UNIFORM AND GRADUALLY VARIED FLOWS IN COMPOUND CHANNEL VERSUS FREE MIXING LAYERS

PROUST, S.[(1)], FERNANDES, J.N.[(2)], RIVIERE, N.[(3)], LEAL, J.B.[(4)], PELTIER, Y.[(5)], & CARDOSO, A.H[(6)]

[(1)] *Irstea, Villeurbanne, France. E-mail: sebastien.proust@irstea.fr*

[(2)] *VAW-ETHZ, Zürich, Switzerland. E-mail: fernandes@vaw.baug.ethz.ch*

[(3)] *LMFA, Lyon, France. E-mail: nicolas.riviere@insa-lyon.fr*

[(4)]*Universitetet i Agder, Grimstad, Norway. Email: joao.leal@uia.no*

[(5)] *University of Liege, Liège, Belgium. Email: y.peltier@ulg.ac.be*

[(5)]*Universidade de Lisboa, Lisbon, Portugal. Email: antonio.cardoso@ist.utl.pt*

ABSTRACT

Mixing layers associated with uniform and gradually varied flows (GVF) in compound channel are experimentally investigated in two flumes, featuring a rectangular or a trapezoidal main channel (MC). These shear layers are compared with free mixing layers. Starting with uniform flow, the GVF are generated by an imbalance in the upstream discharge distribution between the floodplain (FP) and the MC. The GVF are longitudinally evolving under the influence of four external forcings: (i) a two-stage geometry, (ii) a varying vertical flow confinement (quantified by the relative flow depth, $D_r = h_f / h_m$, where h_f and h_m are the flow depths in the FP and MC); (iii) a variable lateral depth-averaged mean flow; (iv) a variable velocity ratio, $\lambda = U_s/(2U_c)$, where $U_s = U_{d2}–U_{d1}$ is the velocity difference, $U_c = 0.5(U_{d1}+U_{d2})$ is the mean velocity across the mixing layer, U_{d1} and U_{d2} are the depth-averaged velocities outside the mixing layer in the FP and MC, respectively. In the case of weakly or moderately sheared flows ($\lambda < 0.3 - 0.35$), the peak values of scaled depth-averaged Reynolds-stress, denoted Max (g_d), are independent of λ, but increase with a decrease in flow confinement, to reach the maximum values observed for free mixing layers. In the case of highly sheared flows ($\lambda > 0.3 - 0.35$), the values of Max (g_d) become independent of the flow confinement as λ increases, reaching values that can be greater than the ones observed for free mixing layers. Despite the flow confinement, the high values of λ trigger the development of 2D large coherent structures without interaction with the 3D bed-induced turbulence. Lastly, with nearly constant values of λ and D_r, it was found that the scaled shear-layer turbulence was mainly dictated by the lateral flow. For both uniform flows and test cases with a lateral flow to the FP, the Rayleigh's inflection point criterion is fulfilled. This gives rise to large 2D structures and high values of Max (g_d). By contrast, for test cases with a significant lateral flow to the MC, the convex velocity profiles without inflection-point are associated with low levels of Max (g_d). Lastly, the trapezoidal MC was found to enhance the turbulent exchange compared with the rectangular one.

Keywords: Mixing layer; Compound channel, Velocity ratio, Flow confinement, Lateral flow

1. INTRODUCTION

Uniform and GVF flows are experimentally investigated in two compound channel flumes, located at the Laboratory of Fluid Mechanics and Acoustics (LMFA), Lyon, France, and at the National Laboratory of Civil Engineering (LNEC), Lisbon, Portugal. Their detailed characteristics are reported in Proust et al. (2013). At LNEC, the flume is 10m long, 2m wide, symmetrical, with two FP and one trapezoidal MC. At LMFA, the flume is 8m long and 1.2m wide, asymmetrical, with one FP only, and with a rectangular MC. Starting with uniform flow conditions, to obtain GVF, the upstream discharge distribution between the MC and the FP was varied from one test to another, while keeping the total flow rate Q unchanged. The variation in FP inflow with respect to uniform flow conditions is denoted $\Delta Q_f / Q_f^u = (Q_f - Q_f^u)/ Q_f^u$. The same values of this parameter are investigated in both flumes, three cases with an excess in FP inflow (+19%, +38%, +53%) and one case with a deficit (–19%). An excess in FP flow, results in a lateral depth-averaged mean flow from FP to MC, and the opposite occurs for a deficit in FP flow. The dataset is composed of 25 test cases, with the relative depth D_r ranging from 0.2 to 0.4, and the velocity ratio λ ranging from 0.1 to 0.5. The velocity ratio λ quantifies the shear, due to velocity difference $U_s = U_{d2}–U_{d1}$, with respect to the convection velocity of the structures, $U_c = 0.5(U_{d1}+U_{d2})$ (see e.g. Huerre and Rossi 1998). The objective of this study is to examine in a simple compound geometry the combined effects of four external forcings on the scaled shear-layer turbulence: (i) the two-stage geometry, (ii) a variable velocity ratio λ, (iii) a varying flow confinement, and (iv) a lateral depth-averaged mean flow of variable magnitude and direction. Free mixing layers are considered as reference flows. Mean velocity and turbulent fluctuations were measured with a side-looking ADV probe (Vectrino+, Nortek) in both flumes. Turbulent statistics are calculated from 18000 samples.

