TURBULENCE CHARACTERISTICS OF A SHALLOW MIXING LAYER DEVELOPING OVER FLAT SURFACE AND 2-D DUNES

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Key words: shallow mixing layer, shallow flows, detached eddy simulation.

Summary. 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 over flat surface and two-dimensional (2D) dunes. The study discusses the vertical non-uniformity in the mixing layer and provides a quantitative characterization of the growth of the large-scale quasi 2D coherent structures with the distance from the splitter plate. 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 very rapid and larger shift of the centerline of the mixing layer due to the increased influence of the bottom roughness. Results show that in streamwise sections situated after 100D (D is the channel depth) from the splitter plate, the width of the mixing layer close to the free surface stays constant. The tilting of the mixing layer interface toward the low speed stream is observed as the free surface is approached in all vertical sections.

1 INTRODUCTION

The mixing layer region controls the exchange of mass and momentum between two streams of different velocities. Turbulent shallow mixing layers are observed in rivers, coastal regions and atmosphere. A typical example relevant for environmental flows is the flow downstream of a river confluence with a small angle between the two tributaries. 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 bottom friction significantly affect the dynamics of a shallow mixing layer compared to that of a free (deep) mixing layer (Uijttewaal and Booij, 2000). As a result in a shallow mixing layer: a) the transverse spreading rate reduces with the distance from the origin of the mixing layer (end of splitter plate) 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; and c) the axis of the mixing layer shifts toward the low-speed side. The vertical development of the large-scale eddies in a shallow mixing layer is constrained by the bed and free surface. Though the large-scale eddies are quasi two-dimensional (2D), the interaction of the flow with the bed generates 3D small-scale eddies.
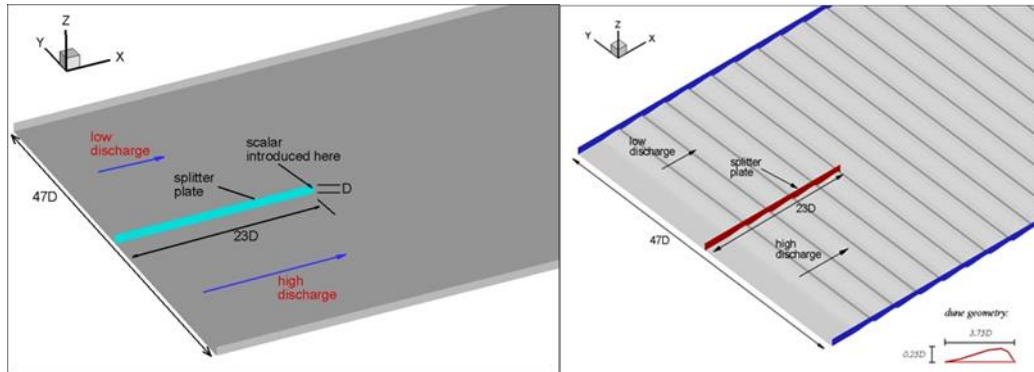
Figure 1: Sketch showing the computational domain around the splitter plate.

The development of a shallow mixing layer developing between two parallel streams with unequal bulk velocities U_{10} and U_{20} (the index '0' denotes in-coming flow values upstream of the splitter end) in a long open channel is investigated numerically using Detached Eddy Simulation (DES). Previous experimental investigations of shallow mixing layers with similar parameters (flow depth D, mean flow velocity $U_0=(U_{10}+U_{20})/2$) to the one considered in the present numerical study were reported by Chu and Babarutsi (1987), Uijttewaal and Booij (2000) and van Prooijen and Uijttewaal (2002). 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 large-scale turbulent structures in the mixing layer is constrained with respect to the widely studied case of a free mixing layer. The growth of the large-scale coherent structures in the mixing layer takes place mostly in the horizontal directions and is driven by the transverse shear induced by the difference in the mean velocities of the two streams.

2 NUMERICAL SIMULATIONS

A general description of the DES code is given in Chang et al. (2007). The 3D incompressible Navier-Stokes equations are integrated using a fully-implicit fractional-step method. The governing equations are transformed to generalized curvilinear coordinates on a non-staggered grid. Convective terms in the momentum equations are discretized using a blend of fifth-order accurate upwind biased scheme and second-order central scheme. All other terms in the momentum and pressure-Poisson equations are approximated using second-order central differences. In the present DES simulation, the Spalart-Allmaras (SA) one-equation model was used.

The Reynolds number defined with the channel depth, D (=0.067mm), and the mean velocity of the two currents, U_0 (=0.23 m/s), is close to 15,500. The splitter length is 23D. The width of the channel is 47D and the length of the channel downstream of the splitter is 157D (=10.55 m) (Fig. 1). The channel bottom is smooth. The depth-averaged mean velocities of the two streams are $U_{10}=0.61U_0$ and $U_{20}=1.39U_0$, respectively. The mean velocities in the z/D=0.9 plane are $0.7U0$ and $1.56U0$, respectively. These conditions are similar to those present in the second test case studied by Uijttewaal and Booij (2000) where the streamwise velocity values at z/D~0.9

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were used to estimate U_{10} and U_{20}. The bed-friction velocities non-dimensionalized by the bulk velocity in each stream are 0.052 and 0.048. The spatial development of the shallow mixing layer is analyzed using DES on a mesh containing close to 10 million cells (912*336*32 in the streamwise, spanwise and vertical directions). The viscous sub-layer is resolved in the simulation and no-wall functions are used. In a second simulation, an array of identical 2D dunes is present. The wavelength of the dunes is 3.75D and their height is 0.25D. The dunes have a generic shape that approximates dunes developing in medium-size rivers. The equivalent non-dimensional bed roughness is close to 500 wall units (fully-rough regime). Mass exchange processes are studied by considering the transport of a passive scalar for which an advection-diffusion equation is solved. The passive scalar is introduced continuously at the end of the splitter plate over the whole depth of the channel.

