks model experiment and a 2-dimensional numerical simulation. Sailor (2002) has indicated diurnal albedo distributions associated with building height variability simulation cases by using the 2-dimensional radiation model (TURM). Based on 3-dimensional radiation model, Kondo (2001) investigated the influence of urban canopy configuration on net radiation flux. The albedo has been calculated by Monte Carlo photon tracking method.

However, those researches seemed to lack comprehensive explanation on the comparison of factorial effects to albedo value and the magnitude of effectiveness by each one, by which, it is useful to systematically clarify albedo characteristics.

Consequently, we established the simple method but more reliable and practicable; an *Albedo Calculation Model*, to provide the calculation of urban albedo. Additionally, the numerical experiments dealing with the model were also carried out to determine the magnitude of significant factors such as urban configuration and solar angle to albedo characteristics. The model was developed into 3-dimensional simulation model provided an accurate computing, that model takes in to account in the building height distribution, also the effects of multiple reflections and shading with in the urban canopy.

*1 Department of Energy and Environmental Engineering Science, Graduate student
*2 Department of Energy and Environmental Engineering Science
*3 Department of Energy and Environmental Engineering Science

2. The Albedo Calculation Model

2.1 Principle of Calculation

In fact, the real urban structures are not simply geometric and have no uniformity, so it is difficult to determine the certain value of their albedo. Thus, we supposed the urban configurations as followings to facilitate the simulation.

- the entire buildings are uniform size (W_bxW_b) and located homogeneously along identical roads,
- the set of building blocks has the same height or only two different heights upon specified patterns (Fig. 1).

The road width-to-building height ratio (W/H_a) and ground coverage percentage by buildings (η) are given by

$$W/H_a = \frac{W_r}{\sum_{i=1}^{n} H_i} \quad (1)$$

$$\eta = \frac{W_b^{\,2}}{(W_b + W_r)^2} \quad (2)$$

where H_a is the average of building heights, n is the total number of buildings in an unit area (n=4), and W_r and W_b is the road width and building width, respectively.

Radiation exchanges are taken into account within a range of only one unit area, since four surroundings boundaries are treated as cyclic-loop. Each facade of the unit area, including roofs, walls, and road, is specified rectangular grids (n grids) in order to precisely calculate solar radiation emitted into the urban canopy. The 1st order incidental solar radiation received by grid i ($SR_{i,1}$) is obtained from

$$SR_{i,1} = \begin{cases} D_i R_{dir,1} \sin\theta |\cos\alpha| + F_{sky,i} R_{diff,1} & ;\text{walls} \\ D_i R_{dir,1} \cos\theta + F_{sky,i} R_{diff,1} & ;\text{roofs \& road} \end{cases} \quad (3)$$

where θ is the solar zenith angle (rad), α is the angle of the solar azimuth against with facade (rad), F_{sky} is the sky view factor, R_{dir} and R_{diff} is the direct and diffused solar radiation (Wm^{-2}), respectively. The shadow effect (D) is given as: D_i=1 if grid i is in the sun, D_i=0 if grid i is in the shade (Fig. 2).

An iterative calculation of multiple reflections damped by walls, roofs and road is considered until when the multiple reflections turns to be less than 1% of the total 1-order incidental solar radiation for all grids. This is calculated from

$$SR_{i,m} = \frac{\sum_j (SR_{i,m-1} \rho_j F_{j,i} A_j)}{A_i} \quad (4)$$

where $SR_{i,m}$ is the radiation absorbed by grid i after m^{th} reflections (Wm^{-2}), ρ_j is the reflectance of facade j, $F_{j,i}$ is the configuration factor between grid j and grid i. A_i and A_j is the grid area of i and that of j (m^2), respectively.

Then, the albedo of unit area is defined by

$$Albedo = \frac{\sum_m \sum_i (SR_{i,m} F_{sky,i} \rho_i A_i)}{(R_{dir,1} \cos\theta + R_{diff}) \cdot A_a} \quad (5)$$

where A_a is the total area of an unit area (m^2).

It is noted that, in this model, the perfect isotropic reflection is supposed for all surface reflections.