2. EFFECT OF VELOCITY RATIO, FLOW CONFINEMENT, AND TWO-STAGE GEOMETRY

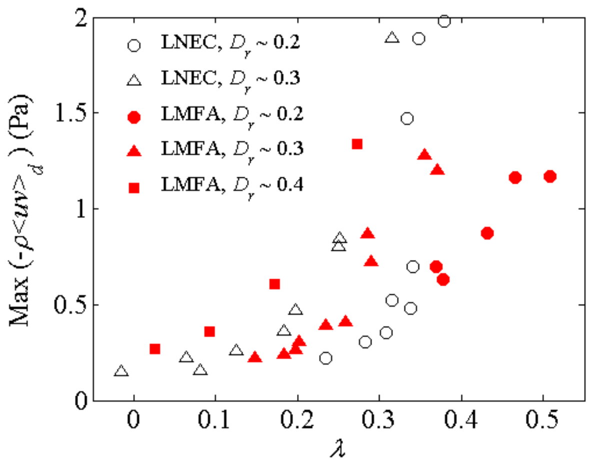

Figure 1. Peak values of depth-averaged Reynolds-stress, Max ($-\rho<uv>_d$), against velocity ratio, λ. LNEC flume: measurements at downstream distances x = 5 and 7.5m. LMFA flume, measurements at x = 4.5 and 6.5 m.

The effects of velocity ratio λ, flow confinement (relative depth D_r), and MC bank slope on shear-layer turbulence was investigated in the far-field region in both flumes. Results are shown in Figure 1. First, irrespective of the uniformity or non-uniformity of flow, for a given relative depth D_r in each flume, shear-layer turbulence increases with the scaled velocity difference, λ. Second, as the relative depth D_r decreases in each flume, an increasing velocity difference λ is required to obtain a fixed peak value of Reynolds-stress. This highlights the constraining effect of the flow confinement on the levels of lateral shear. Third, for a fixed relative depth D_r, a higher scaled velocity difference, λ, is required at LMFA than at LNEC to get a fixed peak value of Reynolds-stress. With similar aspect ratio in the MC in both flumes (see Proust *et al*. 2013), the inclined bank at LNEC therefore enhances the turbulent diffusion compared with the vertical bank at LMFA, whatever the direction and magnitude of the lateral flow.

The flow confinement has also a significant impact on the transverse development of shear layer turbulence across the compound section. This is shown in Figure 2, in the case of two highly sheared flows, the cases -19% at LMFA with D_r ~ 0.3 and 0.4. Similarly to free mixing layers, the Reynolds-stress is scaled by the square velocity difference U_s^2. Though both the velocity difference U_s and ratio λ are lower for the deeper case, the transverse development of scaled shear-layer turbulence is larger for this flow. For instance, the region of levels of shear $-<uv>/U_s^2$ higher than 1 is markedly greater. In addition, for the deeper case, the width of the shear region markedly increases from bottom to water surface. In this particular case, the turbulent motion is clearly not two-dimensional.

