APPLICATION OF PHYSICAL MODEL TO STUDY EFFECTIVE ALBEDO OF THE URBAN CANYON

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Abstract

The aim of this paper is to examine the influence of urban canyon parameters on its effective albedo. For that purpose the physical urban canyon model was constructed a bricks which enable measurements at horizontal surface, the canyon height (H), width (W) and azimuth changes. Preliminary results show that effective albedo of urban canyon is closely related to the Sun height, the Sun azimuth and ratio between diffuse and direct solar radiation. Effective albedo of the urban canyon with H/W = 1, roof width = 0.5 of W and north – south orientation on sunny days albedo values are about 15 - 20% lower in comparison with a horizontal surface. The second part of this study contains simulation of effective albedo by Monte Carlo method.

Key words: urban climate, multiple reflection, Monte Carlo simulation

1. INTRODUCTION

Influence of the urban geometry on the effective albedo of the urban canyon is one of the most important issue of urban climatology. This problem was examined with physical (Aida 1982, Kanda and Katsuyama 2002) and numerical models. The latter consider only the limited number of sunrays reflections in the urban canyon. In recent investigations, Monte Carlo simulation is very common technique (Aida and Gotoh, 1982, Kondo et al., 2001; Montavez and Jiménes, 2000; Sievers and Zdunkowski, 1985), and other solutions which allow multiple reflections (Masson, V., 2000, Fortuniak, 2002, Sailor and Fan 2002).

2. PHYSICAL MODEL DESCRIPTION

Estimation of the influence of the canyon geometry on the effective albedo is very problematic to measure in real conditions. In order to investigate urban building influence on the effective albedo of the urban surface, physical models (made by bricks or concrete blocks) and numerical models are used. Such models enable to investigate effective albedo of the urban canyons with different width of street and roof, height of walls and azimuth.

Fig. 1. Physical model used for the effective albedo measurements: fish-eye photography (a), flat surface (b), canyon H/W = 1, W_R = 0.5W, NS orientation (c), canyon H/W = 1, W_R = 0.5W, WE orientation (d).

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The physical model was built on the roof of the Department of Meteorology and Climatology building ($\varphi = 51^\circ46'\ N, \lambda = 19^\circ20'\ E$). To level the roof, the platform made of wood (2.8 m width and 2.5 m long) was used. At this platform flat brick surface was placed and then the canyons with specified parameters like $W_R$ (width of roof), $H$ (height of walls) and $W$ (width of street) were built. In the model (both flat surface and canyons) identical red bricks ($12 \times 6 \times 25$ cm) were used. Reflected shortwave radiation was measured by pyranometer hung up 30 cm above the model. The second pyranometer measuring incoming shortwave radiation was installed on the actinometrical bench within the distance of 5 m. The first pyranometer was hung up 30 cm above the model surface which to a high degree (about 95%) eliminated influence of the black roof on the measurements correctness (fig. 1a). Bricks application enabled quick changes of the canyon parameters and its azimuth. The measurements were made for $H = 12$ cm, $W = 12$ cm, ($H/W$ ratio equals 1) and $W_R = 0.5W$ with the canyon north – south (fig. 1c) and west – east (fig. 1d) oriented. The results were compared with flat surface measurements ($H/W$ ratio equals 0, fig. 1b). Two methods were used for day long measurements: one, setting and orientation all day long and the other with parameters and orientation changes every ten or fifteen minutes (for example: flat surface – canyon NS – canyon WE). The measurements were made on cloudless days in the winter (January 1 and February 25, 2003) and spring (April 15, 16 and 25, 2003). This way authors tried to established the dependence between effective albedo value and solar height and azimuth.

3. MEASUREMENTS RESULTS

Apart from configuration, the effective albedo measured in the winter was higher then in the spring (fig. 2). In case of a flat surface, the difference amounted to about 15%, while in cases of canyons (both NS and WE) reached 10%. Moreover, regardless of the seasons, effective albedo of the urban canyons (both NS and WE) was lower than flat surface albedo (in the winter the difference amounted to about 20%, in the spring about 15%). Therefore, effective albedo decreases with $H/W$ ratio increase. What is more, the increase of sunrays angle causes a decrease of the effective albedo. In spite of different values, in all cases, a characteristic daily albedo course (minimum at noon, maximum after sunrise and before sunset) appeared. Daily courses for NS and WE canyons are very similar. One difference is a small increase of albedo at noon for canyon NS in comparison with canyon WE in the spring. It is caused by a strong canyon street heating when the Sun azimuth and the canyon azimuth are coincide. In this case the canyon street is a main source of light for the walls.

![Daily courses of effective albedo in the winter and spring in Lodz for flat surface (a), canyon H/W = 1, $W_R = 0.5W$, NS orientation (b), canyon H/W = 1, $W_R = 0.5W$, WE orientation (c).](image)

Fig. 2. Daily courses of effective albedo in the winter and spring in Lodz for flat surface (a), canyon H/W = 1, $W_R = 0.5W$, NS orientation (b), canyon H/W = 1, $W_R = 0.5W$, WE orientation (c).