2.2 Configuration factor and Sky view factor

In order to calculate the configuration factor and sky view factor, we applied the 3 dimensional vectors tracking method by casting 9x10^6 uniform vectors from a hemisphere positioned on the center of each grid. The hemisphere base area A_c is divided into small equal parts (9x10^6 pieces), and then, the distance r between point O to the center of

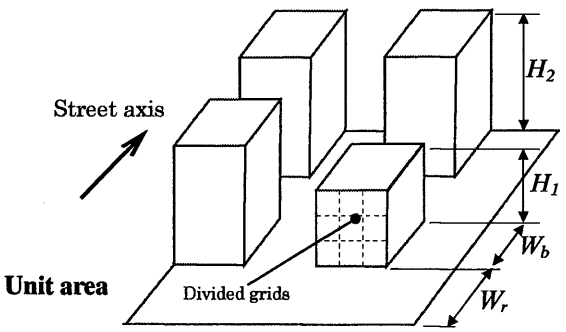

Fig. 1 Schematic diagram of building unit

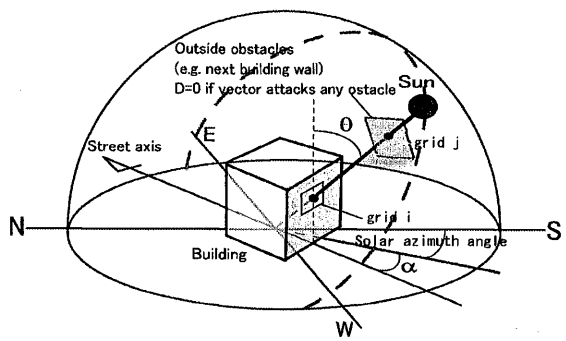

Fig. 2 Street axis and solar angle

each small part (point a), and angle ϕ ($0<\phi\leq\pi$) are given (Fig. 3). The direction of each vector can be expressed into (x, y, z) dimension as a function of r and ϕ. This gives;

$$\overline{OB}_n = \begin{bmatrix} r_n \cos\phi_n \\ r_n \sin\phi_n \\ \sqrt{1-r_n^2} \end{bmatrix} \quad ;1 \leq n \leq N_{\max} \qquad (6)$$

where N_{max} is the number of vectors casted from the center of hemisphere (N_{max}=9x10^6).

For a rectangular facade, the distinction of intersection point on the facade by a vector can be simply carried out according to equation (7) and Fig. 4.

$$\overline{OB} = u \cdot \overline{QR} + v \cdot \overline{QT} + \overline{OQ} \qquad (7)$$

where □QRST is a facade or a grid divided on facade. If $0\leq u\leq 1$ and $0\leq v\leq 1$, then point B is in the □QRST, that is vector OB collides the facade.

As the distinction result described above, the fraction of those vectors collided with a facade is the corresponding configuration factor, and the remainder that is not reflected on any facade is defined as the sky view factor. The configuration factor from the center of grid i to grid j divided on a facade reads,

$$F_{j,i} = \frac{N_{j,i}}{N_i} \qquad (8)$$

where N_i is the number of vectors casted from grid i, and $N_{j,i}$ is the number of vectors among N_i that are collided by grid j.

The sky view factor of grid i is determined from

$$F_{sky,i} = 1 - \sum_{j=1}^{J_{\max}} F_{j,i} \qquad (9)$$

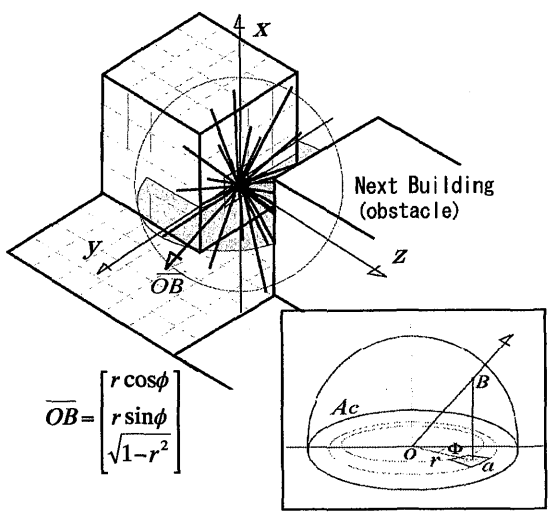

Fig. 3　Diagram of Vectors tracking method

where J_{max} is the number of all grids where absorbed vectors released from grid i.

3. Model Validation

The albedo results given by the model are now compared to the observed data presented by Katsuyama (2002) and the simulated data obtained by Kawai (2003). To evaluate our model performance, the validation for the case of building blocks having the same height was conducted. Katsuyama et al. proposed the small-scale model for observing canopy albedo in 3-dimensional model cities. The models of urban structure with cubic concrete blocks (15cm x 15cm x 15cm) were built and measured the solar radiation reflected by this surface. On the other hand, the 3-dimensional radiation model presented by Kawai was established based on the urban structure and experiment reported previously by Katsuyama enable to simulate canopy albedo.