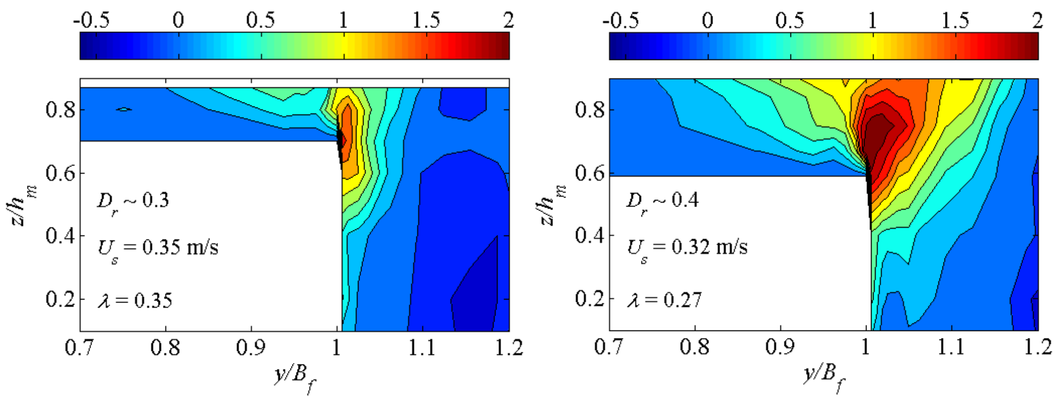

Figure 2. Effect of flow confinement: cross-sectional distribution of scaled Reynolds stress $-<uv>/U_s^2$. Cases $\Delta Q_f / Q_f^u$ = -19%, x = 4.5 m at LMFA. y-axis is the lateral direction, z-axis is the vertical direction and B_f, is the width of the FP.

3. EFFECT OF LATERAL FLOW

The effect of lateral flow was investigated for test cases with similar ratios λ and flow confinement. Results are shown in Figure 3 for cases with D_r ~ 0.2 at LNEC. From case -19% to case +53%, λ ranges from 0.38 to 0.31. To investigate the effect of the lateral flow inside the mixing layer, the profiles of mean velocity and Reynolds-stress are drawn in similarity coordinates, similarly to free mixing layers. The similarity coordinate, ξ, is defined as $\xi = (y-\phi)/\delta$, where ϕ is the centerline position in the mixing layer, and δ is the mixing layer width obtained from the mean velocity profile, according to Pope (2000), Eq. [5.204] p 140. This definition does not require the existence of an inflection point in the velocity profile, contrary to the definition based on the maximum slope thickness. The scaled velocity is denoted, $f_d(\xi)$, where $f_d(\xi) = (U_d–U_c)/U_s$, U_d being the local depth-averaged velocity. The scaled depth-averaged Reynolds-stress is denoted, $g_d(\xi)$, with $g_d(\xi) = –<uv>_d /U_s^2$.

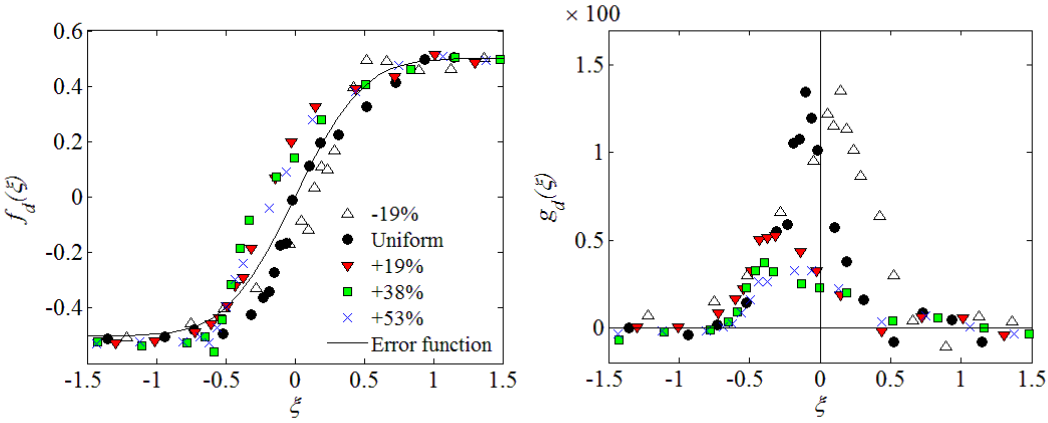

Figure 3. Scaled depth-averaged mean velocity profiles, $f_d(\xi)$, and scaled depth-averaged Reynolds-stress profiles, $g_d(\xi)$. LNEC, $D_r \sim 0.2$, x= 7.5 m. The error function is a usual approximation for free mixing layer velocity profile.

Figure 3(left) shows that, with an increasing lateral transfer to the MC (from case +19% to +53%), the mean velocity profile becomes convex without inflexion point. The Rayleigh's inflection point criterion is not fulfilled (e.g. Huerre and Rossi 1998). This results in a strong reduction in the peak values of scaled shear stress $g_d(\xi)$, which is connected to the absence of 2D-large coherent structures, as shown in Figure 4(left) by the power density spectra of lateral velocity fluctuation (the 2D structures are characterized by a -3 slope in the intermediate range of wave number k), and in Figure 4(right) by the temporal auto-correlation function (no temporal coherence is observed for those cases). By contrast, the case -19% and the uniform flow in Figure 3(left) feature an inflection-point velocity profile, with peak values of $g_d(\xi)$ of the order of magnitude of those observed for free mixing layers (see next section).

