Sundsbø, P.A., 1997, Numerical modelling and simulation of snow-accumulations around porous fences, Proc. of The International Snow Science Workshop, Oct. 1996, Banff, Alberta, Canada., 135-139.

NUMERICAL MODELLING AND SIMULATION OF SNOW-ACCUMULATIONS AROUND POROUS FENCES

by

Per-Arne Sundsbø
Narvik Institute of Technology, Dept. of Building Science, Narvik, Norway

ABSTRACT

This paper presents a method for two-dimensional numerical simulations of snow drift. The numerical model is based on two-phase, gas-gas theory where snow and air mainly are transported as dilute suspension. Transport by creep and saltation is considered by imposing transport above the snow surface according to experimental knowledge. Snow is accumulated where the calculated friction velocity is below the threshold for particle movements and the new snow surface will affect the wind velocity field similar to real conditions. The numerical model is implemented in a general transient computer code based on finite-volume technique. Effects on the packing due to storage conditions, such as rainfall and temperature variations are not considered. Simulation of the development of snow accumulations around a typical porous snow fence is performed and, the result seems to be in good agreement with experimental data.

INTRODUCTION

The mechanism of snow drift has been the subject for many investigators during the years (Schmidt, 1980). Most studies have been carried out by performing experiments in the field (Tabler, 1988b) or in wind tunnels (Iversen, 1979). These methods are still important to strengthen our knowledge regarding the physics of snow drift but of less value as design tools for the common engineer.

Initiation of particle movements along the ground occur where the surface shear stress reaches a certain critical value. A further increase above this threshold shear stress will extend the vertical distribution of snow particles and consequently increase the snow transport. Snow will be transported downwind until the surface shear stress is reduced beneath the threshold value for relocation of deposited particles. The wind can no longer maintain a vertical distribution of particles and depositions are formed.

The surface shear stress is related to the vertical wind profile by the friction velocity ($u_* \equiv \sqrt{\tau_0/\rho}$), which is determined by field measurements. A given type of snow with a certain quality and particle distribution seems to have a characteristic threshold value for friction velocity or surface shear stress for which transport properties are defined.

Snow drift may occur as creep, saltation or suspension. In most situations where snow drift analysis is requested, all the three transport modes are present. Creep, saltation and suspension refer, respectively, to the way particles move by rolling on the surface, jumping near the surface and being suspended in the wind and brought further away from the surface. Investigation of blowing snow performed by Kobayashi (1972) concludes that saltation is the dominant mechanism for snow transport at wind speeds of about 10 m/s, measured at a reference height of 10 m. He estimated that 90% of the total mass flux was within the saltation layer. This is probably true for most snow drift situations with a similar velocity and snow quality, but average snow particle sizes may vary due to climate and storage conditions. Creep may be the prevailing drift factor for snow consisting of large grains that are aged for a few days without being exposed to drifting winds (Tabler, 1988b). In this situation snow deposition forms in wave patterns similar to sand waves that often can be observed on a sandy beach. Other drift occurrences are dominated by drift of particles small enough to go into suspension. These smaller particles are easily carried away by large eddies extending up to hundreds of metres above the snow surface. Since saltation is a phenomenon limited by short trajectory heights it is reasonable to assume that transport by suspension is significant around tall constructions or in high mountain terrain.

The flow problem considered

Snow drift is considered as a two-phase flow problem that is modelled by gas-gas technique and with the use of some empirical rules. Transport of the snow phase is governed by the airflow and a small relative velocity between the two phases allows drift and settling with respect to the air phase. It is assumed that the volume fraction of the airborne snow is small compared to the total mixture of snow and air. Effects by drifting snow particles on the mean airflow are therefore neglected. This one-way coupling where the air phase mainly controls the snow transport, is debatable, especially for the rather important process of saltation. On the other hand, the deposited snow is considered to affect mean velocity calculations. Deposited snow is treated as a solid surface as long as the surface shear stress is below the limit for erosion. Thus, the one-way coupling situation between airborne snow and wind is now reversed since the deposited snow is the controlling factor.

Snow transport in the saltation layer is dominated by heavy particle transport and there exists no rigorous theory for this type of modelling. Consequently, empirical knowledge is applied to model transport by both creep and saltation. Transport of snow in suspension by the mean flow is considered, but the contribution of turbulent diffusion on suspended snow is neglected.

In general, the flow situation considered in this paper is two dimensional, mechanical snow drift. Temperature variations, phase changes and storage conditions are neglected even if they might have a substantial effect on the overall result. There are some questions arising about how to apply such statistically expected climate factors in numerical modelling.