Fig. 5 shows the measurements of albedo (from Katsuyama, 2002), as dots, compared with the simulating of canopy albedo (from Kawai, 2003), and the albedo obtained from our calculation model. The observation was carried out during summer of July in Tokyo. The results of albedo are shown with building coverage (η) of 0.31 and 0.51, respectively (Fig 5-(a), 5-(b)). The results of our model nearly coincide with both observed and simulated data. For the sun at the zenith, approximately 12:00PM, albedo of η = 0.31 case varies more than 0.26-0.27, and one of η = 0.51 case is growing decrease to less than 0.258. This behavior shows when the road surface becomes smaller, it affects decreasing of albedo value.

Particularly, there are 2 points to be point out: (1) slight difference between calculated and observed data through out the day, and (2) arising rapidly when the sun is low. It is probably because we assumed perfect isotropic reflection for all facades, also the scattered component ratio is supposed as 0.2 constantly throughout this validation. However, in fact, it

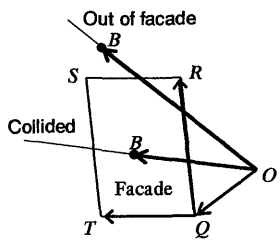

Fig. 4　The distinction of an intersection point

merely lacks consistency with the nature aspect. Additionally, as comparison with simulated data from Kawai, although our curves correspond to that of tendency, yet it indicates a little discrepancy. This might be due to the differences of, such as, vector tracking method, the limits of multiple reflections, and so forth.

4. Numerical Experiments

4.1 Design of Experiment

The experiments were carried out to allow for more systematic investigation of factorial effects to urban albedo characteristics. The concept is that, with the significant factorial factors such as urban configurations, reflectance of surface materials, solar angles including 3-6 levels in each factor, a full factorial design for experiments which correspond to the model were conducted. Subsequently, a numerous results of urban albedo were attained. With these results, the magnitude of how factorial factors affect urban albedo characteristics could be given.

To investigate these significant effects, the simulations of four building patterns were developed. In one unit area of each pattern, 4 buildings having both the same and different heights are assumed. The patterns included all same-height buildings (pattern 1), and the others are alternating low and high buildings (pattern 2, 3, and 4). These patterns have same H_a that are averaged throughout the other factors respectively, which are illustrated in Fig. 6. The experiments were conducted separately into 2 parts; Experiment 1 for building pattern 1, and Experiment 2 for a group of pattern 2 to 4.

The main factors with that of reasonable levels identified as primarily affecting the urban albedo are shown in Table 1. Full factorial experiments for Experiment 2 consist of 103,680 simulation cases and for Experiment 1 are 34,560 simulation cases. With the full factorial design, the experiment results are more accurate and reliability due to the statistical error becomes insignificant.

4.2 Results and discussion

The results obtained for the full factorial experiments are shown in Table 2. It is noted that the response data focused in this paper are for the main factors excluding for the results of interactions. Concerning these interactions, 8x7 for Experiment 1 and 10x9 for Experiment 2, are disclosed at out web-site. The response albedo values dealing with W/H_a, η, and reflectance of roof are plotted as representative results in Fig. 7. The respond curves illustrate clearly that the increasing of those three factors respectively influence on the larger albedo values. Further, in order to systematically study the role of urban