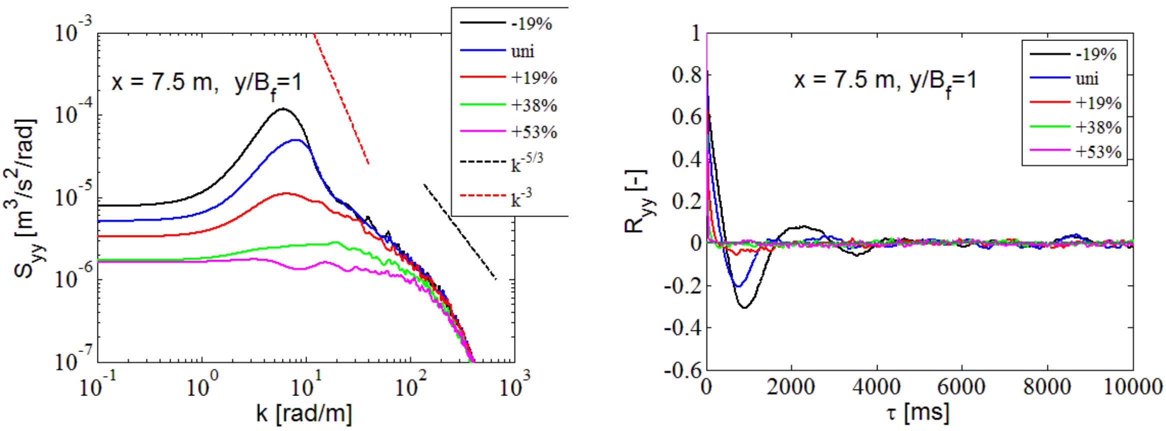

Figure 4. LNEC, $D_r \sim 0.2$. Power density spectra of lateral velocity fluctuation, S_{yy}, and temporal auto-correlation function R_{yy}. Measurements at the junction MC/FP (y/B_f = 1, i.e. top of the sloped bank in the MC)

4. CONCLUDING REMARKS ON THE COMBINED EFFECTS OF THE FOUR EXTERNAL FORCINGS

The peak values of scaled Reynolds-stress, Max[$g_d(\xi)$], across the mixing layer are shown in Figure 5 for the data from LNEC, and compared with values for free mixing layers and shallow mixing layers in single open-channel. Uniform flows studied by Fernandes (2013) in the LNEC flume, with D_r ~ 0.10, 0.15, 0.25 and 0.38, are also shown. Figure 5 shows that the weakly and moderately sheared flows (λ < 0.3 - 0.35) are mostly driven by flow confinement, as the values of Max[$g_d(\xi)$] are independent of λ, but increase with an increasing relative depth D_r, to reach values observed for free mixing layers or mixing layers in single channel. By contrast, in the case of highly sheared flows (λ > 0.3 - 0.35), scaled-shear layer turbulence becomes independent on flow confinement as λ increases. The peak scaled shear Max[$g_d(\xi)$] can reach values that can be greater than the ones observed for free mixing layers. Despite the flow confinement, the high values of λ trigger the development of 2D large coherent structures without interaction with the 3D bed-induced turbulence. Figure 5 also shows that, when the flow confinement is fixed, and for close values of λ, the levels of scaled shear-layer turbulence are essentially driven by the lateral mean flow. For instance, when analyzing data from LNEC, D_r ~ 0.2 , with the uniform flow and the test case with a lateral flow to the FP (case -19%), the Rayleigh's inflection point criterion is fulfilled (Figure 3 left). This gives rise to large 2D coherent structures (Figure 4) and high values of Max[$g_d(\xi)$] as shown in Figure 5. By contrast, for test cases with a significant lateral flow to the MC (cases +19%, +38% and +53%), the convex velocity profiles without inflection-point are associated with very low levels of Max[$g_d(\xi)$]. Lastly, it was shown that for the whole data set, inclined bank in the MC (slope = 45°) enhances turbulent exchange, compared with the vertical one.

