Flow around a 5:1 rectangular cylinder: effects of corner roundings

A. Mariotti, B. Rocchio, E. Pasqualetto, C. Mannini, and M.V. Salvetti

1 Introduction

The high Reynolds number flow around a rectangular cylinder, having chord-to-depth ratio equal to 5, is the object of the benchmark BARC. This configuration is of practical interest, e.g. in civil engineering, and, in spite of the simple geometry, the related flow dynamics and topology is complex. The experimental and numerical results obtained by the contributors during the first four years of activity were reviewed in [1]. Good agreement between different results in terms of near-wake flow, base pressure and drag coefficient was found. However, it was observed that some quantities of interest, as the standard deviation of the lift coefficient or the distribution of mean and fluctuating pressure on the cylinder sides, are affected by a significant dispersion, both in experiments and in simulations.

Sensitivity analyses carried out by the BARC contributors were not conclusive to explain the observed dispersion; rather, in some cases, they led to controversial results (see e.g. [2, 3, 4, 5, 6]). In particular, a crucial quantity is the length of the mean recirculation regions forming on the lateral sides of the cylinder, which in turns are related with the pressure distribution on the cylinder side and the oscillating loads. Wind tunnel tests [5] clearly showed that in for a low intensity of the freestream turbulence the time-averaged location of the point of flow reattachment is close to the downstream edges. On the other hand, the study carried out in [2] indicated that increasing grid resolution in the spanwise direction led to a significant reduction of the recirculation region mean length and thus to a deterioration of the agreement with the experiments. This was recently confirmed in [4] by a stochastic analysis of

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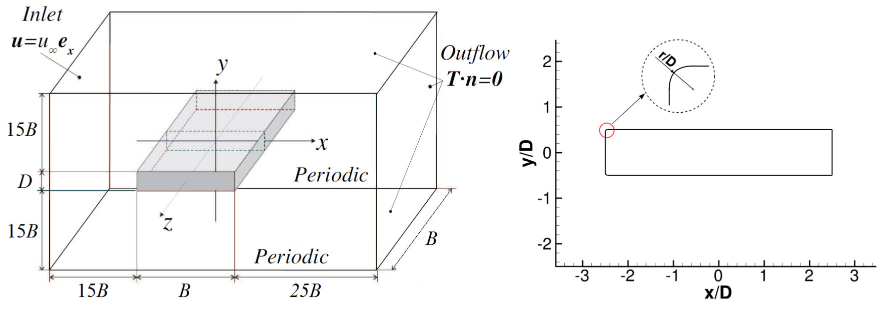
the sensitivity of LES results to grid resolution in the spanwise direction and to the amount of subgrid scale (SGS) dissipation. Indeed, it was observed that numerical simulations tend to underpredict significantly the distance from the upstream corners at which the mean flow reattachment occurs, either for a fine discretization in the spanwise direction or for a low SGS dissipation.

The present work aims at shedding some light on this counter-intuitive behavior of the numerical simulations. In particular, it was shown in [4] that the length of the mean recirculation bubble on the cylinder side is strictly connected with the location at which the shear layers separating from the upstream corners lose coherence and roll-up in vortical structures. Simulations with low SGS dissipation and highly refined grids were characterized by early roll-up and by small vortical structures. Following this result, additional simulations are carried out to investigate the effect of a small rounding in the upstream corners of the rectangular cylinder. We want to investigate whether the presence of perfectly sharp corners can generate some disturbances which are not damped in numerical simulations characterized by low numerical and SGS dissipation as the present ones, which may in turn lead to a premature instability of the shear layers.