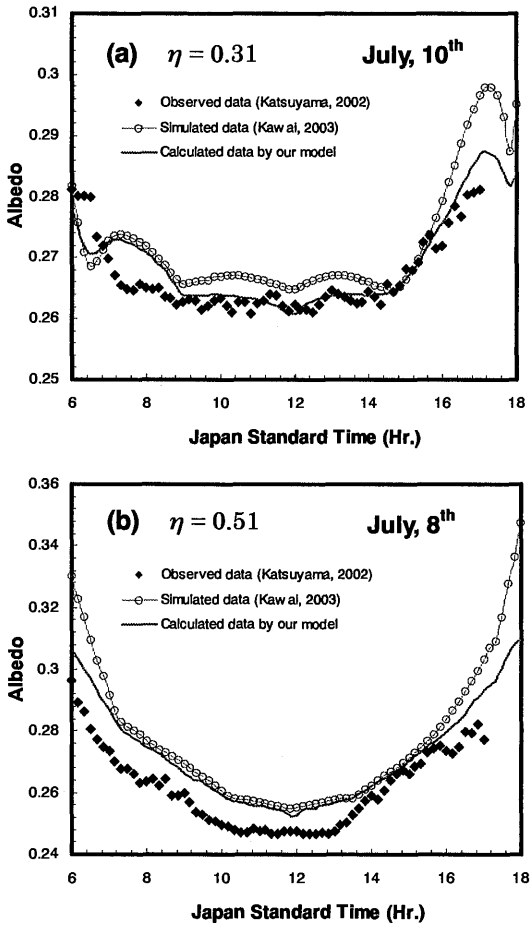

Fig. 5 Diurnal albedo validated with exist data

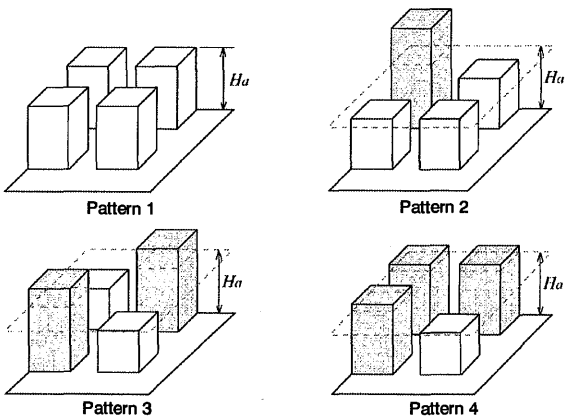

Fig. 6 Pattern scenarios used in the experiments

configuration variability on canyon albedo, we assumed the set of simulations will each surface being assigned reflectance values range from 0.1 to 0.5. That is due to make out the variety effects of multiple reflections. Regarding comparing of typical situations, the cases of various facade reflecitivities are assumed to be separate into Case A, Case B, and Case C. Case A has relatively high reflectance of ground (=0.3) and wall (=0.5), and low roof reflectance (=0.1). Case B has relatively high reflectance of roof (=0.3) and wall (=0.5), and low ground reflectance (=0.1). Case C is the case in which reflectance of all surfaces are 0.3. Fig. 8 and Fig. 9 show the effective albedos obtained from the

Table 1　Factor & Level Descriptions for the Experiment 1 (for Pattern 1), and Experiment 2

	Factors	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Experiment 1	1. Road Width-to-Building Average Height Ratio (W/H)	0.5	1.0	1.5			
	2. Ground Coverage Percentage by Building (η) [%]	20	40	60			
	3. Reflectance of Roof	0.1	0.2	0.3	0.4		
	4. Reflectance of Road or Ground	0.1	0.2	0.3	0.4		
	5. Reflectance of Wall	0.1	0.2	0.3	0.4	0.5	
	6. Solar Altitude Angle (β) [Deg] 1)	15	30	45	60	75	90
	7. Solar Azimuth Angle (ϕ) [Deg] 2)	0	15	30	45		
	8. Direct Solar Radiation Fraction (DS) 3)	0.0	1.0				
Experiment 2	1. Road Width-to-Building Average Height Ratio (W/H_a) 4)	0.5	1.0	1.5			
	2. Ground Coverage Percentage by Building (η) [%]	20	40	60			
	3. Building Pattern Scenarios	Pattern 2	Pattern 3	Pattern 4			
	4. Building Height Fraction (Hi / Lo) 5)	1.5	2.0	2.5			
	5. Reflectance of Roof	0.1	0.2	0.3	0.4		
	6. Reflectance of Road or Ground	0.1	0.2	0.3	0.4		
	7. Reflectance of Wall	0.1	0.2	0.3	0.4	0.5	
	8. Solar Altitude Angle (β) [Deg]	15	30	45	60	75	90
	9. Solar Azimuth Angle (ϕ) [Deg]	0	15	30	45		
	10. Direct Solar Radiation Fraction (DS)	0.0	1.0				

1) The angle between the solar beam and a horizontal surface.
2) The angle on a horizontal surface between the projected solar beam and the line which points true south.
3) The ratio of direct solar radiation beam to Global solar radiation.
DS = Dir / (Diff + Dir); where Dir is the direct component of sunlight, and Diff is the diffuse component of skylight.
4) H_a is building height average in one unit area.
5) For example, high building = 15 m. height, and low building = 10 m. height, hence Hi/Lo = 15 / 10 = 1.5.
Note that Hi/Lo does not make any sense in the Building Pattern 1.

