Numerical Study on Thermal Effects of Cold and High-albedo Surfaces Covered with Snow in Outdoor Environments

Akashi Mochida¹, Yoshihide Tominaga², Hiroshi Yoshino³
Kiyoshi Sasaki⁴ and Makiko Ohba⁵

¹ Assoc. Professor, Graduate School of Engineering, Tohoku University
Aoba 06, Sendai 980-8579 Japan (mochida@sabine.pln.archi.tohoku.ac.jp)

² Assoc. Prof., Niigata Institute of Technology
Fujihashi 1719, Kashiwazaki 945-1195 Japan (tominaga@abe.niit.ac.jp)

³ Professor, Graduate School of Engineering, Tohoku University
(yoshino@sabine.pln.archi.tohoku.ac.jp)

⁴ Graduate Student, Graduate School of Engineering, Tohoku University
(sasa@sabine.pln.archi.tohoku.ac.jp)

⁵ Mitsui Home Design Institute
23-2 Sakamachi, Sinjuku-ku, Tokyo 160-0002 Japan

Abstract

In this study, a numerical method for predicting the radiative and convective heat transports around building blocks in a snowy region is developed. A field measurement is also carried out to clarify the effects of cold and high-albedo surfaces covered with snow. Although the surface temperature of the ground covered with snow was lower than that without snow, MRT and SET* above the snow surface were predicted to be higher than those without snow. This reflects the large effect of an increased albedo of the ground surface due to snow.

Keywords: Snow; High-albedo; Outdoor thermal environment; Radiation; CFD

1. Introduction

Accumulations of snow greatly change the physical properties of the urban surface. The cold and high-albedo urban surfaces covered with snow strongly affect the heat transfer mechanism within the outdoor space as illustrated in Fig. 1. The effects of snow at ground surface are an important topic in the field of meteorology and many investigations have been carried out over the years, e.g. Kondo and Yamazaki (1986, 1987, 1990). However, those works were merely placed on the heat energy balance at the surface of the ground. Studies of the heat transfer above the snow at pedestrian level, involving air movement, are lacking. In addition, research studies on the radiative heat transfer between the ground surface covered with snow and building walls, and its effects on convective heat transfer due to the airflow movement around buildings are also limited at present.

In this study, a numerical method is developed for predicting radiative and convective heat transports in an

Fig. 1. Effects of snow on outdoor environment

Contact author: Akashi Mochida, Graduate School of Eng., Tohoku Univ., Aoba 06, Sendai 980-8579 Japan
Tel: +81-22-217-7884, Fax: +81-22-217-7886
e-mail: mochida@sabine.pln.archi.tohoku.ac.jp
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Fig.2. Situation of field measurement

Table 1. Measured quantities

Global solar radiation (E_D) (direct solar radiation + diffuse radiation)
Reflected solar radiation (E_R) (from the snow covered surface)
Wet and dry bulb temperature
Globe temperature (θ_{globe})
Ground surface temperature (θ_s)
Radiation temperature on ground surface
Wind direction, wind velocity

outdoor space of a snowy region. The effects of the changes in surface parameters, i.e. the decrease of surface temperature and increase of albedo caused by snow, on the outdoor thermal environment are numerically investigated. In the first part of this paper, the results from the field measurement are presented to clarify the basic effects of cold and high-albedo ground surface covered with snow. The accuracy of the radiation computation is confirmed by comparing its result with field measurements. The latter part describes the computations of radiative and convective heat transports around the model of building blocks. Four cases of computations are carried out here in order to examine the effects of the snow surface on the outdoor thermal environment.

2. Field Measurements

2.1 Outlines of the Measurement

A full-scale field measurement was carried out in a playground at the Niigata Institute of Technology, Niigata Prefecture, Japan, on February 23, 2000. The weather was cloudy, fine at times, and the snow was 8 cm deep. Fig. 2 shows the configuration of the field measurement. Measurements were taken from two different areas; with snow and without snow. The size of the area without snow was 10 square meters. Table 1 summarizes the measured quantities.

