HIGH-RESOLUTION NUMERICAL ANALYSIS OF TURBULENT FLOW IN STRAIGHT OPEN DUCTS WITH RECTANGULAR CROSS-SECTION

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Abstract Turbulent secondary flow in straight open ducts with rectangular cross-section are studied numerically by means of pseudo-spectral direct numerical simulation (DNS). Similarly to the corresponding closed duct flows, the mean streamwise vorticity pattern in turbulent open duct flows were found to be the statistical footprint of the most probable locations of the quasi-streamwise vortices. A major difference between the two configurations was found in the vicinity of mixed-boundary corners where noticeably persistent vortical structures exist.

KEYWORDS: open duct flow, secondary flow, coherent structure, direct numerical simulation.

BACKGROUND

Fluid flow in a straight duct with rectangular cross-section exhibits turbulence-induced secondary motion of small amplitude (few percent of the bulk velocity intensity), but with large consequences for momentum, heat and mass transport; hence the difficulties in experimental measurements and engineering significance co-exist. Much of the previous attention was paid upon the closed duct configuration with the square cross-section at marginal to moderate Reynolds numbers (e.g. [1], [2], where high-resolution direct numerical simulations were performed up to bulk Reynolds number at 3500). As the consequence, understanding in Reynolds number dependence up to a point where exhibits a clear scale separation between near-wall structures and outer-scale structures still needs to be established. Furthermore, thorough numerical investigations in aspect ratio dependence covering a range over where the flow structures start to be detached from the side-walls, to the point where the side-wall influence vanishes at the duct centre need to be achieved. Rigorous understanding in such phenomenon will, for instance, serve as a theoretical backbone of wind/water-tunnel design in fluid labs, where the side-wall effects need to be negligible at the measurement windows. The corresponding open duct flow — featuring a free surface — is characterized by a distinct secondary flow pattern, leading to such practically important effects as the so-called "dip phenomenon": the maximum of average streamwise velocity is not found at the surface of a river, but somewhat below. Although such practical importance, understanding of open duct flows is less established than the closed-duct counter part. In the present work, we investigate the mechanism of secondary flow formation in open duct flows. Here, free-surface deformation is neglected by enforcing the planer free-slip boundary condition on the top boundary. Particular emphasis in our analysis is placed upon the dynamics of coherent structures and the consequences for Reynolds number and aspect-ratio scaling.

COMPUTATIONAL SET-UP

For the purpose of current studies, the pseudo-spectral DNS code previously used in the several studies in closed square duct flows [1, 2, 3] has been extended to incorporate free-slip boundary condition. The code integrates the Navier-Stokes equations by expanding flow variables in terms of truncated Fourier series in the streamwise direction on equidistant grid points, while Chebyshev polynomials are used in the two cross-stream directions on collocated Chebyshev–Gauss–Lobatto points. A fractional step method is employed in order to decouple the momentum equations from the continuity constraint. The temporal integration is based on the Crank–Nicolson scheme for the viscous terms and a three-step low-storage Runge–Kutta method for the nonlinear terms.

We performed direct numerical simulations on open duct flows over a range of aspect ratio from 0.5 to 8, and bulk Reynolds number from 2205 to 4920. For each simulation, the turbulent fields are averaged typically over 8000 H/U_b, where U_b is bulk velocity and H is duct height, to ensure reliable statistics.

RESULTS

We have identified the centres of vortical structures by the technique proposed by Kida & Miura [4] for the open duct case at bulk Reynolds number $Re_b = 2205$ with the aspect ratio set at unity. It was found that the mean streamwise vorticity pattern in the turbulent open duct flows is the statistical footprint of the most probable locations of the quasi-streamwise vortices, similarly to the corresponding closed duct cases (cf. Figure 1, also [1, 2]). There is, however, a significant difference between the open and the closed duct statistics, which is the tightly-concentrated vortices with preferable rotational directions that exist in the mixed-boundary corners. Our results show that those vortices persist in the mixed-boundary corners much more likely than anywhere else in the duct domain. This finding is consistent with those low-speed streaks restricted near mixed-boundary corners found experimentally by Grega et al. [5]. We have also investigated the aspect ratio dependence of the secondary flow intensity, where the ratio ranges from 0.5 to 8.0. It was found that with the aspect ratio larger than 2.0, the secondary flow intensity scales with the distance away from the side-walls normalised by the duct hight up to $z/H \approx 1.7$, then decays exponentially at different rates depending on the aspect ratio. Our results show that the decay rate becomes smaller (i.e. the intensity decays slower) as the aspect ratio becomes larger.