3   RESULTS

Comparison of the instantaneous concentration fields in horizontal planes situated near the bed (z/D=0.1) and the free surface (z/D=0.9) in Fig. 2 shows the coherence of the quasi-2D eddies is decreasing as the channel bottom is approached. Also, there is a clear loss of the coherence of the large-scale eddies for x> 100D (~6.7 m, x is measured from the end of the splitter plate). This explains the observed decrease in the rate of growth of the mixing layer width in the streamwise direction (see discussion of Fig. 3) at all flow depths. The decay in the rate of growth increases with the decrease of the distance from the bed (see Kirkil and Constantinescu, 2008 for more details). The concentration contours in Fig. 2 suggest a rate of growth close to zero at z/D=0.1 for x/D>120D. Close to the free surface the average size of the largest eddies in the transverse direction is around 10D-15D (0.67-1.00 m) in the downstream part of the channel (x/D>120).

Comparison of the mean concentration profiles at z/D=0.9 and z/D=0.1 in Fig. 2 shows the positions of the centerline inferred from the mean streamwise velocity profiles and from the mean concentration fields are not identical. Based on the distribution of the mean concentration, the vertical tilt of centerline surface in the transverse direction is larger than 1.5D (~0.1 m) for x>120D. The vertical shift is slightly smaller in the case in which the velocity profiles are used to calculate the position of the centerline.

The development of the mixing-layer in the vertical direction is strongly non-uniform. This can be inferred from Fig. 2 where the width of the mixing layer inferred from the mean concentration field at a given streamwise location is significantly smaller at z/D=0.1 compared to z/D=0.9. Figure 3 allows a more quantitative comparison of the width of the mixing layer at different levels (z/D=0.1 and z/D=0.9) and in the depth-averaged flow. The width of the mixing layer in Fig. 3 was estimated based on the mean streamwise velocity field. The local width of the mixing layer is defined as the maximum slope thickness (Uijttewaal and Booij, 2000):

$$\delta = \frac{U_1 - U_2}{(\partial u / \partial y)_{max}} \qquad (1)$$

where $U_1(x)$ and $U_2(x)$ are the streamwise velocities in the two streams at a given streamwise location, y is the spanwise direction and u is the streamwise velocity. The curves in Figure 3 are obtained by using eqn. (1).
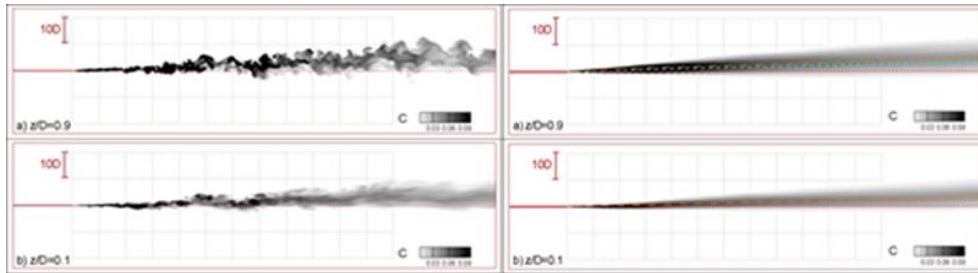
Figure 2: Contours of scalar concentration in the instantaneous (left) and mean (right) flow. a) z/D=0.9; b) z/D=0.1. The dashed-dot-dot line corresponds to the jet centerline determined from the mean concentration profiles. The dashed line corresponds to the jet centerline determined from the mean streamwise velocity profiles.
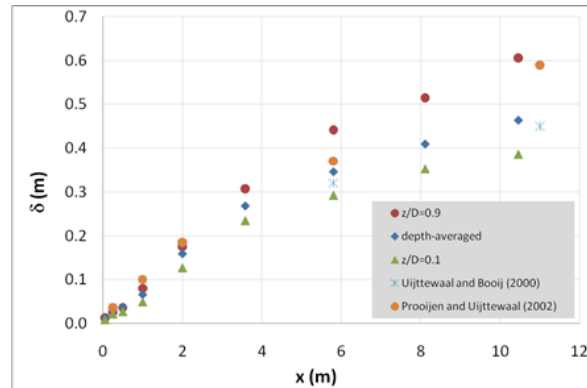

Figure 3: Mixing layer width vs. downstream distance from the splitter obtained from the profiles of the mean streamwise velocity. Also shown are two sets of experimental measurements performed close to the free surface.

4   CONCLUSIONS

DES predictions of the shallow mixing layer development close to the free surface were found to agree reasonably well with experimental observations. Meanwhile, the numerical results showed that the vertical variations of the width and centerline position of the shallow mixing layer are significant. For example, at distances between 75D 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.

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