NUMERICAL STUDY ON RELATIONSHIP BETWEEN RESIDENTIAL BUILDING ARRANGEMENT AND SNOW DISTRIBUTION

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Abstract

A method is developed for simulating snow distribution around buildings considering the effect of snowdrift and heat exchange on the snow surface. This method combines snowdrift simulation using CFD (Computational Fluid Dynamics) with the heat balance model. Furthermore, it is used to investigate the relationship between residential building arrangement and snow distribution. Little difference was observed in the results for different building arrangements obtained from snowdrift analysis only. However, large differences were observed in the results obtained from combined snowdrift and snowmelt simulations. It is confirmed that snowmelt can be increased by increasing distances between buildings.

Key words: Snow distribution, Residential Building Arrangement, CFD

1. INTRODUCTION

Inconvenience due to heavy snow in living spaces, such as snowdrift around buildings, snow blown into passages and snow accumulation in traffic areas, are serious problems for building and city planning in snowy regions. Thus, building arrangements should be considered to facilitate snow removal and control operations around buildings. For the snowdrift problem, a simulation method based on wind tunnel testing using imitation snow particles has traditionally been used. However, snow distribution around buildings in the Hokuriku District in Japan, which has higher daily-lowest temperatures than the northern part of Japan, is affected not only by snowdrift but also by snowmelt due to heat exchange on the snow surface.

In this study, a method is developed for simulating snow distribution around buildings considering the effect of snowdrift and heat exchange on the snow surface. This method combines snowdrift simulation using CFD with the heat balance model. Furthermore, it is used to investigate the relationship between residential building arrangement and snow distribution.

2. OUTLINES OF NUMERICAL METHODS

2.1. Analysis procedure

The analysis procedure is illustrated in Fig.1. It is divided into two parts, the snowdrift part and the snowmelt part. In the snowdrift part, the distribution of drifting snow around buildings is simulated by snowdrift analysis based on CFD under snowy weather conditions. Then, the change of snow depth due to snowmelt is computed by snowmelt analysis based on heat balance analysis on the snow surface under weather conditions including thermal components such as temperature. In the present study, the two analyses were conducted separately because the influence of undulation of the snow surface on the flow field is assumed to be negligible. The final snow depth distributions can be obtained by summing the two snow depth changes obtained from the two analyses. Only snow accumulated around buildings is considered in the present study.
2.2 Snowdrift and models

The modified k-ε model proposed by Durbin was used as a turbulence model (Durbin, 1996). Firstly, the steady flowfield was calculated without snowdrift, and then the unsteady computation was conducted considering snowdrift. The treatment of snow particles and the method of estimating snow depth are as follows.

The transport equation for snowdrift density $\Phi$ [kg/m$^3$] is solved to represent the suspension of snow particles (Uematsu et al., 1991).

$$\frac{\partial \Phi}{\partial t} + \frac{\partial (\Phi U_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \nu_j \frac{\partial \Phi}{\partial x_j} \right) + S$$

(1)

Here, $w_f$ is snowfall velocity, which is set as a constant. Coefficient $\sigma_S$ is assumed to be 1.0.

Snowdrift flux in the saltation layer is expressed by the model proposed by Pomeroy and Gray (1990):

$$\rho = \frac{0.68 \rho u^*}{u^*} (u^* - u^*_t)$$

(2)

where $u^*$: friction velocity [m/s], $u^*_t$: threshold value of friction velocity [m/s], $\rho$: fluid density [kg/m$^3$], $g$: acceleration due to gravity [m/s$^2$]

Snow deposition and erosion are calculated using the mass balance equation of snow in the control volume (CV) adjacent to the snow surface (Tominaga et al., 2006). Here, the CV is assumed to be equal to the first cell adjacent to the snow surface in the CFD calculation.

$$M_{\text{total}} = M_{\text{dep}} + M_{\text{eros}} + M_{\text{eros}}$$

(3)

If the amount of snow entering the CV exceeded that exiting the CV, deposition would occur. Conversely, if the amount of exiting snow was higher, the snow surface would be eroded.

The deposition rate $M_{\text{dep}}$ is calculated using $\Phi$ from eqn.(1), the snowfall velocity $w_f$ and the horizontal area of the CV($\Delta x \Delta y$). The difference in horizontal mass flux $M_{\text{eros}}$ is calculated using the saltation flux model expressed as eqn. (2) at the side surfaces. The erosion rate $M_{\text{eros}}$ due to the shear stress on the horizontal surface of the CV is given by the model proposed by Beyers et al. (1988).

Variation of snow depth per unit time $\Delta z_S$ is calculated using $M_{\text{total}}$ from eqn. (3), snow density $\rho_S$ and the horizontal area of the CV.

$$\Delta z_S = \frac{M_{\text{total}} \rho_S}{\Delta x \Delta y}$$

(4)

In this analysis, when $M_{\text{total}}$ becomes negative, the negative part is incorporated as the source term of eqn. (1).