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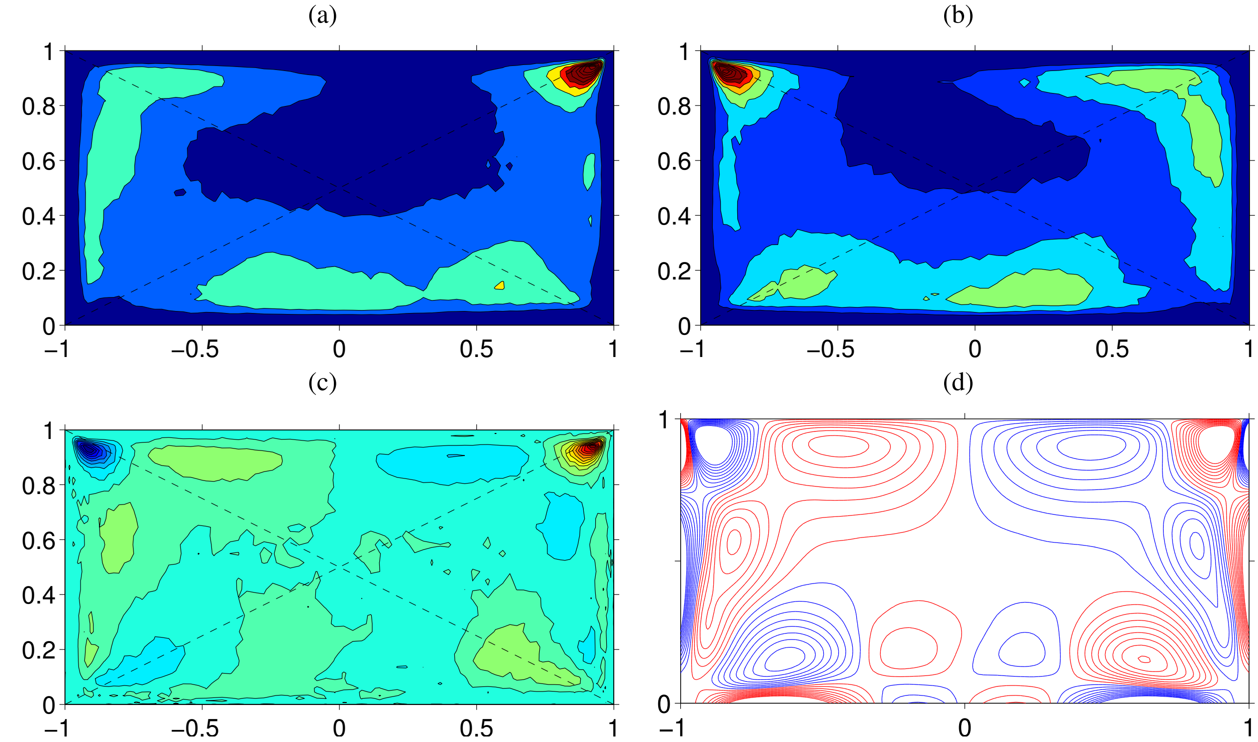

Figure 1. Probability of occurrence of vortex centres for the open duct case with $Re_b = 2205$, detected by the technique proposed by Kida & Miura [4]. (a) *positive* streamwise vorticity; (b) *negative* streamwise vorticity; and (c) the difference of (a) and (b). The iso-contours indicate 0.1(0.1)0.9 times the maximum values (except (c), where the contour-level is doubled). The probabilistic data (a)-(c) were accumulated from 1000 instantaneous snapshots over a time interval of $\approx 721.5H/U_b$. (d) Mean streamwise vorticity contours indicate -0.9(0.1)0.9 times the maximum absolute value where red and blue lines correspond to positive and negative values. The vorticity field was averaged over a time interval of $\approx 8000H/U_b$.

References

[1] Uhlmann, M., Pinelli, A., Kawahara, G., and Sekimoto, A. Marginally turbulent flow in a square duct. *J. Fluid Mech.* **588**: 153–162, 2007.

[2] Pinelli, A., Uhlmann, M., Sekimoto, A. and Kawahara, G. Reynolds number dependence of mean flow structure in square duct turbulence. *J. Fluid Mech.* **644**: 107–122, 2010.

[3] Sekimoto, A., Kawahara, G. Sekiyama, K., Uhlmann, M. and Pinelli, A. Turbulence- and buoyancy-driven secondary flow in a horizontal square duct heated from below. *Phys. Fluids* **23**: 75–103, 2011.

[4] Kida, S. and Miura, H. Swirl condition in low-pressure vortices. *J. Phys. Soc. Japan* **7**: 2166–2169, 1998.

[5] Grega, L. M., Wei, T., Leighton, R. I. and Neves, J. C. Turbulent mixed-boundary flow in a corner formed by a solid wall and a free surface. *J. Fluid Mech.* **294**: 17–46, 1995.