Environmental Modelling and Software 107 (2018) 141–147

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

# Optimisation of flow resistance and turbulent mixing over bed forms

A. Arfaie[a], A.D. Burns[a,*], R.M. Dorrell[b], D.B. Ingham[c], J.T. Eggenhuisen[d], W.D. McCaffrey[e]

[a] School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK
[b] Institute of Energy and Environment, University of Hull, Hull, HU6 7RX, UK
[c] Department of Mechanical Engineering, University of Sheffield, Sheffield, S10 2TN, UK
[d] Department of Earth Sciences, Utrecht University, PO Box 80021, 3508 TA Utrecht, Netherlands
[e] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK

## ARTICLE INFO

*Keywords:*
Turbulent flow
Roughness
CFD
Bed forms

## ABSTRACT

Previous work on the interplay between turbulent mixing and flow resistance for flows over periodic rib roughness elements is extended to consider the flow over idealized shapes representative of naturally occurring sedimentary bed forms. The primary motivation is to understand how bed form roughness affects the carrying capacity of sediment-bearing flows in environmental fluid dynamics applications, and in engineering applications involving the transport of particulate matter in pipelines. For all bed form shapes considered, it is found that flow resistance and turbulent mixing are strongly correlated, with maximum resistance coinciding with maximum mixing, as was previously found for the special case of rectangular roughness elements. Furthermore, it is found that the relation between flow resistance to eddy viscosity collapses to a single monotonically increasing linear function for all bed form shapes considered, indicating that the mixing characteristics of the flows are independent of the detailed morphology of individual roughness elements.

## 1. Introduction

Many industrial and environmental flows are subject to diminished or enhanced turbulence, and flow resistance due to presence of rough surfaces. In heat transfer applications, rib roughened surfaces are employed to enhance heat transfer characteristics in heat exchanger design (Webb and Eckert, 1972). Experimental and numerical studies have been performed to investigate the enhancement of heat transfer by the presence of roughness elements of a wide range of shapes (Moon et al., 2014; Orlandi et al., 2016). Furthermore, analytical and numerical optimisation studies have been performed in order to search for roughness shapes which optimise both heat transfer and friction loss performances (Kim and Kim, 2006).

Applications in the natural environment include the evolution of ribbed scales in sharks (Fletcher et al., 2014), and the formation of bed forms, such as dunes, in sediment carrying flows (Best, 2005). Previous work of Arfaie et al. (Arfaie et al., 2014; Arfaie, 2015) has shown that there are optimal patterns of large-scale roughness elements, such as ribs, to maximise turbulence or to minimize flow resistance. This conclusion apparently supported the work of Eggenhuisen and McCaffrey (2012), who proposed that run-out lengths of particulate gravity currents are enhanced by the presence of rugose bed forms on the ocean floor, such as scours and dunes. Eggenhuisen and McCaffrey conducted gravity current experiments where the flow was perturbed by the presence of a single rectangular roughness element. They observed that the profiles for vertical turbulent normal stresses showed enhanced mixing compared to unperturbed turbulence profiles and concluded that enhanced mixing via bed forms result in a net distribution of sediments towards the upper region of the flow, and thus a reduction in density stratification and an increase in the run-out distance of the flow.

Turbidity current run-out length is controlled by the balance of potential to kinetic energy conversion as a function of the rate of energy dissipation through drag, diffusion and viscous dissipation. The potential energy is controlled by the balance of turbulent particle diffusion with gravitational settling. Thus maximizing flow turbulence is expected to increase the eddy diffusivity of particles, the potential energy of the flow and hence promote greater run out (Eggenhuisen et al., 2010, 2011; Straub et al., 2011; Tokyay et al., 2011).

Arfaie et al. (2014) sought to find further support for this hypothesis by performing a series of numerical investigations to study the effect of lower boundary roughness on turbulent flow in a two-dimensional channel. Periodic arrays of rectangular roughness elements were considered over a wide range of roughness spacing to height ratios, $w/k$. Computations of volume averaged eddy viscosity were performed over this range in order to establish the optimum spacing that produces maximum turbulence enhancement and mixing. This was found to

---

[*] Corresponding author.
*E-mail address:* a.d.burns@leeds.ac.uk (A.D. Burns).

https://doi.org/10.1016/j.envsoft.2018.06.002
Received 5 December 2017; Received in revised form 19 April 2018; Accepted 1 June 2018

occur when $w/k$ is approximately equal to 7. Moreover, this value is only weakly dependent on Reynolds number, and the decay rate of turbulence enhancement as a function of $w/k$ beyond the optimum spacing is slow. In addition to this, computations of friction factor as a function of $w/k$ indicated that maximum resistance to flow also occurs at the same value of $w/k = 7$. Consequently, the implications on particulate gravity current run-out length were inconclusive, as optimized turbulence mixing tends to act to keep particles in suspension, hence increasing run-out length, whilst optimized resistance acts as a large drain on turbulence kinetic energy, hence decreasing run-out length.

