PREDICTION OF SNOWDRIFT AROUND A CUBE USING CFD MODEL INCORPORATING EFFECT OF SNOW PARTICLES ON TURBULENT FLOW

Yoshihide Tominaga\textsuperscript{1}, Tsubasa Okaze\textsuperscript{2}, Akashi Mochida\textsuperscript{2}
Masaki Nemoto\textsuperscript{3}, Yu Ito\textsuperscript{2}
\textsuperscript{1}Niigata Institute of Technology, 1719, Fujihashi, Kashiwazaki, 945-1196, Japan
tominaga@abe.niit.ac.jp
\textsuperscript{2}Tohoku University, 6-6-11-1202, Aramaki-Aoba, Sendai, 980-8579, Japan
okaze@sabine.pln.archi.tohoku.ac.jp, mochida@sabine.pln.archi.tohoku.ac.jp
itto@sabine.pln.archi.tohoku.ac.jp
\textsuperscript{3}Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention, 1400 Tokamachi, Shinjo, Yamagata 996-0091, Japan
mnemoto@bosai.go.jp

ABSTRACT
This paper presents the results of CFD prediction of snowdrift around a cubic building model, and examines a new snowdrift model developed by the present authors. Numerical results using this new model are compared with results obtained by the previous model and field measurements. It is confirmed that the predicted snowdrift patterns, i.e., erosion around the upwind corners and deposition in front of and behind the model obtained from the new CFD method, correspond well with those of the field measurements.

KEYWORDS: CFD, SNOWDRIFT, CUBE, FIELD MEASUREMENT

Introduction

Snowdrift formation around buildings is a major problem in snowy regions. Wind and water tunnels using modeled snow particles have often been used to predict it. However, these apparatuses are not easily adaptable to snowdrift and have limitations with regard to similarity law. Therefore, CFD (Computational Fluid Dynamics) methods have been investigated as design tools for snowdrift around buildings in snowy regions.

Several researches on CFD prediction of snowdrift around buildings have been reported over the years. A pioneering work was carried out by Uematsu et al.(1991) using a snowdrift density equation with saltation layer snow fluxes determined from empirical functions. As a different approach, a drift flux model with two-phase flow equations was applied to snowdrift around different buildings (Bang et al., 1994; Thiis, 2002). Beyers et al.(2004) compared and verified results of numerical simulation of snowdrift around a cubic structure with experimental data obtained in Antarctica. They concluded that the snowdrift predictions compared well in both location and magnitude with measured values, but the accumulation near the cube walls was not generally in accordance with observations. Recently, Beyers and Weachter (2008) demonstrated application results of snowdrift for more complex structures. However, no method has been established for modeling snow particle motions including erosion and deposition around obstacles, because detailed measurement data sufficient to compare with CFD results is not available. More validation study of
prediction accuracy of snowdrift around buildings by CFD using detailed measurement data is required.

The present authors developed the snow deposition/erosion model, including horizontal transport of drifting snow by saltation, which was calculated by considering the three-dimensional mass balance equation of snow in a Control Volume set adjacent to the snow surface and applied it to predict the snowdrift around a building model (Tominaga et al., 2006). The model is outlined in the Appendix. In the CFD results of our previous study using this model, a large deposition of snow was observed in areas near the sidewalls of the building, but this was not seen in the measurement.

This paper presents the results of CFD prediction of snowdrift around a cubic building model using a new snowdrift model based on experimental and numerical studies by the authors. This model includes the effect of buoyancy due to local difference in drifting snow densities and turbulence dissipation due to snow particles. The numerical results are compared with data obtained from detailed field measurements taken to validate the accuracy of the snowdrift modeling.

