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Numerical Simulation of Drag Partition over Rough Surfaces

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Introduction

The momentum flux, τ_t, generated by a turbulent flow over a rough surface is attributed mainly to a pressure drag on roughness elements, τ_r, and a skin drag on the underlying surface, τ_s, i.e.,

$$\tau_t=\tau_r+\tau_s$$

The prediction of τ_t and the partition of τ_t into τ_r and τ_s are important to the studies of aeolian processes, because τ_s is responsible for the movement of soil particles. The problem of drag partition has been under investigations for over 60 years. A review of the early studies on the subject has been given by Wooding et al. (1973). Marshall (1971) carried out a wind tunnel experiment to examine the effect of roughness element on drag partition. Marshall placed cylinders and hemispheres in the wind tunnel and measured the total drag and the pressure drags on individual elements. Based on Marshall's dataset, Wooding et al. (1973), Arya (1975) and Raupach (1992) developed theories for drag partition.

Despite the success of the theories in describing wind tunnel data, three important questions remain unanswered. The first one is that the wind tunnel experiments are limited to a small sample of simple geometries and arrangements of roughtness elements. It is not clear whether the proposed theories are universal and how they should be modified if the quantities, such as roughness-element size and arrangement, differ from the wind tunnel experiment. The second question is that while the functional forms of the Ayra (1975) model and the Raupach (1992) model have captured the basic features of drag partition, the key hypotheses which underpin these theories have not been fully tested and hence the physics involved in drag partition is not well understood. The third question is that natural surfaces usually consist of roughness elements of various sizes that are complicated distributed in space. It is not certain whether simple models can be applied to natural surfaces. Even if they can be, it is not clear how the model parameters can be estimated. The field measurements of Wyatt and Nickling (1997) indicate that drag partition over sparsely vegetated surfaces can be different from that over surfaces with simple roughness elements.

It is difficult to examine the above problems through wind tunnel experiments. Computational fluid dynamic models offer an alternative. With the rapid development of computational techniques, numerical models for turbulent flows can be applied effectively to simulating flows over rough surfaces with roughness elements of any shape, size and arrangements. Hence, numerical experiments provide a great deal of information that is not available from wind tunnel and/or field studies. In this study, we present a numerical simulation of drag partition over rough surfaces. A large-eddy flow model with a k-e closure is run with very high resolution to simulate fully developed shear flows over regular and irregular arrays of cylinders of various sizes mounted on a smooth surface. The skin drag on the ground surface and the pressure drag on the roughness elements are computed. These numerical simulations allow an examination of the interactions of turbulent wakes arising from different roughness elements. They offer an independent validation of the existing theories and a possible foundation for developing new theories of drag partition over natural surfaces. In this study, we first describe the methodology used for the computational simulation of drag partition and then compare the numerical results with the measurements of Marshall (1971) and the theories of Wooding et al. (1973), Arya (1975) and Raupach (1992). We then apply the numerical simulation technique to examine how drag partition depends on the geometry and arrangements of roughness elements.

The Large-eddy Flow Model

A large-eddy simulation model with a k-e closure is used to generate turbulent flows over roughness elements. The large-eddy type of flow simulation is important for the study because the spatial and temporal resolutions must be high in order to represent the rapidly varying turbulent flows around roughness elements. The domain configuration for the simulation is illustrated in Figure 1. It consists of three 1m high and 1.3m wide sections. The first and last sections are 1m long. The length of the second section is adjustable according to the number and size of the roughness elements placed on a plate in this section. The plate has the same length as the second section, but is narrower. The average vertical resolution in all three sections is 10 mm. Grids in the vertical direction are non-uniform with a logarithmically decreasing resolution with height. The horizontal resolution in the first and last sections in the x direction is uniformly 10 mm. Grids in the lateral direction in all sections are the same but non-uniform. Grids on the test plate (x-y plane) are uniform with resolution of 1x1 to 3x3 mm^2, while grids on the remaining parts of the second section are uniform with resolution 1x5 to 3x5 mm^2. Thus, grids in the x-y plane of the first section and last section are uniform with resolution 10x1 to 10x3 mm^2. The maximum computational domain contains 500x100x100 nodes.

