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Numerical simulation of sand and snow drift at porous fences

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Introduction

Computational Fluid Dynamics (CFD) has become a key tool for a broad range of today's research studies and industrial applications. They are as varied as the dispersion of passive pollutant particles in the atmosphere to the complex flow system involving chemical reactions. The numerical prediction of the natural phenomena of wind blown particles such as sand or snow and particle deposition around objects has attracted attentions of researchers from a wide range of engineering and scientific backgrounds.

Wind blown particles occur as the result of a natural phenomenon known as an Aeolian process. The Aeolian process is divided into three stages, erosion, transportation and deposition, commencing when the wind entrains a particle from rest and carries it for some distance. When the aerodynamic forces applied to a particle become less than the gravitational force, the particle finally settles back to the ground (Bagnold 1941). A large number of field and wind tunnel studies have been conducted to study the physical behavior of wind blown particles as they approach obstacles of different shapes. Since field and wind tunnel experiments are costly, numerical modeling has been applied to many engineering and environmental applications (Ishii, 1975).

This paper presents a practical application of the numerical model based on two-phase flow theory. Two numerical experiments were conducted using this model for snow and sand drift around porous fence. The results show a good agreement with both field and wind tunnel observations.

Numerical Model

The key consideration in the numerical model is the representation of the solid particles as a second continuum flow phase superimposed upon the primary phase, the air, as described by the conventional Navier-Stokes equations (Ishii, 1975). A flow regime containing two or more flow phases of different physical properties may be treated as a multi-phase flow system, which can be solved numerically based on the theory for a multi-phase flow system (Manninen, 1996). However, considering the air as the continuous phase (carrier phase) and the particles as the discrete phase, the simplest two-phase flow model, known as the *Homogenous two-phase flow model,* was employed in this paper. The conservation equations can be expressed as:

$$\underbrace{\frac{\partial(\rho\phi_i)}{\partial t}}_{\text{Rate of change in }\phi} + \underbrace{\frac{\partial}{\partial x_j}(\rho u_j \phi_i)}_{\text{Convection term}} = \underbrace{\frac{\partial}{\partial x_j}\left[\Gamma_\phi \frac{\partial \phi_i}{\partial x_j}\right]}_{\text{Diffusion term}} + \underbrace{S_\phi}_{\text{Source term}} \qquad (1)$$

Where ϕ represents the solution variable to be solved, u, v, w, k: Kinetic energy, ε: rate of dissipation of kinetic energy and α_p: particle volume fraction. x_j is the space components x,y,z.

The flow governing equations may be formed by substituting the variable ϕ, the diffusion coefficient Γ_ϕ and the source term S_ϕ with the appropriate values (Alhajraf, 2000).

Particles transported by wind usually occur in one of three modes, surface creep, saltation or suspension (Bagnold, 1941). These processes depend upon the physical properties of the particle such as size, density and on the strength of the wind velocity component parallel to the particle bed. In this paper, models of the particle transport by saltation and suspension were considered as two separate source terms ($S_p = S_{Sus.} + S_{Sal.}$) added to the particle transport equation of α_p. The suspension source term is formulated as:

$$S_{sus.} = -\beta_{sus} \frac{\partial}{\partial X_j}\left[\alpha_p \, u_{Driftj}\right] \tag{2}$$

where the diffusion velocity is $u_{Drift} = (1-\alpha_p)u_{\text{Rel.}}$ and β_{Sus} is valid between 0.05 and 0.1 in flow regimes involving sand drift, (Alhajraf, 2001).

The saltation particle zone usually has a layer thickness of a few centimetres (Bagnold, 1941). In this layer the suspension source term is modified to take into account the saltated particles. For a quartz particle with 0.25mm diameters and 2650 kg/m^3 density the threshold velocity was found to be about 0.22 m/s.

In this paper, the saltation source term was written in terms of particle volume fraction, the relative velocity and the dimensionless friction to threshold ratio as follows:

$$S_{sal.} = \beta_{Sal} \frac{\partial}{\partial X_j}\left[\alpha_p \,(1-\alpha_p)\, u_{\text{Rel}j}\, U_R^*\right] \tag{3}$$

β_{Sal} is a constant that varies between 0.15 and 0.6, (Alhajraf, 2001).

The saltation source term is applied only in the control volumes adjacent to the solid boundaries. Thus, there are three possibilities in this case for the saltation source term in each control volume:

1. If the friction velocity is greater than threshold value then the source term will have a negative sign and therefore an erosion process will occur.
2. If the friction velocity is equal to threshold value then the source term will be zero and neither erosion nor deposition will occur.
3. If the friction velocity is less than threshold value then the source term will have a positive sign and therefore a deposition process will occur.