NUMERICAL METHOD

Equations

Numerical modelling and simulations of air flow fields are performed with FLOW-3D (Hirt, 1975), a general purpose computer program based on finite-volume technique. FLOW-3D uses the Fractional Area / Volume Obstacle Representation method or often referred to as the FAVOR technique (Hirt, 1993), to model obstacles and porous baffles. Obstacles are defined with zero volume porosity regions while thin porous baffles are given by area porosities. In the following transport equations, V denotes the fractional volume open to flow and A is the fractional area open to flow:

The continuity equation for the air phase:

$$\nabla \cdot \overrightarrow{UA} = 0 \tag{1}$$

The momentum equation for the air phase:

$$\frac{\partial \vec{U}}{\partial t} + \frac{\overrightarrow{UA}}{V} \cdot \nabla \vec{U} = -\frac{1}{\rho}\nabla p - \vec{g} + \vec{a} - \vec{b} \tag{2}$$

where a and b represent viscous accelerations and flow losses across porous baffles, respectively.

The friction velocity for the air phase:

$$u_* = u(z)\kappa / \ln\left(\frac{z}{z_{snow}}\right) \tag{3}$$

where u is the horizontal velocity at height z, κ the von Kármáns constant and z_{snow} the surface roughness height for calculations of the friction velocity. A procedure for calculating the friction velocity is proposed by Sundsbø and Hansen (1996).

Scalar advection for the snow phase:

$$V\frac{\partial f}{\partial t} + \nabla \cdot (f\overrightarrow{UA}) = -w_f\frac{\partial}{\partial z}(fA_z) \tag{4}$$

w_f is the terminal snowfall velocity and A_z is the fractional area open to flow in vertical direction.

The relative velocity between the two phases:

$$\vec{U}_r = \frac{(\rho_{air} - \rho_{snow})}{K}(1-f)f\,\frac{\nabla p}{\rho_m} \tag{5}$$

where mixture density, $\rho_m = f\rho_{snow} + (1-f)\rho_{air}$, depends on the snow volume fraction f and the air volume-fraction *(1-f)*, respectively. K is the drag function between the two phases and ∇p is the pressure gradient in the air.

Simulation procedures

The air velocity model is based on an Eulerian description that mainly involves solving Navier-Stokes equations to obtain the mean velocity field. The following procedures are repeated for each time step:

1. Calculation of air velocity profile basically by ensuring conservation of mass and momentum of the airflow.

2. Calculation of the friction velocity.

3. Calculation of snow drift based on air velocities and friction velocity from step 1 and 2, respectively. Snow transport is first evaluated byeq. 4 and then by estimating some drift fromeq. 5.

4. Evaluating of the snow surface. A new snow surface is formed where the snow density is sufficiently high and the friction velocity is below the threshold value for snow drift. Erosion of old surfaces will occur at higher friction velocities.

Simulation of creep, saltation and suspension

A scalar advection equation (eq. 4) is used as the basis for modelling of snow transport. Suspension by mean flow is considered by solving this advection equation for the snow phase based on the Eulerian wind velocity field. Thus the airborne snow phase is treated as a dilute suspension, and relative drift between snow and air phase is additionally given byeq. 5. The drift velocity is a result of the balance between pressure forces and interfacial drag forces. Drift-flux modelling of snow drift without accumulation or saltation can be found in Bang et al. (1994).

Modelling of saltation can be boiled down to a vertical lift problem regarding the snow phase. A vertical snow density profile based on empirical knowledge (Mellor and Fellers, 1986) is maintained above the snow surface, by introducing vertical transport in the advection equation. Horizontal fluxes are then calculated as for suspension of snow by the mean flow. The lift effect is included until the calculated friction velocity ineq. 3 decreases below the threshold value for saltation. The snow is then left to settle for possible accumulations. Deposition on the snow surface is accomplished by accumulating a specific part of the incoming snow fraction. It is also assumed that the amount of snow transport by creep is small and included in the saltation drifting process.

Boundary conditions

Left inlet boundary condition

Measurements during blowing snow conditions show that the mean wind profile is proportional to the logarithm of height above the snow surface (Male, 1980), which also is true for observations of non-blowing snow conditions. The mean wind profile in snow drift seems to be smaller near the surface than for situations without blowing snow. This reduction in wind speed may be explained by a transfer of momentum through the saltating particles, from the wind to the surface, or by the vigorous stirring of saltating particles which results in a reduction of the shear of the wind velocity (Maeno et al., 1979).

Mean inlet velocity is in agreement with field observations given by the logarithmic profile:

$$u(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \qquad when \qquad z \gg z_0 \tag{6}$$

The inlet snow profile is given as a vertical mass concentration according to multiple regression analysis of field measurements, Fig. 1. In this work it is assumed that the velocity at the height of 10 m is representative for the vertical distribution of snow. The highest snow concentration is confined to a narrow zone close to the surface, and the vertical size of computational mesh cells must therefore be carefully chosen in order to obtain acceptable resolution of the ground drift.