Table 2　Response table of the experiment results for main factors

	Factors (Total average albedo for Exp1=0.18326, for Exp2=0.17488)	Response Albedo Values					
		Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Experiment 1	1. Road Width-to-Building Average Height Ratio (W/H)	-0.01877	-0.00260	0.01617			
	2. Ground Coverage Percentage by Building (η) [%]	-0.01577	-0.00228	0.01805			
	3. Reflectance of Roof	-0.06014	-0.02005	0.02005	0.06014		
	4. Reflectance of Road or Ground	-0.03162	-0.01068	0.01045	0.03185		
	5. Reflectance of Wall	-0.02708	-0.01477	-0.00124	0.01344	0.02964	
	6. Solar Altitude Angle (β) [Deg]	0.00181	-0.00042	-0.00084	-0.00056	-0.00008	0.00008
	7. Solar Azimuth Angle (ϕ) [Deg]	0.00078	-0.00011	-0.00035	-0.00033		
	8. Direct Solar Radiation Fraction (DS)	-0.00024	0.00024				
Experiment 2	1. Road Width-to-Building Average Height Ratio (W/H_a)	-0.02311	0.00361	0.01949			
	2. Ground Coverage Percentage by Building (η) [%]	-0.01470	-0.00277	0.01747			
	3. Building Pattern Scenarios	0.00430	-0.01032	0.00601			
	4. Building Height Fraction (Hi / Lo)	0.00251	-0.00055	-0.00197			
	5. Reflectance of Roof	-0.05374	-0.01792	0.01791	0.05374		
	6. Reflectance of Road or Ground	-0.03136	-0.01060	0.01036	0.03158		
	7. Reflectance of Wall	-0.02993	-0.01624	-0.00135	0.01482	0.03267	
	8. Solar Altitude Angle (β) [Deg]	-0.00005	-0.00014	-0.00011	0.00000	0.00016	0.00012
	9. Solar Azimuth Angle (ϕ) [Deg]	0.00045	-0.00005	-0.00019	-0.00023		
	10. Direct Solar Radiation Fraction (DS)	0.00005	-0.00004				

experiments for each case regarding the urban configurations. The results shown in Fig 8 indicate that larger W/H_a affects the increasing of albedo values. The reason comes from the fact that the trapping effect by multiple reflections became less significant. Case B gives a small effect due to the low surface reflectance of ground was assumed, so that the incidental solar radiation reflected by ground has been decreased (Fig. 8-b). The percentage of ground coverage by building (η) has a strong influence on the albedo value as shown in Fig. 9. The characteristic value also seems to be influenced by surface reflectance especially the reflectance of roof. Fig. 9-a illustrates Case A having the low reflectance of roof has the opposite effect to that were expressed in Fig. 9-b and Fig. 9-c. Fig. 10 and

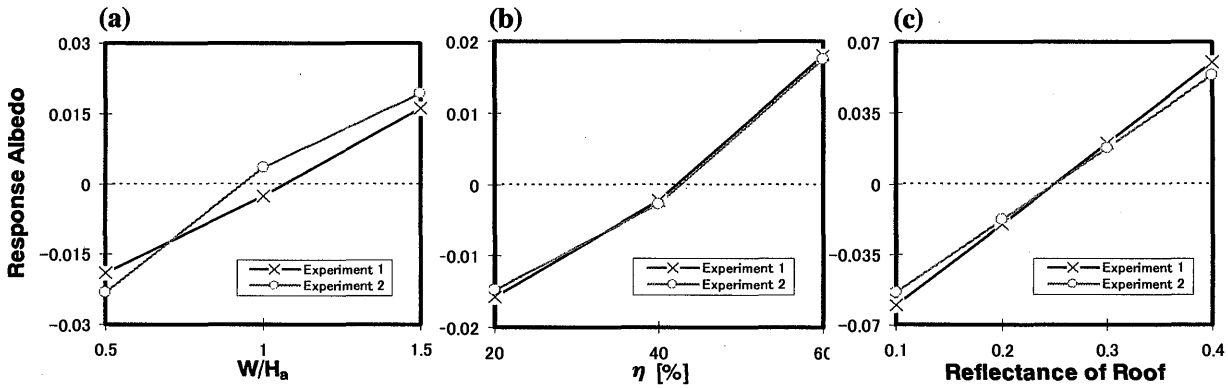

Fig. 7 Plots of response data for Experiment 1 and Experiment 2. Note that, the total average albedo of Experiment 1 and Experiment 2 is 0.18326, and 0.17488, respectively.