The purpose of this paper is to extend the work of Arfaie et al. (2014) to consider the flow over idealized bed form shapes encountered in geophysical flows, such as dunes, anti-dunes, and symmetric triangular bed forms. This builds on work by McLean et al. (1999) who constructed semi-analytical models based on boundary layer theory for velocity profiles, and boundary shear stresses for flows over two-dimensional dunes. They emphasized the importance of splitting the total drag force on the bed into the pressure drag, or form drag, and the viscous drag, or skin friction. The former is largely responsible for draining the flow of mean kinetic energy, whilst the latter is largely responsible for erosion of particles from the bed into suspension, hence increasing potential energy. Subsequent developments are reviewed by Best (2005) in the context of dunes in rivers. Furthermore, similar CFD research has been carried out to model air flows and sediment transport over aeolian dunes (Feng and Ning, 2010; Parsons et al., 2004; Takahashi et al., 1998; Wakes et al., 2010) and air pollution dispersion over urban canyons (Yang and Shao, 2008; Solazzo et al., 2009; Chu et al., 2005). We perform computational fluid dynamics (CFD) calculations to obtain detailed information on the flow over a variety of idealized two-dimensional dunes. The results are then used to obtain information on the resistive drag and turbulence mixing characteristics as a function of dune shapes and aspect ratios, with particular emphasis on the correlation between flow resistance and turbulent mixing for the different shapes.

In addition to the environmental flow applications considered here, dunes deposited from suspended particles have a significant effect on the flow resistance and sediment carrying capacity of engineering conduits and pipelines, such as those employed in sewage systems (May 1993; Skipworth et al., 1999; Coleman et al., 2003). May 1993 reported on experimental results and models for the effects of a wide range of dune types deposited by non-cohesive particles in sewage systems, noting that their effects were indeed significant, as minimum slope and flow velocities need to be specified in order for sewers to become self-cleansing. This work was extended to cohesive particles by Skipworth et al. (1999). Coleman et al. (2003) performed experiments that indicated that dunes deposited in closed conduits have much in common with dunes formed under free surface flows.

## 2. Methods

### 2.1. Numerical method

Simulated flow over complex bedforms was modelled using the numerical method employed by Arfaie et al. (2014). Further details may be found in the PhD thesis of Arfaie (2015). Arfaie et al. used a commercial CFD code ANSYS CFX-14.0 (ANSYS CFX, 2011) to compare the predictions of a wide range of Reynolds Averaged Navier-Stokes (RANS) based turbulence models with the experimental results of Djenidi et al. (1999) and the numerical Large Eddy Simulations of Cui et al. (2003). The standard k-$\varepsilon$ model (Launder and Spalding, 1974), used herein, was found to give adequate predictions of flow velocity profiles, and to provide the best compromise between accuracy and computational efficiency in order to permit the exploration of a wide parameter space.

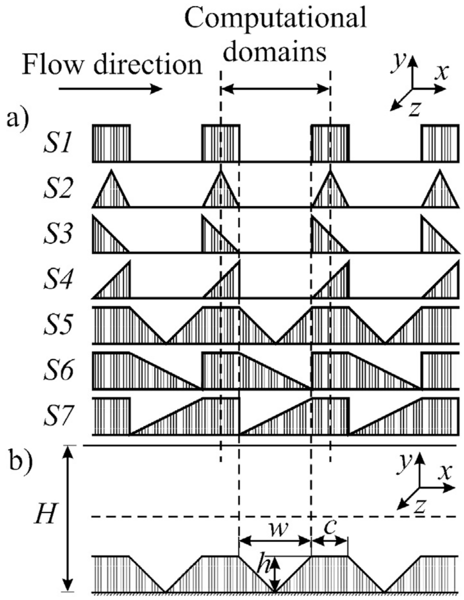

Fig. 1. (a) Schematic illustration of the computational domains shown by the dashed lines for pressure driven flow over idealized bedforms under a periodic condition. (b) Channel flow configuration with roughness segment S5 positioned at the solid bed.

### 2.2. Idealized bedforms

The rib roughness elements studied by Arfaie et al. (2014) are generalised to idealized shapes, similar to those studied by Moon et al. (2014). The shapes considered here are intended to represent bed forms occurring in the natural environment, see Fig. 1. The shapes $S1$ are the rectangular roughness elements considered by Arfaie et al. (2014). Shapes $S2 - S4$ represent symmetric bed forms, anti-dunes and dunes respectively. Shapes $S5 - S7$ combine the simple shapes $S1 - S4$ to approximate more realistic natural lower boundary rugosities of symmetric dunes, anti-dunes and normal dunes, respectively. Arfaie et al. (2014) employ the categorisation of Perry et al. (1969) of roughness elements into two distinct types of roughness, namely, $d - type$ and $k - type$, where $d$ and $k$ denote channel height and roughness height, respectively. For a sufficiently low width-to-height ratio, $w/k \lesssim 2$, the flow undergoes a skimming flow regime, in which there is little interaction from the vicinity of the roughness element to the outer flow region. This is known as $d - type$ roughness. The $k - type$ roughness regime is associated with $w/k \gtrsim 4$, where the flow in the roughness cavity begins to interact with the main body of the flow. See Jimenez (2004) for a detailed discussion of $d - type$ and $k - type$ roughness regimes. Here, the roughness element height is denoted by $h$, and we perform a study of the effect of axial roughness length to height ratio ($c/h$). The upper flat surface length of the roughness element $c$ is varied while the roughness element height is held fixed to cover aspect ratios $c/h = 1$, 2,4 and 8 for each of the bed geometries. The width-to-height ratio $w/h$ is kept fixed at the value $w/h = 7$ which was determined by Arfaie et al. (2014) to give optimal turbulent mixing and flow resistance for rectangular roughness elements. We have not established that this is optimal for all the shapes considered here; it is kept fixed in order to reduce the number of simulations that need to be performed.

### 2.3. Model assumptions

A shear flow of pure seawater over the idealized bed forms is considered. It is assumed that the particle concentrations are sufficiently small that they do not have a significant influence on the flow field. There is strong evidence that this configuration also gives insight into behavior of dilute sediment gravity flows over bed forms; the velocity