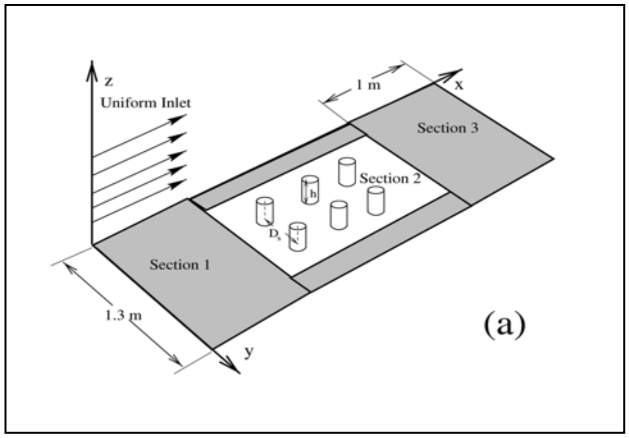

Figure 1: Domain configuration for the drag partition simulation.

Drag Partition

We first simulate the wind tunnel experiment of Marshall (1971) and compare the numerical results with observed data and the estimates based on existing theories. To mimic Marshall's experimental configuration, identical cylinders of h=25.4mm are placed regularly on the surface, and the number of cylinders is increased one by one to allow λ to increase from 0 to 0.1. The cylinder height-diameter ratio h/d is allowed to vary between 0.5 to 2, and the cylinder spacing-height ratio D_s/h between 2 and 30. The flow velocity at z=46 mm is maintained at 20.3ms^{-1} identical to the free stream flow speed used in Marshall's experiment. Figure~2 shows an example of the velocity distributions.

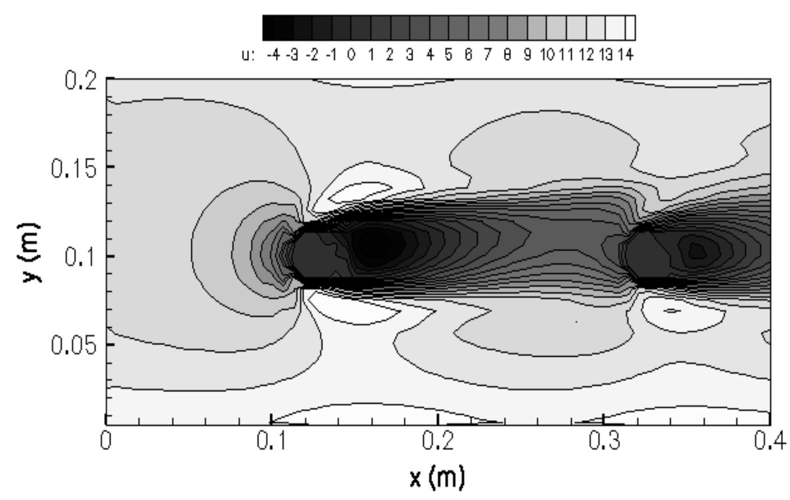

Figure 2. A cross-section of velocity distribution around two cylinders of d=h=25.4 mm at z=10 mm for u_H=20.3 ms^{-1}.

Figure~3 compares the simulated $(\tau_r/\tau_t)^{1/2}$ and τ_s/τ_t with Marshall's (1971) data and the predictions of Raupach (1992), Arya (1975) and Wooding et al. (1973). The observed values of $(\tau_r/\tau_t)^{1/2}$ are in good agreement with the simulated data, except for the two values at around λ=0.02, which are slightly larger. The simulated values of $(\tau_r/\tau_t)^{1/2}$ are also in good agreement with the predictions of Raupach (1992) and Arya (1975) for λ between 0 and 0.2. The simulated τ_s/τ_t is also in good agreement with Marshall's data and the predictions of Raupach (1992) and Arya (1975).