Results

The numerical computations were employed to simulate particle deposition at 50% porous fence. First run were performed for Wyoming snow fence used to protect Wyoming highway. Steady deposition profile from the field observation of Tabler, 1986 and wind tunnel measurement of Iversen, 1981 were compared with the numerical prediction.

A steady state solution was achieved with the particle deposition profile reaching an equilibrium state. Fig. 1, shows the different stages of the deposition process for different time steps. It shows that the majority of the deposition area is concentrated behind the fence with the crest of the dune found at a distance from the fence varying between 5 and 8 times the fence height H. The maximum height of the dune was found to be similar to the observations, about 20%H over the height of the fence.

The crest of the dune begins in the earlier stages at a distance downstream from the fence equal to about 6 to 8 times the fence height H. However, as more particles are deposited, the dune increases in size whilst the height of the crest point increases and moves backwards towards the fence. At the equilibrium state, the height of the crest point reaches 1.2H from the ground and 5H downstream from the position of the fence.

The full-scale, wind tunnel and numerical model deposition profiles are shown in Fig. 2a. The portion of the snow drift immediately downstream the fence in the wind tunnel experiment is just under the full-scale profile. Iversen (1981) explained this discrepancy by saying that the full-scale friction velocity is at times just above the particle threshold value while in the wind tunnel experiment it was set to some significant value above the threshold value. This is probably the reason for the lack of deposition in front of the fence in the wind tunnel experiment. It is also possible that the wind tunnel experiment had not reached the state of equilibrium.

The deposition profile predicted by the numerical model is shown to be comparable to those measured. The predicted profile shows fairly good agreement with the full-scale rather than the wind tunnel upstream and immediately down stream of the fence.

The area of deposition in front of the wall was predicted as a result of the drop in the friction velocity to values below the particle threshold in the weak zone just upstream of the fence. This behavior of the numerical model strengthens Iversen's explanation of the discrepancy between the full-scale and wind tunnel measurements. In a further investigation of this behavior, the same simulation was repeated under identical conditions with the exception of the inlet friction velocity, which was increased to a value 20% above the threshold value instead of 2% used in the previous exercise, Fig. 2b.

Fig. 3a. shows the drift around short fence of 0.762-m depth placed in the middle of the flow domain Fig. 3b shows the deposition volume where the fence spanned the whole domain width. The simulation of the domain in which the fence spans the whole width produced a dune, which is symmetrical along the length of the domain. The prediction in the case of the centrally positioned fence produced a dome shape dune due to the effect of the change in the flow field at the fence edges.

For sand drift at porous fence, the model has been employed to simulate the drift at the double row fence system used in the Kuwaiti desert to protect installations. Fig. 4, shows a photograph of the 2-Km front fence in the equilibrium state. An intermediate and equilibrium state profiles produced from the model are compared to the field measurements in Fig. 5. It is clearly shown that the front fence profile is in good agreement since they both reached the equilibrium shape. The rear fence profile over predicted the measured one and that is because the fence in the field did not reach its final capacity. This is demonstrating the potential of the model to predict the shape of the deposition profile even before it happens. Finally, Fig. 6 shows the different stages of the deposition procedure and clearly shows that the front fence reached it maximum capacity before the rear one. This behavior of the model is in a good agreement with what happens in the nature where the front fence reached the steady shape while the rear one still can trap more sand particles.

Conclusion

A numerical model based on the homogenous two-phase theory was introduced to simulate sand and snow drift at porous fences. The model shows a good qualitative and quantitative agreement with both field and wind tunnel observations.

In conclusion, a practical CFD tool has been developed and validated, incorporating novel physical and numerical models. The tool can be utilised by scientists and engineers to further understand the real world problem of drifting sand and snow in urban and industrial areas.

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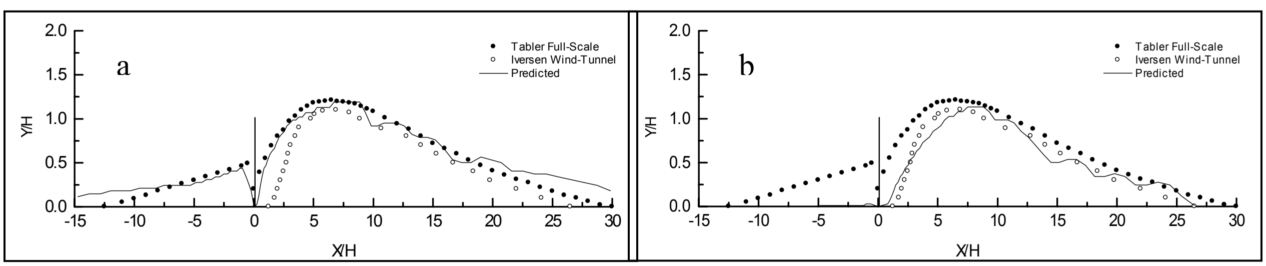

Figure 1: Numerical prediction against full -Scale and wind tunnel measurements at 50% porous fence a. inlet friction velocity is 2% above the threshold value. b. inlet friction velocity is 20% above the threshold value.