2.2 Results of the Field Measurement

Fig. 3. shows the global solar radiation (E_D , direct radiation + diffuse radiation) and the albedo of ground covered with snow. The maximum of E_D is about 600 W/m^2 observed at 1:30 p.m. The albedo of ground cov-

Fig.3. Global solar radiation and albedo of the snow surface

Fig.4. Air temperature and ground surface temperature

Fig.5. MRT value at 1.5m height

Table 2. Comparison of MRT values at 1:30p.m (at 1.5m height)

	measurement	computation
with snow	50.1°C	48.4°C
without snow	43.1°C	38.9°C

ered with snow is around 0.8 throughout the day.

Fig. 4 illustrates the time variations of air temperatures, θ_a , at the height of 1.5m, and ground surface temperatures, θ_s . θ_a recorded at 1.5m are approximately $3^\circ\text{C} \sim 4^\circ\text{C}$ throughout the measurement period. θ_s with and without snow are 0°C and $3^\circ\text{C} \sim 14^\circ\text{C}$ respectively.

Variations of Mean Radiative Temperature (MRT) at a height of 1.5m, calculated based on the measured data, are compared in Fig. 5. MRT value, θ_r , for the ground covered with snow, which is evaluated from the globe temperature (cf. Appendix 1), is found to be higher than that without snow throughout the day. Although the surface temperature of ground covered with snow is lower, MRT above this area is higher than the surface without snow. This is because the albedo of the surface covered with snow is much higher than that without snow.

Table 3. Computation Conducted for All Test Cases

Case	Albedo of ground surface	Ground surface temperature(θ s)	Soil moisture availability
case 1 (ground: without snow)	0.2	given from radiation computation (7~27°C)	0.15
case 2	0.2	0°C	1.0
case 3	0.8	given from radiation computation (5~15°C)	0.15
case 4 (ground: with snow)	0.8	0°C	1.0

Radiation computation based on the Monte-Carlo simulation is carried out to confirm its accuracy by using data at 1:30 p.m. where the solar radiation shows its maximum. The outline of radiation computation for predicting the outdoor thermal environment in a snowy region is summarized in Appendix 2. In this study, the effect of the energy of snowmelt is included in the equation of heat energy balance at the ground surface (cf. eq. (4) in Appendix 2).

Table 2 shows the comparison of MRT values between the results of measurement and computation. As already noted, the MRT value above the snow surface is much higher than that without snow. It can be seen that a fairly good agreement of such tendency is obtained computationally.

The effects of snow on the mechanism of heat transports around buildings are investigated, by using the numerical approach described in Appendix 2, and highlighted in the next section.

3. Effects of Snow Covered Ground Surface on Radiative and Convective Heat Transports around Buildings

3.1 Outlines of the Computation

Fig.6. Computation domain

Table 4. Model for sensible and latent heat fluxes including buoyancy effect

$$1. \text{ Sensible heat flux } -\langle u'_3 \theta'_a \rangle = \frac{v_t}{\sigma_\theta} \frac{\partial \langle \theta_a \rangle}{\partial x_3} + \frac{k}{\varepsilon} C_{\theta 3} g_3 \beta \langle \theta_a'^2 \rangle$$

$$2. \text{ Latent heat flux } -\langle u'_3 q'_w \rangle = \frac{v_t}{\sigma_w} \frac{\partial \langle q_w \rangle}{\partial x_3} + \frac{k}{\varepsilon} C_{\theta 3} g_3 \beta \langle \theta'_a q'_w \rangle$$

$$g_3 = -9.8 \text{ m/s}^2, C_{\theta 1} = 0.25, C_{\theta 3} = 0.25, \sigma_\theta = 0.5, \sigma_w = 0.5$$

Fig. 6 details the model of building block used for the present study. Four five-story buildings are arranged within the computational flow domain.

Table 3 lists all the test cases for the computation. Cases 1 and 4 consider the ground without snow and with snow covering, respectively. Two different features peculiar to the surface covered with snow, cold and high-albedo, are adopted and investigated in Cases 2 and 3 separately. Case 2 considers only the decrease of long-wave radiation from a cold snow surface, while Case 3 examines the effects of increased short-wave radiation caused by the high-albedo of snow. In all cases, the albedo of the building surfaces is set to 0.2.