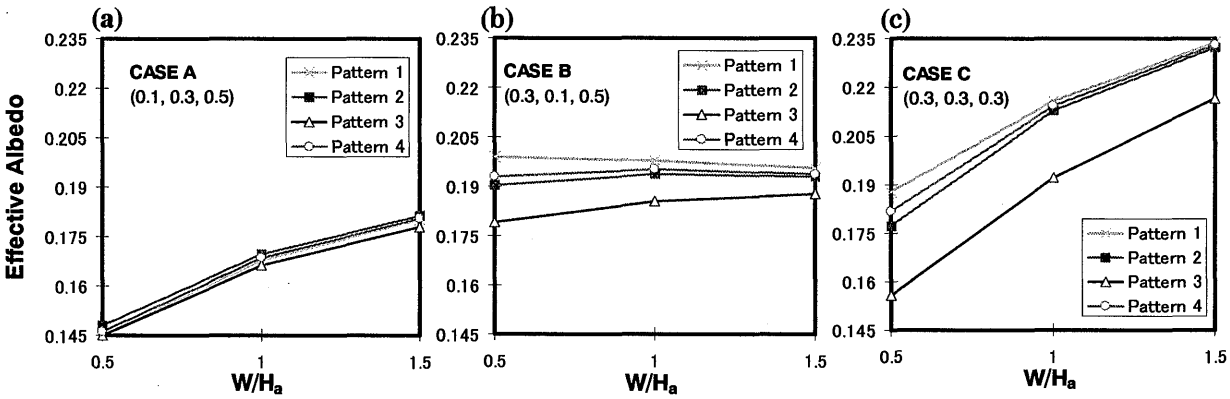

Fig. 8 Factorial effect of W/H_a to effective albedo for each case of surface reflectance and building pattern. Note that the values indicated in the parenthesis refer to the reflectance of (roof, ground, wall).

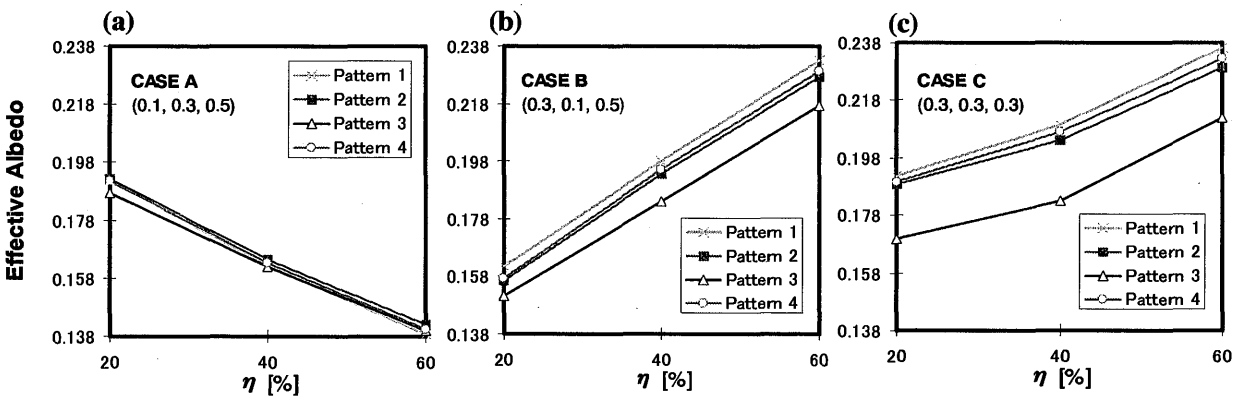

Fig. 9 Factorial effect of η to effective albedo for each case of surface reflectance and building pattern.

Fig. 11 show the influence of solar altitude angle (β) and that of building height fraction (Hi/Lo) on the albedo values, respectively. The results indicate a lower albedo value at the higher solar altitude angle or when the sun is high. Further, there appears to be no strong effect, additionally slight lower albedo value for the case of reflectance of wall being lower (Fig. 10-c). Regarding the building having different heights patterns (pattern 2 to 4), the building height fraction seems to have little effect on the effective albedo (Fig. 11). The high fraction takes the slight decreasing of albedo values. Anyway, at the low reflectance of roof (Case A), it appears to have an opposite minimal affect on the albedo (Fig. 11-a).

These figures explain that alternating low and high buildings (pattern 3) result in the lowest albedo values. The uniform buildings (pattern 1) seem to have a higher effective albedo than the patterns included one high building surrounded by low buildings group (pattern 2), and one low building surrounded by high buildings group (pattern 4). It is attributed to the varieties of building heights generate more canyon spaces where have more shading and trapping effects by multiple reflections which cause the lower albedos.