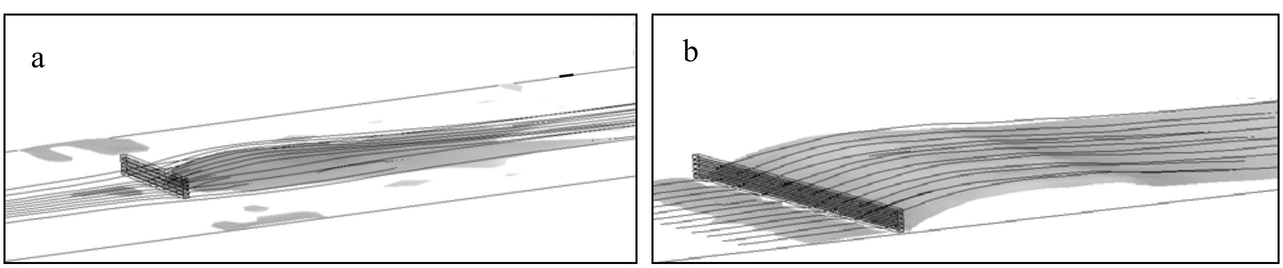

Figure 2: 3-D deposition dune behind 50% porous fence. Isosurface of volume fraction at 0.75.

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Figure 3: Drift formed at the 1st fence line, 2m height, facing the wind direction at KISR site. Photograph by author, December 1999.

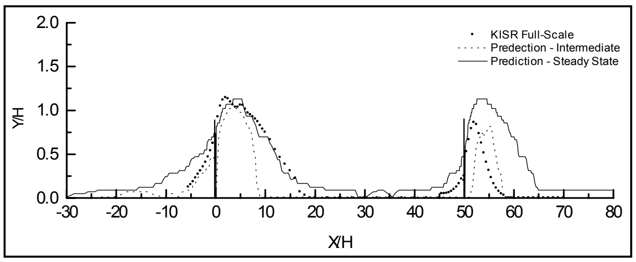

Figure 4: Comparison between KISR station double row fence system and the numerical model prediction.

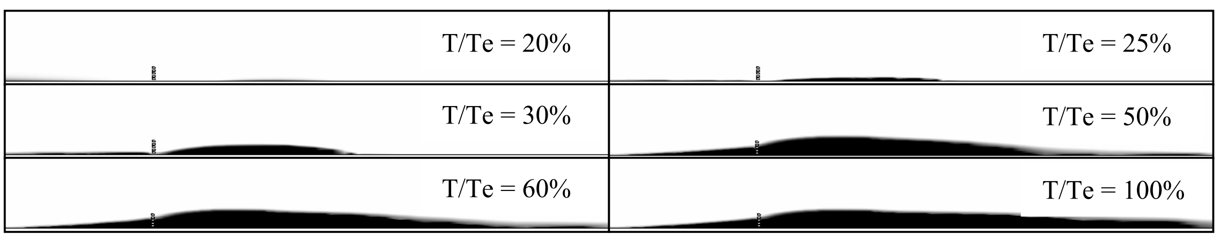

Figure 5: Deposition stages at 50% porous fence. Volume fraction equal 0.75

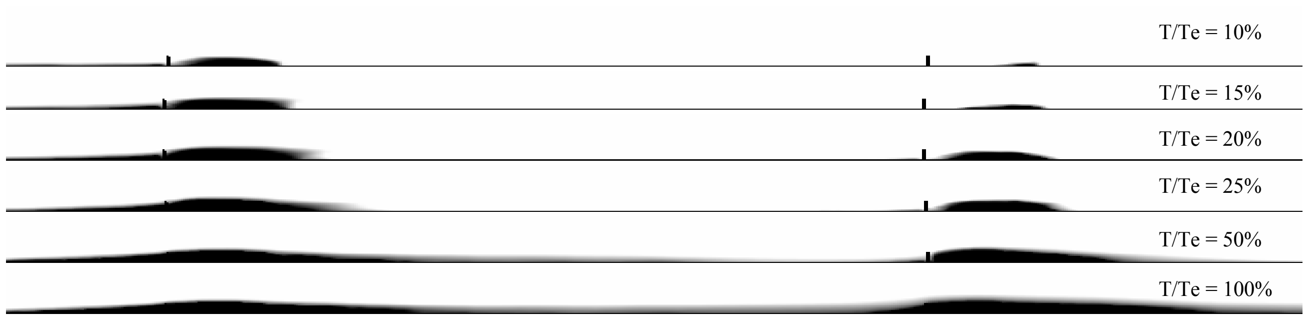

Figure 6: Deposition stages at multi row fence system using the numerical model.