The outdoor thermal environments on a sunny day are numerically studied in these computations. The meteorological data of Nagaoka City, Niigata Prefecture, Japan, at 1:30 p.m. on February 23 is used to specify the numerical conditions. The air temperature and relative humidity on average in the past 15 years are 1.4 °C and 70%, respectively. These values are imposed as the boundary conditions. Wind conditions are given based on the mean velocity value and prevailing wind direction in February in Nagaoka city. Wind velocity at 6.5m height and wind direction at inflow boundary are set at 1.71m/s and SSW respectively. The vertical profile of mean velocity at the inflow boundary is assumed to obey a 1/4 power law.

A revised k-ε model, in which some modifications are added to Launder-Kato type k-ε model (Kato and Launder (1993)) by the present authors (Yoshida et al. (2000)), is used to predict convective heat transports around the buildings. This modified LK model is further revised to include the correct buoyancy effects on sensible and latent heat fluxes as shown in Table 4 (Murakami et al. (1999), Yoshida et al. (2000)). Radiative heat transport is computed using the method based on the Monte – Carlo simulation described in Appendix 2.

Spatial distribution of SET* (Standard Effective Temperature) proposed by Gagge et al (1986) is calcu-

lated in order to assess pedestrian level thermal comfort using the data given from CFD predictions (cf. Appendix 3).

For boundary conditions at the ground surface, the log law expression that incorporates the influence of roughness length z_0 is employed. The values of z_0 and mean friction velocity $\langle u^* \rangle$ are set equal to 0.3m and 0.22m/s respectively. The boundary conditions at building surfaces are given by the generalized log law proposed by Launder et. al. (1974). The sensible heat fluxes, H_i , at the ground surface and building walls are evaluated by

$$H_i = \alpha_c (\langle \theta_{ap} \rangle - \langle \theta_s \rangle),$$

where α_c : convective heat transfer coefficient (11.6W/m² in this study),

$\langle \theta_{ap} \rangle$: mean air temperature at the grid adjacent to the wall,

$\langle \theta_s \rangle$: mean surface temperature.

The computational domain covers 215m (x_1 , east-west direction) $\times$ 144m (x_2 , north-south direction) $\times$ 192m (x_3 , vertical direction). The domain is discretized into 42(x_1) $\times$ 30(x_2) $\times$ 14(x_3) grids. The value of mesh interval adjacent to the solid wall is set at 2.0m. The QUICK scheme is used for the convection terms and the second-order central difference scheme is adopted for other spatial derivatives.

3.2 Results of Numerical Studies

(1) Ground Surface Temperature

The ground surface temperatures, θ_s , of Cases 1 and 3 are compared in Fig. 7. Only the values of these two cases are shown here since θ_s for other two cases (Cases 2 and 4) are set at 0°C as shown in Table 3. The surface temperature, θ_s , of Case 3 is lower than that of Case 1. The spatial averaged values in the computational domain of Cases 1 and 3 are 17.3°C and 7.8°C respectively. This is because the albedo of the ground is increased in Case 3 in comparison with Case 1.

(2) Wall Surface Temperature

Fig. 8 shows the averaged temperature of each wall surface in all cases. The ground temperatures, θ_s , in Cases 2 and 4 are 0°C, which corresponds to the value of ground surface covered with snow. On the other hand, θ_s is given from the radiation computation in Cases 1 and 3. Although θ_s is much lower in Case 4 compared to Case 1, the wall temperatures in Case 4 are generally higher than those in Case 1. This clearly indicates the large effect of an increased albedo caused by the snow in Case 4. In Case 3, θ_s is predicted to be lower in comparison with Case 1, since the value of albedo increases from 0.2, in Case, 1 to 0.8 in this case. However, the wall temperatures in Case 3 become much

(1) Case 1 (albedo:0.2)

(2) Case3 (albedo:0.8)

Fig.7. Ground surface temperature θ_s (1:30 p.m on February 23, Nagaoka) (°C)

Fig.8. Averaged temperature of wall surface (°C)

Fig.9. Horizontal distribution of MRT at 1.5m height (°C)

Fig.10. Distributions of MRT at 1.5m height (°C)
(locations of A-A' and B-B' sections: cf. Fig. 9)

higher than those in Case 1. This difference in the wall temperatures between Cases 1 and 3 also reflects the large effect of the change in the albedo due to snow.