As the above results, it may be noted that the surface reflectance of each facade (roof, ground, and wall) is significant to raise or reduce the magnitude of albedo effectiveness. Fig. 12 demonstrates that the albedos affected by each factor including W/H, η, and β, depend on the response surface reflectivities. Here, we pointed out the uniform buildings case (pattern 1) as a representation. Fig. 12-a shows that the albedo value affected by W/H increases with an increase in the reflectance of ground. In the same way, the albedo value affected by η increases as the reflectance of roof increases (Fig. 12-b). Fig. 12-c illustrates the effective albedos related to the β for various wall reflectivities. It is described that when the reflectances range over than 0.3, the albedos gradually decreases with increasing β but they have an opposite effect when the reflectances are less than 0.3.

5. Conclusions

The Albedo Calculation Model is a 3-dimensional model which developed to simulate the urban albedo. Subsequently, the

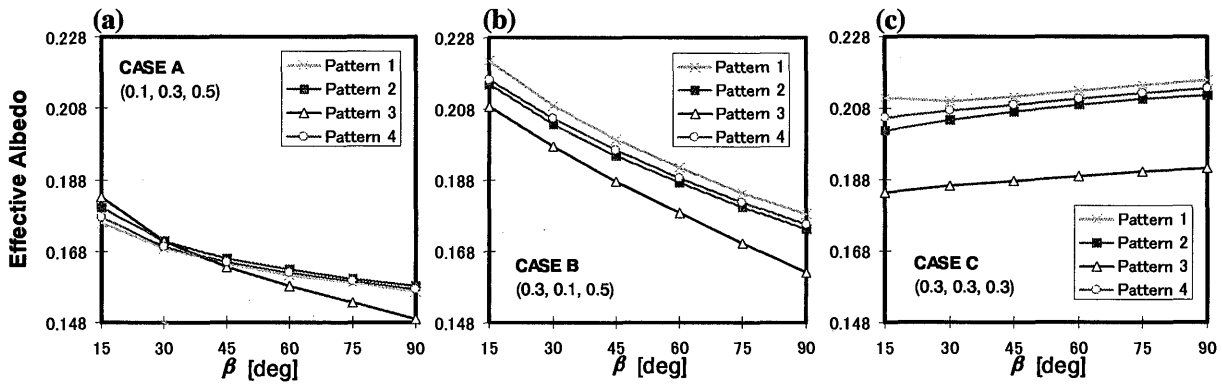

Fig. 10 Factorial effect of solar altitude angle to effective albedo

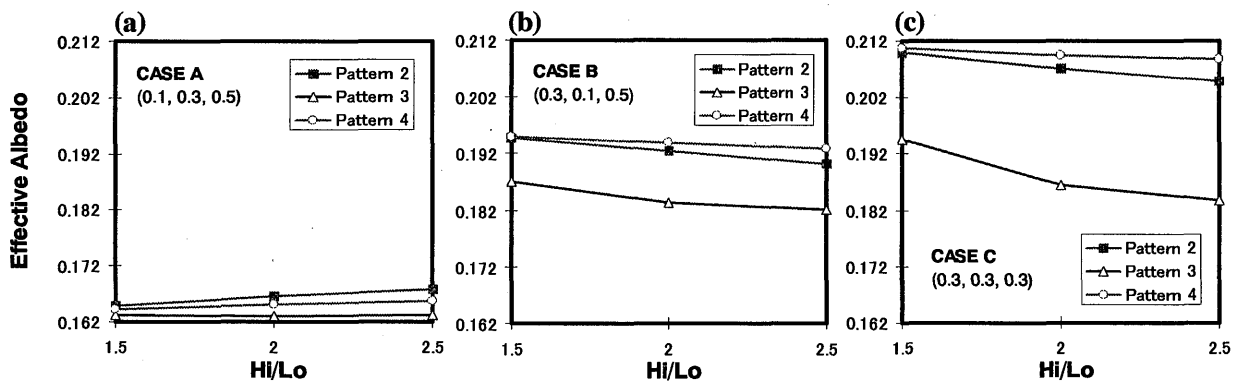

Fig. 11 Factorial effect of building height fraction to effective albedo

numerical experiments related to the model have been conducted to investigate how various factorial factors influence albedo characteristics. The results of the experiments were summarized in terms of response albedo profiles with a function of levels for investigating the influence of main factors, and effective albedo profiles for supplementary case of various surface reflectivities. These results strongly agree with the hypothesis that urban structure or urban canyon geometry plays an important role in the albedo value. Particularly, the effects from each factorial factor have been also clarified in this paper. As the obtained results, the surface reflectance which is a physical characteristic of facades seems to have the most influence in addition it seems to be significant interacting in relation to the albedo. Therefore, in order to study any effects of other factorial factors, it is necessary to fix the reflectivity for each facade previously as case by case.