2.3 heat balance model on snow surface

Assuming that the heat balance on the snow surface is expressed as eqn. (5), the energy $M$ consumed for melting snow can be obtained (Kondo and Yamazaki, 1990; Mochida et al., 2002).

$$M = R - L + H + E$$

(5)

R: Direct and diffuse solar heat gain [W/m$^2$]
L: Net long-wave radiation [W/m$^2$]
H: Sensible heat flux [W/m$^2$]
E: Latent heat flux [W/m$^2$]

When $M$ becomes positive, snow melt occurs. In the present model, transformation of snow inside was not considered and the heat balance applied only to the snow surface with no thickness. In this study, distinction of sunlit or shaded place for each computational mesh was calculated to ensure correct estimation of short-wave solar heat gain.

2.4 Residential building model

"N new town" located in Nagaoka City, Niigata prefecture was selected as an example of a typical residential house cluster in a snowy region in Japan. The detached house model was designed based on the average value of the area, the number of houses, and building density within one cluster. Two terrace house models combining several dwelling units to give the same ground coverage ratio as the detached house model were considered for comparison. A medium-rise apartment model with 4 floors, which increased the floor area ratio, was also compared. The tested residential building models are outlined in Fig. 2. They were assumed to be arranged in the same shape in 3x3 arrays, and one central cluster was treated as a target area for comparison and examination.

2.5 Meteorological data

A typical day with a certain snowfall (hereafter "snowy day") was defined as one with 0.10m or more daily snowfall. On the other hand, a typical day with a certain snowmelt (hereafter "snowmelt day") was defined as one with 5 hours or more of sunlight in inter (from December to February). Days meeting these conditions were extracted from the meteorological data (expanded AMeDAS Weather data provided by AIJ (2005) and the AMeDAS data provided by Japan Meteorological Agency) at Nagaoka City from 1981 to 2000. Typical weather conditions were then obtained for the analyses by averaging the extracted data. In the snowdrift analysis, only wind velocity, wind
direction and daily snowfall depth (0.19m) were used as calculation conditions. Temperature, humidity, irradiation and sun location were also used as calculation conditions in the snowmelt analysis.

3. RESULT AND DISCUSSIONS

3.1. Distribution of snow depth obtained by snowdrift analysis

The predicted snow depth is normalized by the reference snow depth, which corresponds to the snowfall rate at the upper and inflow boundary conditions. The normalized snow depth is shown in Fig. 3. The spatial distribution of snow depth is generally small in all cases. This is why the saltation of snow does is not so strong under the present condition in which the friction velocity on the snow surface is smaller than the threshold friction velocity in most regions. However, since erosion by saltation has occurred near the windward edge of the computational domain, the drifting snow is advected by southerly wind (the prevailing wind direction in this location) through the production term in eqn. (1). Therefore, the snow depth becomes larger in spaces running N-S than in spaces running E-W. Moreover, in the upwind corner of the medium-rise apartment model, erosion occurred due to the strong separation flow.

3.2. Distribution of snowmelt potential obtained by snowmelt analysis

The amount of energy required to melt snow is represented by a “snowmelt coefficient”, which is defined as the daily snowmelt energy at one point normalized by that in a place without surroundings. The distributions of snowmelt coefficient for different residential arrangements are shown in Fig. 4. In all cases, the snowmelt coefficients in spaces between houses running N-S are larger than those in spaces running E-W. These coefficients are due to solar radiation. Moreover, those in the terrace house models are larger than those in the detached house model, because the larger spaces between houses in the terrace house models contribute to the longer time during which they receive sunshine.

3.3. Distribution of snow depth obtained by combined analysis

The predicted snow depth given by the present simulation method under ideal weather conditions including 2 snowy days and 5 snowmelt days are illustrated in Fig. 5. The snow depth given by the boundary condition for snowdrift analysis as the snowfall rate is 0.38[m]. In the spaces between houses running N-S, in all models the hours of sunlight are longer than in the other direction, resulting in large decreases of snow depth (about 0.20m in maximum). By comparing the spatial average of snow depth, the values for the detached house, 6 terrace houses, 4 terrace houses, and the medium-rise apartment house were 0.26m, 0.24m, 0.22m, and 0.27m, respectively.
The 4-terrace-house model shows minimum values. It should be noted that a low-rise combined residence like a terrace house could decrease the snow depth distribution around houses by using solar radiation effectively.

![Diagram of house models]

(1) Detached house model
(2) Terrace house model (6 buildings)
(3) Terrace house model (4 buildings)
(4) Medium-rise apartment model

Fig. 5 Predicted snow depth given by present simulation method

4. CONCLUSIONS

1) A method has been developed for simulating snow distribution around buildings considering the effect of snowdrift and heat exchange on the snow surface by combining snowdrift simulation using CFD with the heat balance model.

2) Under the present boundary conditions, there is little difference among the results obtained by snowdrift simulation using CFD only. However, there are large differences among the results obtained by combined CFD and heat balance simulation.

3) It is shown that a low-rise combined residence like a terrace house could decrease snow depth distribution around houses.

4) With the present simulation method, snow depth distribution with a longer time scale than that obtained by snowdrift simulation only can be predicted easily, and this method is expected to be an effective tool for architectural design and city planning in snowy regions.

References