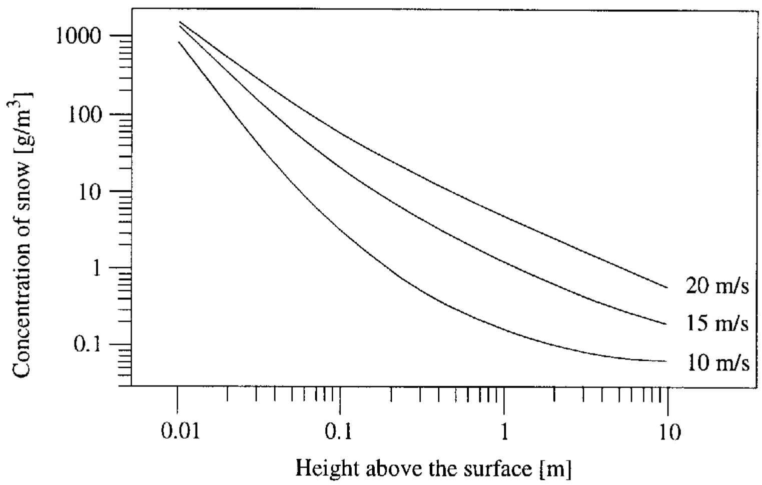

Figure 1. Concentration of snow as a function of height above the snow surface, for drift situations with velocities at 10, 15, and 20 m/s, measured at a reference height of 10 m (Mellor and Fellers, 1986).

Right outlet boundary condition

Continuous outflow where all normal derivatives vanishes is selected as the right boundary condition. Upstream effects are minimized through evaluating normal derivatives from only the momentum equations.

Top and Bottom boundary conditions

The bottom boundary condition is defined as a rigid wall with no-slip conditions where wall shear stress is calculated. Snow accumulation is treated as a new surface having a zero velocity boundary condition for the flow simulations. Top boundary is specified as a symmetry condition where free-slip is considered. Possible contribution from vertical snowfall is neglected due to the low concentration compared to ground drifting snow. There are no wind velocities normal to the bottom boundary, the snow surface or the top boundary condition.

Turbulence modelling in snow drift

Turbulence and particle interactions can be divided into two aspects. The first concerns with how particles are affected by turbulence in the carrier fluid. The second is how particle interaction affects the turbulence in the mixture fluid. Hetsroni (1992) indicated that the presence of particles that are small compared to the turbulent scale suppress the turbulence in the mixture flow due to additional energy dissipation. Larger particles seemed to have an opposite effect by enhancing turbulence. The field of turbulence modelling of two-phase, gas-particle flows is poorly understood, and this analysis is confined to treating turbulence in the air phase and neglecting turbulence effects due to particle interactions. Simulation of snow drift around a porous fence is performed using a one equation turbulent energy model (FLOW-3D, 1987). Turbulent quantities are linked to mean flow equations by assuming that the dynamic viscosity is a sum of molecular and turbulent viscosities, $\mu=\rho(\nu_T+\nu)$.

NUMERICAL SIMULATIONS OF SNOW DRIFT

A numerical simulation of snow drift around a typical 50% porous snow fence is performed, and the different stages in the growth of snow drift are shown in figure 2. The fence is similar to 2.74 m tall Wyoming fence with a bottom gap of 14% except for being vertical instead of having a slight inclination. A mean inlet wind profile typical for flat ground conditions is given, where the velocity is 10 m/s, measured at the height of 10 m and the surface roughness is 10^{-3} m. The snow quality in this simulation is assumed to be something in between snow coming from a wind-hardened surface and very light dry snow, and consequently the threshold friction velocity is chosen as 0.2 m/s (Male, 1980). Other constants used in the simulation are chosen as follow: drag constant, K=25.8 kg/m^{2}s, terminal snowfall velocity=0.4 m/s and roughness height for friction velocity calculations=10^{-4} m.

It is not realistic to perform numerical simulations of snow drift with a simulation time as long as for real conditions. Figure 2 shows a simulation for 23 minutes snow drift, and this short simulation time is possible by using a small freezing fraction of 10^{-4} for solidification. Drifting snow is deposited in a surface mesh cell by assuming that 30% of the incoming snow flux accumulates for each time step. This percentage was chosen to match the measured field deposition.