4. NUMERICAL MODEL - MONTE CARLO SIMULATION

Besides measurements, Monte Carlo simulation for infinite long canyon was used to estimate a daily course of effective albedo. In the Monte Carlo simulation multiple reflection was taken into consideration (fig. 3). The photon reaches the canyon at an angle $\Theta$ and is reflected from one of the walls or from the street at the angles $\beta_1$, $\beta_2$ or $\beta_s$. The Lambertian scattering is assumed by $\eta = arccos(1-2x)$ (Kondo et al., 2001), where $x$ is a random generated value between 0 and 1. The reflection takes place when $\alpha$ value (random number between 0 and 1), is lower than the albedo of walls and street value $\alpha_{w1}$, $\alpha_{w2}$ or $\alpha_s$ (in this case 0.34 – red brick albedo). Otherwise, photon is absorbed. The number of reflections is unlimited until photon leaves canyon or is absorbed. In order to get a correct effective albedo, the simulation must be repeated many times. The number of photons necessary to get stable result amounts to about 100 000 (fig. 4a). Apart from that, the result correctness depends on a number of blocks into which the walls and street are divided. In this case its about 100 (fig. 4b).
Solar radiation consists of a diffuse and direct radiation. In the first case Θ angle represents the Sun height above horizon, in the case of a diffuse radiation Θ angle value is generated in accordance with Lambêt’s Law like β angle. To get the correct result, it is necessary to select an adequate number of photons which represent diffuse (β) and direct (Θ), i.e. calculate a relation between these values in relation to the Sun height and the season. In this paper, formulas proposed by Davis (1975) were used:

\[ h = S_o \sin \Theta \psi_w \psi_{ds}(1-\psi_w \psi_{ds})/2 \]
\[ h = S_o \sin \Theta \psi_w \psi_{ds} \psi_{w0} \psi_{ds0} \]

where \( h \) and \( h_o \) are (respectively) diffuse and direct radiation, \( S_o \) is the solar constant (1365 W/m²), \( \psi_w \) and \( \psi_{ds} \) are water vapor and aerosols absorption and \( \psi_{w0} \) and \( \psi_{ds0} \) are water molecules, aerosols and Rayleigh scattering.

Effective albedo of the urban canyon is given by equation:

\[ A_{ef} = (N_{w1} + N_{w2} + N_{w1} + N_{d1} + N_{d2}) / N_l \]

where \( A_{ef} \) is effective albedo, \( N_{w1} \) and \( N_{w2} \) are (respectively) numbers of photons reflected from wall 1, wall 2 or canyon street and leaving the canyon (diffuse radiation) and \( N_{d1} \) and \( N_{d2} \) are (respectively) numbers of photons reflected from wall 1, wall 2 or canyon street and leaving the canyon (direct radiation). \( N_l \) is the number of photons which reach the canyon. Effective albedo of the urban canyon with a roof can be calculated with the equation:

\[ A_{efR} = \frac{\alpha_R W_R + A_{ef} W}{W_R + W} \]

where \( \alpha_R \) is roof albedo with a changeable value related with the Sun height. In this paper the dependence of the Sun height \( \Theta \) on \( \alpha_R \) is determined by the equation \( \alpha_R = 0.48885 + 0.00591 \Theta + 0.000058256 \Theta^2 \) (regression curve for springtime albedo measurements for flat surface). This anisotropic relation was used to flat surface albedo estimation. After the previous equation conversion:

\[ A_{ef} = \frac{A_{efR}(W_R + W) - \alpha_R W_R}{W} \]

can eliminate an influence of a roof from the measured data and obtain effective albedo of the urban canyon only.

This algorithm was tested on Aida’s (1982) data for 3 December 1977 (Pawlak and Fortuniak, 2002) and on the data presented above (fig. 5). Estimated courses correctly represents the measurements. In all cases, a typical daily albedo course with the minimum around noon was well estimated. Simulation for the winter flat surface measurements (fig. 5a) rightly shows a quick albedo decrease after sunrise and a quick increase before sunset. The same situation is in the canyon cases (both NS and WE), and estimated courses are similar to each other, like in the measurements. In the spring (fig. 5b) albedo values were lower and less diversified in comparison with the winter but in these cases Monte Carlo simulation works well too. Estimated courses for canyons were similar to each other. The simulation took into account low albedo increase at noon (canyon NS) caused by sunrays incident directly to canyon street when the Sun and canyon azimuth overlap. In the case of WE canyon the simulated albedo values were constant about 7.00 and 17.00 when the Sun and canyon azimuths were parallel.
5. CONCLUSIONS

Investigations concerning an influence of urban building geometry on a solar radiation absorption are difficult to measure and analyze in real conditions (for example in the street). Application of physical and numerical models simplifies this problem. Measurements based on the physical model, allow to observe diurnal variation of the effective albedo for the different urban building structures (in this case urban canyon with different azimuth). The observed decrease of canyons' effective albedo in relation to flat reference surface allow to estimate (for known values of albedo) how much the solar radiation absorption in the city is higher than the absorption in the rural area. Numerical model is a good tool in effective albedo estimation. With the aid of Monte Carlo simulation it is possible to compute effective albedo of urban canyons with different street width, walls height, roof width and azimuth. With model parameters change (albedo of walls and canyon street, \( h / l_h \) relation) it is possible to compute effective albedo of geometrical structure with radiation parameters similar to reality.

References

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