**Outline of computations**

**Flowfield Analyzed**

Snowdrift around a surface-mounted cubic model employed in detailed field measurements carried out by Oikawa et al. (1999) in Sapporo, Hokkaido was adopted as the analyzed flowfield. The model was 1.0[m] high, which corresponds to the actual size of the cube used in the field measurement. Snowdrift around a cubic model was also investigated using wind tunnel experiments with artificial snow particles (Suwa et al., 2003).

| Table 1 Proposed governing equations for revised k-ε model (Okaze et al., 2008) |
| Continuity equation |
| \[ \frac{\partial \langle u_i \rangle}{\partial x_j} = 0 \] (1) |

Reynolds equation

| \[ \frac{\partial \langle u_j \rangle}{\partial t} + \frac{\partial \langle u_i u_j \rangle}{\partial x_i} = - \frac{1}{\rho_S} \frac{\partial \langle p \rangle}{\partial x_j} + \frac{\partial}{\partial x_i} \left( \frac{\nu}{\sigma_i} \frac{\partial \langle u_j \rangle}{\partial x_j} \right) \] (2) |

\( \rho_a \) : density of air, \( \rho_s \) : density of snow

Transport equation of \( k \)

| \[ \frac{\partial k}{\partial t} + \left( \frac{\partial \langle u_j \rangle}{\partial x_j} \right) \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_i} \left( \frac{\nu}{\sigma_i} \frac{\partial k}{\partial x_i} \right) + P_k - \epsilon S_k \] (3) |

Transport equation of \( \epsilon \)

| \[ \frac{\partial \epsilon}{\partial t} + \left( \frac{\partial \langle u_j \rangle}{\partial x_j} \right) \frac{\partial \epsilon}{\partial x_j} = \frac{\partial}{\partial x_i} \left( \frac{\nu}{\sigma_i} \frac{\partial \epsilon}{\partial x_i} \right) + \frac{\epsilon}{k} \left( C_{1} \rho_S C_{2} S \epsilon - C_{3} k \epsilon \right) + S_\epsilon \] (4) |

| \[ P_k = \nu k T \] (5) |

| \[ T = \min(T_s, T_v) \] (6) |

| \[ T_s = \frac{k}{\epsilon} \] (7) |

| \[ T_v = \frac{1}{C_p S \sqrt{\epsilon}} \] (8) |

\( S = \frac{1}{2} \left( \frac{\partial \langle u_j \rangle}{\partial x_i} + \frac{\partial \langle u_i \rangle}{\partial x_j} \right)^2 \) (9) |

Extra terms for reproducing the effects of snow particles

| \[ S_i = -C_{i} f_i \frac{k}{\rho \nu} \langle \Phi \rangle \] (10) |

| \[ S_\epsilon = -C_{\epsilon} f_\epsilon \frac{\epsilon}{\rho \nu} \langle \Phi \rangle \] (11) |

| \[ f_i = \left[ 1 - \exp \left( -\frac{t_i}{A_i \left( k/\epsilon \right)} \right) \right]^{\sigma_i} \] (12) |

| \[ t_i = \frac{D_i \rho_S}{18 \mu} \] (13) |

\( C_{i}=2.0, C_{\epsilon}=0, A_{i}=10.0, D_i \) : Diameter of snow particle [m]
Outline of Snowdrift Model

The governing equations of the new snowdrift model proposed in this study are shown in Table 1. The modified k-ε model proposed by Durbin (1996) is used as the turbulence model. The underlined terms are added to take into account the effect of snow particles on the turbulence property. In order to express the damping of turbulence energy due to the influence of snow particles, extra terms were introduced into the transport equations of k and ε, according to Naaim et al. (1998). In the model proposed by Naaim et al., extra terms in the transport equation of k, Sk were defined using k, Φ and relaxation time τ, as shown in Table 1. By dividing eq.(10) by the turbulence time-scale k/ε, the extra term in the transport equation of ε, Sε, is given as eq.(11). fs is the damping function and CkS, CεS, AS and α (>0) are model coefficients.

In the snowdrift modeling of most recent studies (Tominaga et al., 2006; Beyers et al., 2008), saltation and suspension of snow particles were modeled separately. The model proposed by Pomeroy and Gray (1990) for the transport rate of drifting snow in a saltation layer \( Q_{salt} \) as shown in eq. (14) has usually been used in these studies.

\[
Q_{salt} = \frac{0.68 \rho_c (u^*)^2}{\nu} \left( \left( \frac{u^*}{\nu} \right)^2 - \left( \frac{u^*}{\nu} \right)^4 \right) \tag{14}
\]

where \( u^* \): friction velocity [m/s], \( u^*_t \): threshold value of friction velocity [m/s] \( \rho_c \): density of air [kg/m³], g: acceleration due to gravity [m/s²]