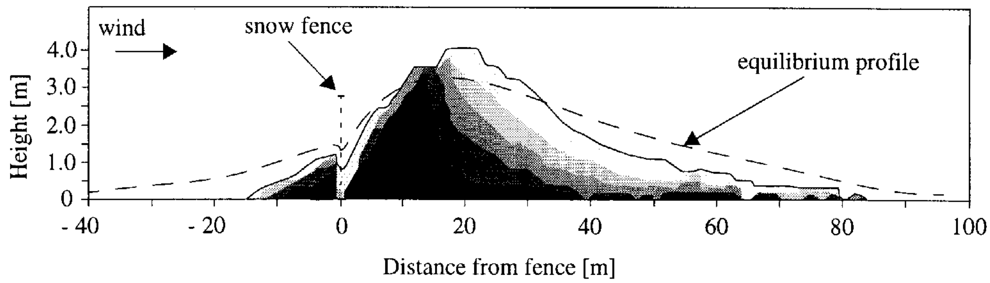

Figure 2. Numerical simulation of snow drift formation around a 2.74 m tall snow fence, with bottom gap of 14% of the fence height and a porosity of 50%. Snow drift profiles are compared with an equilibrium profile based on statistical field analysis made by Tabler (1988b). The drift development in time is illustrated with decreasing shade.

The calculated snow deposition in figure 2 is in satisfactory agreement with the equilibrium drift profile which is characteristic for Wyoming fences, placed on flat ground and less than half filled. There is no point in going for the identical profile when field measurements and boundary conditions are not given. An example of snow formation development around a similar fence is shown in figure 3. Early stage depositions behind the fence show tendency towards formation of a cornice or an abrupt drop off on the leeward side, which is caused by a recirculating zone behind the formation. The same phenomenon can be detected in the numerical simulation in figure 2.

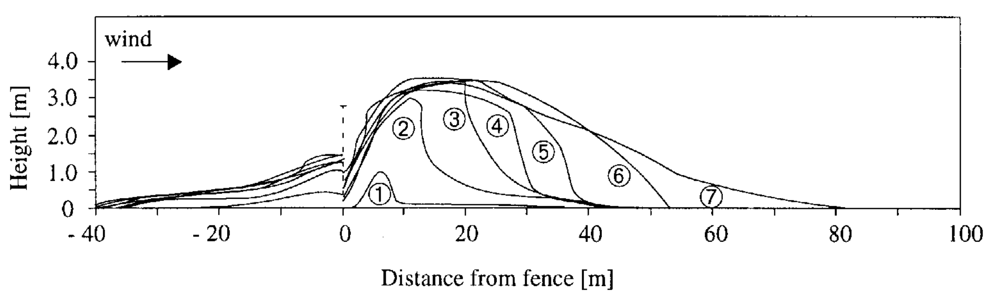

Figure 3. Formation of snow drift around a 2.74 m tall Wyoming fence based on dimensionless field data formed by a 3.78 m tall fence with 15 cm bottom gap (Tabler, 1988a). The number indicates stages in the grow of snow drift.

SUMMARY AND CONCLUDING REMARKS

A numerical method for simulation of snow drift based on two-phase theory is proposed. Snow transport is basically considered by solving a scalar transport equation for suspension by the mean flow and the snow phase is allowed to drift with respect to the air phase. In the absence of rigorous theory the transport by creep and saltation is modelled by means of experimental knowledge. This method has been successfully employed to simulate the development of two dimensional snow accumulations around a 50% porous fence and, as a further development, this model will be extended to handle three dimensional cases.

It is necessary to evaluate drift-heights or snow accumulations by sharp interface techniques in order to study how they affect the wind velocity field.

The physical constants governing phenomenon such as saltation height and accumulation need to be investigated more carefully. These properties may vary as the flow problem changes from creep dominated snow transport to drift where suspension prevails. The choice of turbulence modelling and size of computational mesh cells, should be carefully considered.

Numerical modelling of snow drift means solving a very complex flow problem and at present it is probably not possible to find solutions without implementing some empirical modelling. Even so, the proposed model may be a helpful tool for design purposes.

ACKNOWLEDGMENTS

The author tanks Mr. B. Bang for many helpful discussions during this work and Mr. Ernst W. M. Hansen for reading the manuscript and giving valuable comments.

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NOMENCLATURE

Roman letters

a	viscous acceleration
A	fractional area open to flow
b	flow loss across porous baffle plates
f	snow phase volume fraction
g	gravity
K	drag function
p	pressure
t	time
u	horizontal velocity
u_*	friction speed, $=(\tau_0/\rho)^{1/2}$
U_r	relative velocity between air and snow
U	velocity
V	fractional volume open to flow
W_F	terminal snowfall velocity
x, y, z	coordinates
z_0	roughness height
z_{snow}	roughness height for friction velocity calculations

Greek letters

κ	von Kármáns constant (~ 0.4)
μ	dynamic viscosity
ν	kinematic viscosity
ν_T	turbulent kinematic viscosity
ρ	density
ρ_m	mixture density
τ_0	surface shear stress