The model is a useful tool for simulating the variability of urban albedo that enables to implement and incorporate in a mesoscale model. In addition, the attained outputs have been subsequently produced as a form of smart computer tools. These smart tools have been separated into two portions; the Albedo Calculator version 0.1 and the Albedo Viewer Web-Application. The former deals with a user's demand who has a particular input-condition, whereas, the latter responds very quickly if you have a possible input-condition that has been considered within the data base. Those applications can be obtained at our laboratory web site as follows: *http://ktlabo.cm.kyushu-u.ac.jp*.

Acknowledgments

This particular research was partially funded by a Grant-in-Aid for Scientific Research JSPS awarded to Prof. Tanimoto (#14702047). This research is partially supported by the Japan Science and Technology Corporation, Grant-in-Aid for CREST, Core Research for Evolutional Science and Technology that is awarded to Dr. Kanda, TITech. The authors would like to express their special thanks to those two different funding sources.

References

1) A.J. Arnfield, An approach to the estimation of the surface radiative properties and radiation budgets of cities, *Physical Geography* **3**, p. 97-122 (1982)
2) M. Aida, Urban albedo as a function of the urban structure – A model experiment (Part I), *Boundary Layer Meteorology* **23**, p. 405-413 (1982).
3) M. Aida, K. Gotoh, Urban albedo as a function of the urban structure – A two-dimensional numerical simulation (Part II), *Boundary Layer Meteorology* **23**, p. 415-424 (1982).
4) D.J. Sailor, H. Fan, Modeling the diurnal variability of effective albedo for cities, *Atmospheric Environment* **36**, p. 712-725 (2002)
5) Y. Higuchi, M. Udagawa, M. Satoh, and K. Kimura, Basic study on heat load simulation considering thermal effects of external environment: Part 3. Calculation model for form factor and shadow pattern, AIJ, Summaries of Technical Papers of Annual Convention, p. 15-16 (1999) (In Japanese)
6) S. Katsuyama, M. Kanda, T. Kawai, and K. Nakagawa, Experiment using 3D small scale model in urban canopy, Journal of Hydraulic Engineering **46**, p.85-90 (2002) (In Japanese with English abstract)
7) T. Kawai and M. Kanda, 3-dimensional radiation model for urban canopy, Journal of Hydraulic Engineering **47**, (2003) (In Japanese with English abstract)

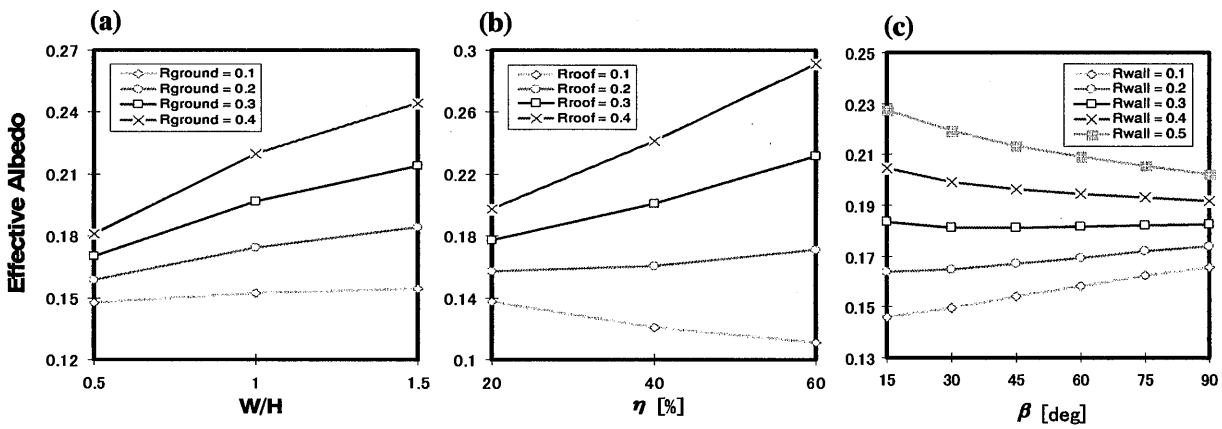

Fig. 12 The significant influence of surface reflectance for each facade to factorial factors. Note that *Rroof*, *Rground*, and *Rwall* refer to the reflectance of roof, ground, and wall, respectively.