However, as demonstrated by the authors (Okaze et al., 2008), this model is applicable only to an equilibrium saltation layer, not to a non-equilibrium region like flow around buildings. Therefore, a new approach to evaluating the transport rate on drifting snow in a saltation layer was developed. In the approach adopted here, the transport equation for drifting snow density \( \Phi_p \) is solved without distinguishing between suspension and saltation. This idea is based on the assumption that horizontal saltation velocity equals horizontal wind velocity.

\[
\frac{\partial \langle \Phi \rangle}{\partial t} + \frac{\partial \langle \Phi \rangle}{\partial x_j} + \frac{\partial \langle \Phi \rangle}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ -\langle u_j \Phi \rangle \right] \tag{15}
\]

The drift density flux is modeled by the gradient diffusion hypothesis:

\[
\langle u_j \Phi \rangle = -\frac{\nu_c}{\sigma_x} \frac{\partial \langle \Phi \rangle}{\partial x_j} \tag{16}
\]

Here, \( \sigma_x = 1.0, C_{S3} = 0.25, C_{S4} = 1.6 \)

Snowfall velocity \( w_f \) [m/s] is defined as the value on the snow surface (except when wind velocity equals zero). Therefore, \( w_f \Phi_p \) [kg/m²s] corresponds to snow deposition flux on the surface. Here, \( \Phi_p \) is the drift density at the first grid adjacent to the snow surface in the CFD calculation. The deposition rate \( M_{dep} \) [kg/s] on the horizontal surface is given by:

\[
M_{dep} = -\langle \Phi_p \rangle \langle w_j \rangle \Delta x \Delta y \tag{17}
\]

where, \( \Delta x \Delta y \) [m²] is the horizontal area of the computational grid.

The erosion rate \( M_{ero} \) [kg/s] due to the shear stress on the horizontal surface is given by eq.(18) (Anderson and Haff (1988)),

\[
M_{ero} = -A \rho_i \left( \frac{u^*}{\nu} \right)^2 \left( \left( \frac{u^*}{\nu} \right)^2 - \left( \frac{u^*}{\nu} \right)^4 \right) \Delta x \Delta y \tag{18}
\]

where, \( A = 5.0 \times 10^{-4}, \rho_i \): density of ice

As described above, the net deposition rate \( M_{total} \) [kg/s] on the horizontal surface is given by:

\[
M_{total} = M_{dep} + M_{ero} \tag{19}
\]
Variation of snow depth per unit time $\Delta z_s [m/s]$ is obtained from $M_{total}$ divided by accumulated snow density $\rho_s [kg/m^3]$ and $\Delta x \Delta y$.

$$\Delta z_s = \frac{M_{total}}{\rho_s \Delta x \Delta y} \quad (20)$$

In addition, when erosion occurs ($\langle u^* \rangle \langle v^* \rangle$), the surface boundary condition for the transport equation of $\Phi$ is given by:

$$-\frac{v_s}{\sigma_s} \left( \frac{\partial \langle \Phi \rangle}{\partial x_s} \right)_{\text{surface}} = \frac{|M_{\text{ero}}|}{\Delta x \Delta y} \quad (21)$$

**Computational conditions**

The computational cases conducted here are summarized in Table 2. The drift density $\langle \Phi \rangle$ at the inflow boundary and the threshold friction velocity are changed as parameters. The profile of drift density $\langle \Phi \rangle$ at inflow for Case 3 is illustrated in Fig. 1. It should be noted that the inflow density of drifting snow should be set as constant with height as long as the influence of saltation is not considered in the transport equation of $\langle \Phi \rangle$, as was done in the previous study (Tominaga et al., 2006).

The computational conditions for the flowfield are followed by the guidelines provided by AIJ (Tominaga et al., 2008). The parameters relating to the physical properties of snow are given by the preliminary study for boundary layer flow by the authors (Okaze et al., 2006) as shown in Table 3. Accumulated snow density $\rho_s$ is set to correspond to the value observed in the field measurement. Firstly, the steady flowfield was calculated without drifting snow, and then the unsteady computation was conducted considering drifting snow.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\langle \Phi \rangle$ at inflow boundary [kg/m$^3$]</th>
<th>Threshold friction velocity $&lt;u^*&gt;$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.05</td>
<td>0.21</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Case 3</td>
<td>cf. Fig. 1</td>
<td>0.15</td>
</tr>
</tbody>
</table>

