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Detached eddy simulation of shallow mixing layer development between parallel streams

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Abstract

Results of a high resolution Detached Eddy Simulation (DES) are used to characterize the evolution of a shallow mixing layer developing between two parallel streams in a long open channel with a smooth flat bed and medium size dunes. The study discusses the vertical non-uniformity in the mixing layer structure and provides a quantitative characterization of the growth of the large-scale quasi two-dimensional (2D) coherent structures with the distance from the splitter plate. Results show that in streamwise sections situated between $75D$ (D is the channel depth) and $150D$ from the splitter plate, the width of the mixing layer close to the free surface is 20–30% more than the width in the near-bed region. This is mostly because of the tilting of the mixing layer interface on the low-speed side toward the low speed stream as the free surface is approached. Power spectra of the horizontal velocity components near the free surface show the presence of a -3 subrange, corresponding to inverse energy cascade in two-dimensional turbulence, at streamwise locations situated more than $10D$ from the splitter plate, consistent with the presence of large-scale quasi 2D horizontal eddies and the transfer of energy (inverse energy cascade) from the smaller scales toward these eddies. Consistent with visualizations of the mass transport of a passive scalar within the mixing layer, close to the free surface, the estimated streamwise length of the quasi 2D mixing layer eddies is about 2.5–3.0 times larger than the local width of the mixing layer. The presence of large-scale roughness elements in the form of an array of two-dimensional dunes with a maximum height of $0.25D$ (D is the channel depth) induces a much more rapid and larger shift of the centerline of the mixing layer due to the increased influence of the bottom roughness.
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1. Introduction

Turbulent shallow mixing layers are observed in rivers, coastal regions and atmosphere. A typical example of turbulent shallow mixing layers relevant for environmental flows is the flow downstream of a river confluence with a small angle between the two tributaries. The flow hydrodynamics and morphodynamics at river confluences are complex (Best, 1988; Rhoads and Kenworthy, 1998; Bradbrook et al., 2000). The two converging streams at the confluence form a mixing interface and develop large-scale coherent turbulent structures within this interface (Sukhodolov and Rhoads, 2001). These coherent structures have been considered mainly as quasi-two-dimensional (quasi 2-D) (Chu and Babarutsi, 1988).

The structure of flow in the confluence hydrodynamic zone shapes the channel bed through different patterns of sediment transport. Scour at confluences is an important environmental and river-management problem, especially for medium to large-rivers. The depth of scour hole can reach up to four times that of the upstream channel (Best and Ashworth, 1997; Paola, 1997). Confluences also provide a variety of favorable living conditions for fish and other aquatic organisms through their diverse morphologic and flow patterns (Rice et al., 2008).

As in most cases the flow depth is much smaller than the width of the river downstream of the confluence, the flow conditions are shallow. The shallowness of the fluid and the

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bottom friction significantly affect the dynamics of a shallow mixing layer compared to that of a free (deep) mixing layer. As a result in a shallow mixing layer: a) the transverse spreading rate reduces with the distance from the origin of the mixing layer until the growth of the mixing layer ceases; b) the velocity difference on the two sides of the mixing layer decreases in the streamwise direction (Kirkil and Constantinescu, 2008, 2009). The vertical development of the large-scale eddies in a shallow mixing layer is constrained by the bed and free surface. This makes anisotropic effects very important. Though the large-scale eddies are quasi two-dimensional (2D), the interaction of the flow with the bed generates 3D small-scale eddies. The effect of these 3D eddies and of the vertical gradient induced by the presence of a no-slip surface at the bed on the development of the large-scale quasi 2D structures is largely unknown.

In this paper the focus will be on the simplest case which corresponds to a mixing layer developing in a straight horizontal channel between two parallel streams with unequal depth-averaged velocities U_{10} and U_{20} (the index ‘0’ denotes incoming flow values upstream of the splitter end). This is the case that was the focus of previous experimental studies (Chu and Babarutsi, 1988; Uijttewaal and Booij, 2000). However, these studies were based only on visualizations of the mixing layer at or in a horizontal plane close to the free surface and on velocity measurements at a limited number of sections. For example, no attempt was made to visualize the vertical structure of the shallow mixing layer or to describe the interaction of the quasi 2D mixing layer eddies with the 3D turbulence generated at the bottom.