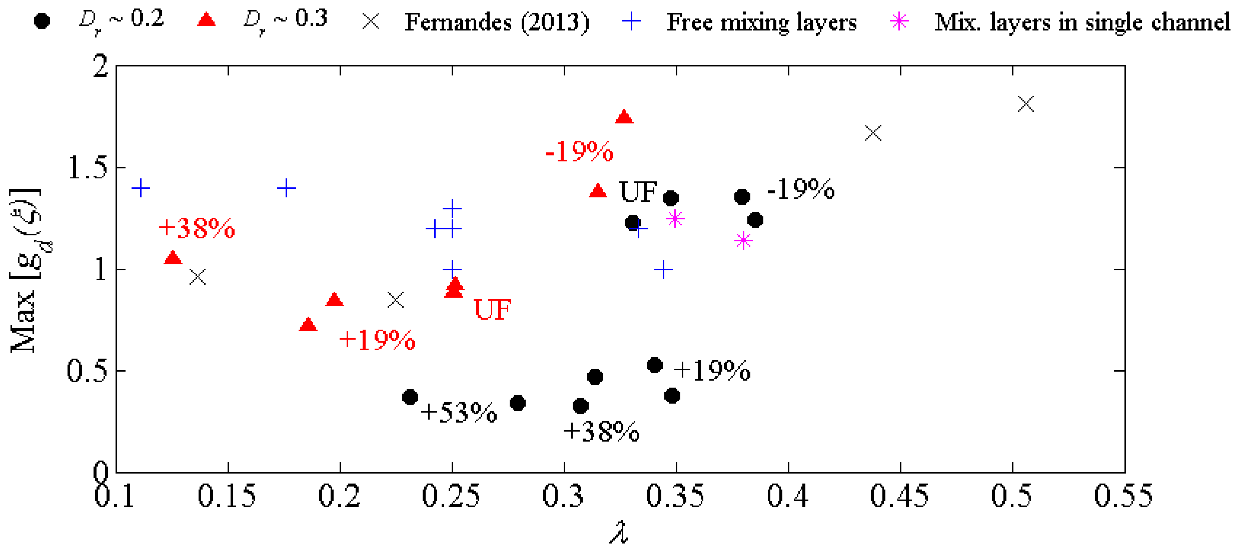

Figure 5. Peak values of scaled depth-averaged Reynolds-stress, $g_d(\xi)$, against scaled velocity difference $\lambda = U_s/(2U_c)$. (Top) LNEC, present data and uniform flows from Fernandes (2013), with D_r ~ 0.10, 0.15, 0.25 and 0.38, from right to left. (Bottom) LMFA, present data; free mixing layers (bottom): data from Oster and Wygnanski (1982), Mehta (1991), Bell and Mehta (1990), Yule (1972), Loucks and Wallace (2012); mixing layers in single open-channel from Uijttewaal and Booij (2000).

REFERENCES

Bell, J. H. and R. D. Mehta (1990). "Development of a two-stream mixing layer from tripped and untripped boundary layers." *AIAA Journal* 28(12): 2034-2042.
Chu, V. H. and S. Babarutsi (1988). "Confinement and bed-friction effects in shallow turbulent mixing layers." *Journal of Hydraulic Engineering* 114(10): 1257-1274.
Chu, V. H., J. H. Wu and R. E. Khayat (1991). "Stability of turbulent shear flows in shallow open channels." *Journal of Hydraulic Engineering* 117(10): 1370-1388.
Fernandes, J. N. (2013). Compound channel uniform and non-uniform flows with and without vegetation in the floodplain. Instituto Superior TécnicoLisboa, Universidade Técnica de Lisboa, Portugal., *PhD Thesis*.
Huerre, P. and M. Rossi (1998). “Hydrodynamic instabilities in open flows” in *Hydrodynamics and Nonlinear Instabilities*, C. Godrèche and P. Manneville, Cambridge University Press: 81-284.
Loucks, R. B. and J. M. Wallace (2012). "Velocity and velocity gradient based properties of a turbulent plane mixing layer." *Journal of Fluid Mechanics* 699: 280-319.
Mehta, R. D. (1991). "Effect of velocity ratio on plane mixing layer development: Influence of the splitter plate wake." *Experiments in Fluids* 10: 194-204.
Oster, D. and I. Wygnanski (1982). "The forced mixing layer between parallel streams." *Journal of Fluid Mechanics* 123: 91-130.
Pope, S. B. (2000). Free shear flows. *Turbulent flows*, Cambridge University Press: 139-144.
Proust, S., J. N. Fernandes, Y. Peltier, J. B. Leal, N. Rivière and A. H. Cardoso (2013). "Turbulent non-uniform flows in straight compound open-channels." *Journal of Hydraulic Research* 51(6): 656-667.
Uijttewaal, W. S. J. and R. Booij (2000). "Effects of shallowness on the development of free-surface mixing layers." *Physics of fluids* 12(2): 392-420.
Yule, A. J. (1972). Two dimensional self-preserving turbulent mixing layers at different free stream velocity ratios. *A. r. c. r. a. memoranda*, Department of the Mechanics of Fluids, University of Manchester.