From these results, it can be concluded that the high-albedo has a much stronger effect on the outdoor thermal environment than the low temperature surface that covered with snow does.

(3) Mean Radiative Temperature (MRT)

Fig. 9 compares the horizontal distributions of MRT at 1.5m height in Cases 1 and 4. The MRT values in Fig. 9 are evaluated from both the long wave and short wave radiations that are absorbed by the human body (Yoshida et al. 2000). The spatial averages of MRT are 29.8°C and 32.9°C in Case 1 and in Case 4, respectively. The MRT value for Case 4 is generally predicted to be higher than that in Case 1, although the ground surface temperature is much higher in Case 1 (7 ~ 27 °C) than that in Case 4 (0°C) (cf. Table 3). This is attributable to an increase of reflected solar radiation, due to snow, in a sunny place.

Fig. 10 compares the MRT distributions at A-A' and B-B' sections. The locations of the sections are indicated in Fig. 9. In both cases, the temperature of the nearest wall surface affects the MRT value significantly.

For example, the surface temperature of the west wall of building ② is about 10°C higher than the temperature of the east wall of building ① (Fig. 8). As a result of this difference in wall temperatures, MRT rises remarkably between buildings ① and ② from west to east as shown in Fig. 10(1). On the other hand, MRT decreases in the area near the east wall of building ②, since the surface temperature of the east wall of building ② is also low. The same tendency is also observed in Fig. 10 (2).

(4) Velocity Vector and Air Temperature

Fig. 11 illustrates the distributions of the wind velocity vector. Since the differences are relatively small between the four cases conducted in this study, only the result of Case 4 is shown here. As mentioned in 3.1, wind direction at the inflow boundaries (left and bottom sides in Fig. 11 (1)) was set at SSW in this study. However, the direction of the wind is found mainly to flow from the west side into an area that surrounded by the four buildings. A recirculation flow is also observed in this area from the vertical section view (cf. Fig. 11 (2)).

Fig. 12 presents the horizontal distributions of air temperatures at 1.5m height for Case 1(without snow)

- Gray zone indicates the area where SET* in Case 4 (with snow) is higher than that in Case 1 (without snow).

and Case 4 (with snow). It is seen, in Fig. 12, that high values of air temperature appear in the areas near the south walls of the buildings in both cases, and the hot air generated from the south walls is convected downstream by the wind flow, shown in Fig. 11. It is also pointed out that the air temperature in Case 1 (without snow) is generally higher than that in Case 4 (with snow) at this height. This reflects the difference in the ground surface temperatures between these two cases (cf. Fig. 7).

(5) SET*

Fig. 13 compares the predicted SET* of Cases 1 and 4 at the same height (Appendix 4). Fig. 14 shows the difference in SET* values between the cases with snow (Case 4) and without snow (Case 1), i.e. SET* in Case 4 minus SET* in Case 1. The gray zone in this figure corresponds to the positive value indicating the area

where SET* in Case 4 is higher than that in Case 1. The SET* value increases in the case with snow (Case 4) compared to the case without snow (Case 1) almost within the whole domain except for a small area surrounded by the four buildings.

As mentioned above, accumulation of snow decreases the ground surface temperature (Fig. 7) and air temperature (Fig. 12), but increases the wall surface temperature (Fig. 8) and MRT value (Fig. 9). As a result of these effects, it can be concluded that the snow covered surface does not necessarily raise thermal discomfort, but improves outdoor human comfort in sunny weather in winter.

5. Conclusions

- (1) A numerical method for predicting the radiative and convective heat transports around building blocks in a snowy region was developed. A field measurement was also carried out to clarify the effects of cold and high-albedo surfaces covered with snow.
- (2) The MRT value at a height of 1.5m above a snow covered surface was found to be 10°C higher, at maximum, than the value without snow from the field measurements. This tendency was reproduced well by the numerical method developed in this study.
- (3) The effects of cold and high albedo surfaces due to snow on radiative and convective heat transports around buildings were numerically investigated. Although the surface temperature of the ground covered with snow was lower than that without snow, the surface temperatures of the building walls and MRT above the snow surface were predicted to be higher than those without snow, and the increase of MRT caused by snow significantly affects the value of SET*.
- (4) The predicated SET* value for the case with snow was higher than that for the case without snow throughout almost the whole domain. This reflects the strong effect of an increased albedo of the ground surface due to the snow.