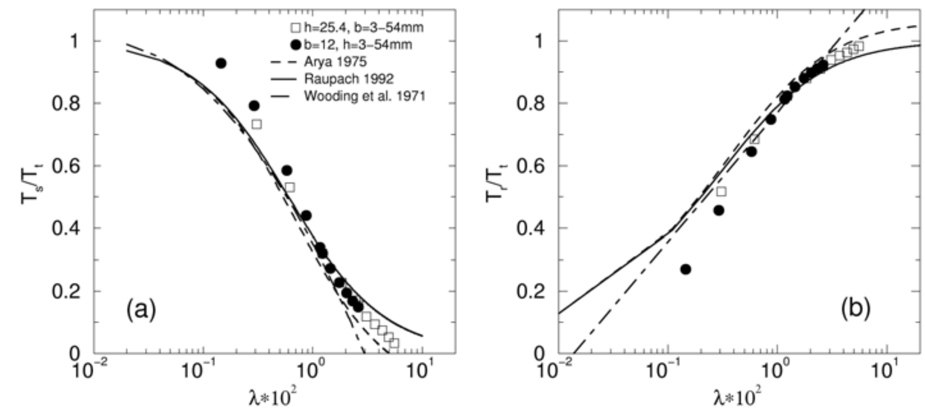

Figure 3: Simulated $(\tau_r/\tau_t)^{1/2}$ and (τ_s/τ_t) for u_H=20.3 ms^{-1} are compared with Marshall's (1971) measurements and the estimates using the theories of Raupach (1992), Arya (1975) and Wooding et al. (1973). The roughness density λ increases with the numbers of cylinders of d=h=25.4 mm.

To study how drag and drag partition depend on the random distribution of roughness elements, we carried out experiments using five roughness elements. Three cases are considered. In Case 1, the five elements differ from each other both in height and diameter; in Case 2, they have the same diameter (25.4 mm) but differ in height; in Case 3, they have the same height (25.4 mm) but differ in diameter. There are five fixed locations on the ground surface and for each test the roughness elements are randomly placed at these locations. Figure 4 shows an example of the flow field.

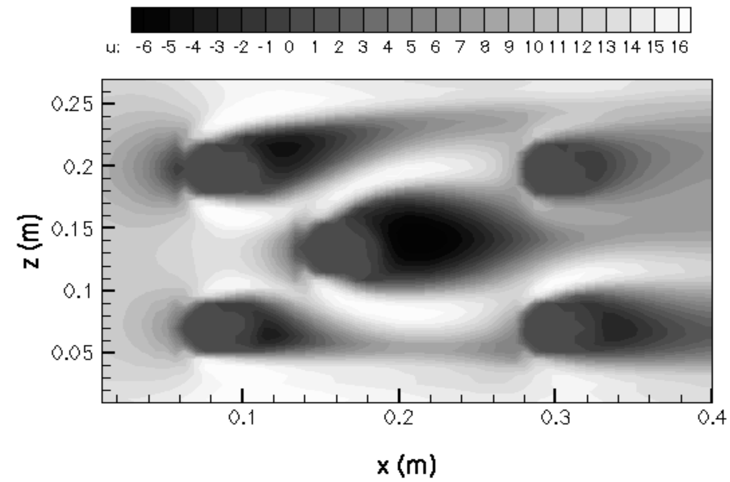

Figure 4: Instantaneous velocity and pressure fields on the x-y plane at z=10 mm for u_H*=20.3 ms*$^{-1}$*.*

The numerical simulations suggest that the arrangement of roughness elements for given λ does affect the pressure drag on roughness elements, the skin drag on exposed ground surface and the drag partition. However, if λ is large, the impact appears to be relatively small. Therefore, applying the theories of Raupach (1992), Arya (1975) and Wooding et al. (1973) to irregular arrays of non-uniform cylinders to predict drag and drag partition produce only a small error. Because of the limitations in the number of numerical simulations, we have not been able to establish a general relationship between the scatter and the variance of the roughness element size. Therefore the above conclusion should be considered as preliminary.