(0.05 at upper boundary)

**Table 2** Computational cases

![Inflow profiles of drift density (Case 3)](image)

**Table 3** Parameters relating to physical properties of snow

<table>
<thead>
<tr>
<th>Snowfall velocity $&lt;\omega&gt;$ [m/s]</th>
<th>Accumulated snow density $\rho_s$ [kg/m$^3$]</th>
<th>Diameter of snow particle $D_s$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>150</td>
<td>1.5$\times 10^{-2}$</td>
</tr>
</tbody>
</table>

| $z_0$ at snow surface [m] | $3.0 \times 10^{-5}$ |
Results and Discussion

Influence of Boundary Condition on Snow Depth

The horizontal distributions of snow depth at $t^*=100$ for all cases using the new snowdrift model are shown in Fig. 2. Here, $t^*$ is non-dimensional time defined by $H$ and $<u_H>$. The deep-colored part in the figure indicates large snow coverage. The snow depths are normalized by the value at the reference point. Only for Case 2, the ideal snow depth, obtained by the boundary condition ($t<<u_f>/{\Phi}>/{\rho_s}$), is made dimensionless because no snow accumulation occurs far from the building. In Case 1 (Fig. 2(1)), there are small undulations of snow over the whole domain, although small erosion regions are formed near the upwind corners of the building. This is because excess shear stress occurs only at the separation regions around the building due to the large threshold friction velocity in this case (cf. Table 2). However, in Case 2, the snow is eroded over a wide region, except for the area in front of and behind the building, due to the small $<u^*>$ value. Where $<u^*>$ at inflow is smaller than $<u^*>$, the vertical profile of $<\Phi>$ at inflow can be set as constant with height because saltation does not occur. However, where $<u^*>$ at inflow is larger than $<u^*>$, such as for Case 2, the large value of $<\Phi>$ due to saltation near the snow surface at inflow must be considered. For this reason, Case 2 underestimates the snow deposition over the whole domain due to this underestimation of incoming drift density.

In Case 3, which has large drift density near the snow surface at inflow due to saltation (cf. Fig. 2), the depositions in front of the building and outside the separation regions become large. As a result, two large erosion regions are clearly observed near the upwind corners of the building.

![Fig. 2](image1)

(1) Case-1                                    (2) Case-2                                   (3) Case-3

Fig. 2 Horizontal distribution of normalized snow depth

![Fig. 3](image2)

(1) $t^*=0$ (without drifting snow)                                       (2) $t^*=100$ (with drifting snow)

Fig. 3 Horizontal distribution of turbulence energy $k/<u_H>^2$ obtained in Case-3 ($z/H=0.025$)

Effect of Snow Particle on Turbulence Property

Fig. 3 compares the horizontal distributions of turbulence energy $k$ at the first grid adjacent to the snow surface obtained in Case 3 with and without drifting snow. The difference between these results indicates the effect of snow particles on the turbulence
property. The value of $k$ in the region far from the building at $t^*=100$ becomes smaller than that at $t^*=0$. This means that the flowfield with drifting snow becomes less turbulent than that without drifting snow due to the energy dissipation due to snow. However, the regions with large $k$ values near the front corners at $t^*=100$ becomes larger than those at $t^*=0$. This is because the separations near the upwind corners at $t^*=100$ become stronger due to the decrease of incoming $k$ value than that at $t^*=0$.

Comparison of Snow Depth Distribution with Field Measurement Results

Figs. 4 and 5 compare the snow depth distributions obtained from the previous CFD model (Tominaga et al., 2006) and the present model with those obtained from the field measurement. Snow depth is normalized by the value at the reference point, which was not affected by the building. The snowdrift pattern obtained from the cold wind tunnel using artificial snow for the same flowfield (Suwa et al., 2003) is also shown in Fig. 5. The erosion regions near the upwind corners of the building in the present CFD result are much larger than the previous results. Furthermore, the large peaks of snow accumulation outside the separation regions near the building, which were observed in the previous model, are not seen in the field measurement. This over-prediction of snow deposition is mainly caused by the fact that Pomeroy’s model overestimates the transport rate in a non-equilibrium saltation layer such as flow around a building. The result of the snowdrift patterns, i.e., erosion around the upwind corners and deposition in front of and behind the building obtained by the present CFD, shows good correspondence with the field measurements.