Here we aim to use an eddy-resolving numerical model, specifically detached eddy simulation (DES), to examine details of a turbulent flow structure within a parallel stream confluence. Fully three-dimensional eddy-resolving numerical simulations have the advantage that they allow a detailed investigation of the variation of the turbulence characteristics over the depth of the mixing layer.

Large Eddy Simulation (LES) with no wall functions is the most ideal method that should be used to simulate shallow mixing layer flows. However, use of this approach is computationally too expensive because high level of mesh refinement is required to resolve the thin attached boundary layers at high Reynolds numbers corresponding to field conditions. In order to reduce the computational cost, the near-wall flow has to be solved with a less expensive method. A first option is to use LES with wall functions. This approach is easy to implement, however the accuracy of the predictions is generally not very good because of inherent assumptions of this approach is not valid in a complex three-dimensional flow. A better, but more expensive option is to resolve the near-wall flow with a Reynolds-averaged Navier–Stokes (RANS) model and then use LES to solve the flow away from the wall. These approaches are called hybrid RANS-LES methods. DES is a one of the hybrid models that uses the same turbulence model in the RANS and LES regions. The solutions at the boundary between the LES and RANS regions are seamless (Spalart, 2009).

Several physical quantities will be used in this paper to quantify the development of the mixing layer. As discussed in Chu and Babarutsi (1988) a bed-friction number, S, can be introduced to characterize the stabilizing influence of the bottom channel friction on the development of the mixing layer.

$$S = \frac{\overline{c_f}\delta}{2D}\frac{U}{\Delta U} \tag{1}$$

where $\overline{c_f} = 0.5(c_{f1} + c_{f2})$, $c_{f1,2} = \tau_{1,2}/\left(\rho \frac{1}{2} U_{1,2}^2\right)$, $U = 0.5(U_1 + U_2)$. $\Delta U = (U_1 - U_2)$ is the velocity difference across the mixing layer; τ is the value of the bed shear stress and D is the channel depth. The local width of the mixing layer is defined as the maximum slope thickness:

$$\delta = \frac{U_1 - U_2}{(\partial u/\partial y)_{max}} \tag{2}$$

where y is the transverse direction and U is the streamwise velocity. The critical value of S is denoted S_c and corresponds to an equilibrium between turbulence production (due to the destabilizing effect of transverse shear) and dissipation (due to stabilizing effect of bed friction) within the mixing layer. Experiments and stability analysis showed that $0.06 < S_c < 0.12$. Reasonable agreement is found between the theoretical predictions from linear stability analysis and experimental data by van Prooijen and Uijttewaal (2002).

By fitting a curve to their experimental data, Chu and Babarutsi (1988) proposed the following law for the streamwise variation of the entrainment coefficient α in a shallow mixing layer:

$$\alpha = \alpha_0(1 - S/S_c) \quad \text{if } S < S_c$$

$$\alpha = 0 \quad \text{if } S > S_c \tag{3}$$

The entrainment coefficient characterizes the reduction of the spreading rate of the mixing layer and is defined as

$$\alpha = \frac{1}{\Delta U}\frac{\mathrm{d}\delta}{\mathrm{d}t} \sim \frac{U}{\Delta U}\frac{\mathrm{d}\delta}{\mathrm{d}x} \tag{4}$$

Thus, when $S = S_c$, $\alpha = 0$ and the mixing layer width remains constant (zero growth rate). To account for the role of bed friction in the development of a shallow mixing layer, $\overline{c_f}$ is used to nondimensionalize the streamwise distance and the width:

$$x^* = \frac{\overline{c_f}x}{D}$$

$$\delta^* = \frac{\overline{c_f}\delta}{D}\frac{U_0}{\Delta U_0} \tag{5}$$

The entrainment coefficient in a free (deep) mixing layer ($U = U_0$, $\Delta U = \Delta U_0$) is $\alpha_0 = \mathrm{d}\delta^*/\mathrm{d}x^*$. A value close to 0.09 was determined experimentally for α_0.

2. Numerical simulation setup

In the numerical simulation, a splitter wall separates two fully-turbulent currents (see Fig. 1). As a result of the presence of the free surface and the bed, the vertical development of the

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