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Appendix 1

MRT is calculated by the conventional method using the equation (1) based on the measured data

$$\theta_r = \theta_{globe} + 2.37\sqrt{V}(\theta_{globe} - \theta_a) \quad (1)$$

θ_r : MRT value evaluated from globe temperature,
 θ_{globe} : globe temperature,
 θ_a : air temperature,
 V : scalar velocity of wind,

$$V = \sqrt{u_1^2 + u_2^2 + u_3^2}.$$

It should be noted that the application of equation (1) to the environment under the influence of solar radiation may involve some inaccuracy. This point will be

Table 5 The coefficients for radiation computation

	β	α	ϵ_s
with snow	1.0	0.75	0.95
without snow	0.3	0.15	0.95

(β : soil moisture availability)

Fig. 15. Calculations of snow surface temperature θ_s
 (θ_s : surface temperature, θ_a : air temperature)

examined further in the near future by the present authors.

Appendix 2

The heat energy balance at the ground surface on a point i is written as follows (Yoshida et al. (2000)):

$$S_i + R_i + H_i + C_i + LE_i = 0 \quad (2)$$

S_i is the direct and diffuse solar heat gain after multiple reflections. It is calculated using the measured values of global solar radiation E_D and surface albedo.

$$S_i = A_i(1 - \alpha)E_{Di} + A_i \sum_{j=1}^n B_{ij} \alpha E_{Di} \quad (3)$$

A_i : surface area, B_{ij} :Gebhart's absorption factor,
 α :albedo

The set of Gebhart's absorption factors, B_{ij} , is calculated using the revised Monte Carlo method [Omori et al., (1997)]. R_i , in equation (2), represents the net long-wave radiation. In this study, the value $\epsilon_s=0.95$ is used for the emissivity at all surfaces [Kondo and Yamazaki, (1986)]. The coefficients employed in the computation of section 2 are summarized in Table 5.

Regarding the snow surface, the energy for snowmelt, M , is added to the right hand side of eq. (2) following Kondo and Yamazaki (1990).

$$S_i + R_i + H_i + C_i + LE_i = M_i \quad (4)$$

M is obtained by substituting θ_s value, which is determined through the process outlined in Fig. 15, for

eq. (4). The ground heat flux C_i is ignored for the snow surface in this study because it is relatively small (Kondo and Yamazaki, 1986).

Appendix 3

In this computation, clothing insulation, metabolic heat generation and solar reflectance of the human body are assumed to be 0.6 [clo], 1.0 [met] and 0.5 [-] respectively.

Fig.16. Distributions of wind velocity at 1.5m height (Case1 (without snow), m/s)

Appendix 4

High peaks of SET* are observed in the north-east areas in Figs. 13 (1) and (2). Fig. 16 shows the horizontal distribution of scalar velocity at the same height as in Fig. 13. It can be seen that an area of low wind velocity is formed in the north-east area where SET* shows very high values (cf. Fig.13). Therefore, it can be concluded that this peak of SET* is mainly caused by the decrease of wind velocity in this area.

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Notation

- $\langle f \rangle$: time-averaged value of f
 f' : deviation from $\langle f \rangle$, $f' = f - \langle f \rangle$
 x_i : three components of spatial coordinate
 (x_1 : east-west direction, x_2 : north-south direction, x_3 : vertical direction)
 u_i : three components of velocity vector
 θ_a : air temperature
 θ_s : ground surface temperature
 θ_{globe} : globe temperature
 MRT : Mean radiative temperature
 θ_r : MRT value evaluated from θ_{globe} (cf. eq. (1))
 q_w : absolute humidity
 k : turbulent kinetic energy
 $\mathcal{E}$: dissipation rate of k