Fig. 4 Comparison of horizontal distribution of normalized snow depth

Fig. 5 (a) Normalized snow depth obtained from field measurement (Oikawa et al., 1999) and (b) Snowdrift pattern obtained from wind tunnel experiment (Suwa et al., 2003)

Fig. 6 compares the horizontal distributions along a lateral line crossing the building. The results of the previous CFD have two large peaks around the building, which are not observed in the present CFD results or the field measurement. However, there were some differences between the field measurements and the experiment. For example, the present CFD shows relatively large depositions at the front of the building (cf. Fig. 4(2)), while those of the field measurement and the experiment were small. This is partly because the present
CFD only considers erosion due to shear stress, although erosion due to vertical impinging flow may be large in this region. This effect should be considered in future investigations.

![Fig. 6 Comparison between normalized snow depths obtained from CFD and field measurements along lateral line (x/H=0.1)](image)

**Conclusions**

A CFD method for predicting snowdrift around a cubic building model using a new snowdrift model proposed by the authors was conducted and its accuracy was examined by comparing results with those of the previous CFD model and field measurements, and the following results were obtained:

1. It was confirmed that the boundary conditions for threshold friction velocity and the inflow profile of drifting snow density have a definite effect on the distribution of snow depth.
2. The snowdrift patterns, i.e., erosion around the upwind corners and deposition in front of and behind the building, obtained by the present CFD shows better correspondence with those obtained from the field measurement and the wind tunnel experiment than the previous CFD results.
3. The present CFD shows relatively large deposition just in front of the building, although the field measurements showed small deposition. This is partly because erosion due to shear stress is considered in the present CFD, although erosion due to vertical impinging flow may be large in this region. This effect should be considered in future investigations.

**Appendix: Outline of previous snowdrift model by the authors (Tominaga et al., 2006)**

The transport equation for drifting snow density \(<\Phi>\) [kg/m^3] (eq. (14)) is solved to simulate the suspension of snow particles (Uematsu et al., 1991).

Drifting snow density in saltaton layer \(<\phi_{sal}>\) is expressed by the model proposed by Oikawa et al. (2003) based on the saltation transport model by Pomeroy and Gray (1990).

\[
\langle \phi_{sal} \rangle = \frac{0.68 \rho_a}{c(u_{*s})g h} \left( \langle u_{*s} \rangle \langle u_{*s} \rangle - \langle u_{*s} \rangle^2 \right)
\]

where \(h\) : height of saltation layer [m], \(c\): empirical coefficient

The snow deposition and erosion are calculated using the mass balance equation of snow in a control volume (CV) adjacent to the snow surface following Oikawa et al. (2003). Here, the CV is assumed to be equal to the first cell adjacent to the snow surface in the CFD calculation.
\[\Delta \left(\frac{Q \langle \Phi_{\text{salt}} \rangle}{Q}\right) + T = B\]  \hfill (23)

where \(Q\): Flow rate at side surface of CV \([m^3/s]\), \(\Delta (Q<\Phi_{\text{salt}}>)\): Budget of snow mass

- \(T\): Snowfall rate (\(T>0\)) \([kg/s]\),
- \(B\): Deposition rate (\(B>0\)) or Erosion rate (\(B<0\)) \([kg/s]\)

If the amount of snow entering the CV exceeds that exiting the CV, deposition occurs. Conversely, if the amount of exiting snow exceeds the amount of entering snow, the snow surface is eroded.

\(T\) is calculated at the top surface of the CV by eq. (24) using \(<\Phi>\) obtained from eq. (15), the snowfall velocity \(<w_f>\) and the horizontal area of the CV \((\Delta x\Delta y)\).

\[T = \langle \Phi \rangle \langle w_f \rangle \Delta x \Delta y\]  \hfill (24)

Variation of snow depth per unit time \(\Delta z_s\) is calculated using \(B\) obtained from eq. (23), snow density \(\rho_s\) and the horizontal area of the CV.

\[\Delta z_s = \frac{B}{\rho_s \Delta x \Delta y}\]  \hfill (25)

In this analysis, when \(B\) becomes negative, the amount of the negative part is incorporated as the source term of eq. (15).

References