2 Numerical methodology and simulation set up

LES simulations are carried out for the incompressible flow around a fixed rectangular cylinder with a chord-to-depth ratio, B/D, equal to 5. The angle of attack is zero. The computational domain is sketched in Fig. 1. A uniform velocity profile is imposed at the inflow (no turbulence), while no-slip conditions are applied at the solid walls. Periodic conditions are imposed in the spanwise direction, while traction-free boundary conditions are used at the outflow and on the remaining lateral sides of the computational domain. Finally, the Reynolds number based on the free-stream velocity and on the cylinder depth, Re, is equal to 40000. The simula-



(a) (b)

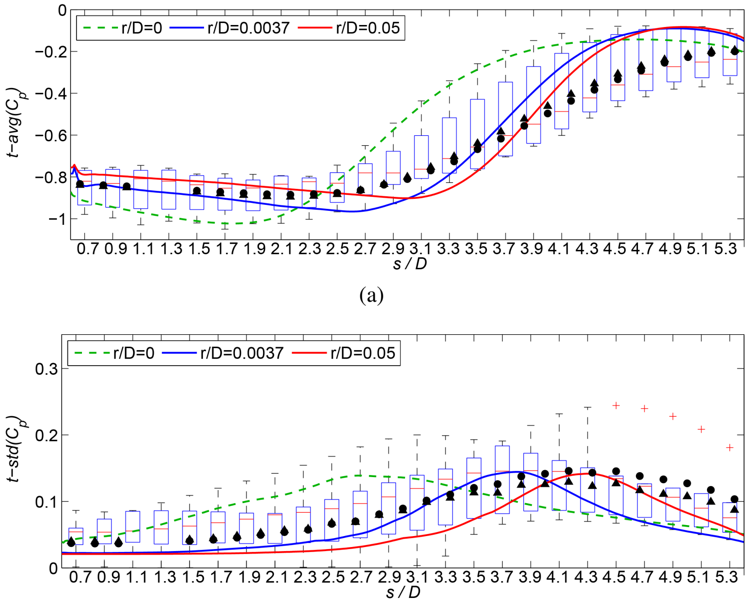
Fig. 1 Sketch of the computational domain (a) and of the upstream corner rounding (b) tions are carried out through an open-source code, Nek5000, based on a high-order accurate spectral-element method. The order of the Legendre polynomials used as basis functions inside each element is kept herein constant $N = 6$. The grid resolution in the streamwise and and lateral directions is $\Delta x = \Delta y = 0.125D$. The grid resolution in the spanwise direction, defined in terms of the average element size, is $\Delta z = 0.558D$, and the weight of the explicit filter, $w = 0.05$. These values are the same as in one of the 13 simulations in [4] having a short mean recirculation region. The parameters chosen for the sensitivity analysis is the rounding of the upstream corners, r/D. The values $r/D = 0.003$ and $r/D = 0.05$ are considered.

As for the LES formulation, a simple approach based on the application of a low-pass explicit filter in the modal space, which is characterized by a cut-off k_c, here equal to $N-3$, and by a weight w, is adopted (see [4] for more details). This modal filter provides a dissipation in the resolved modes that are higher than the cut-off value, and can be interpreted as a SGS dissipation.

3 Results and discussion

The numerical results are first compared to the experimental ones in terms of mean pressure coefficient distribution and its standard deviation over the lateral side of the cylinder (Fig. 2). The pressure coefficient is averaged in time, in the spanwise direction and between the upper and lower half perimeters of the cylinder, and it is denoted as $t-avg(C_p)$; the same holds for the relative standard deviation, $t-std(C_p)$. The local abscissa, s, is the distance from the cylinder stagnation point measured along the cylinder side. The results of the simulations carried out with $r/D = 0.0037$ and $r/D = 0.05$ are characterized by a mean pressure distribution occurring significantly more downstream compared to the simulation with the same numerical set-up and sharp corners. In particular, the simulation having the smaller value of the rounding is in good agreement with the ensemble of the BARC experiments, whereas the mean pressure recovery is moved too downstream in the simulation with large roundings. The position of the maximum of the standard deviation of the C_p along the lateral side of the cylinder, which is directly related with the length of the mean recirculation region, is also moved downstream for increasing rounding values.

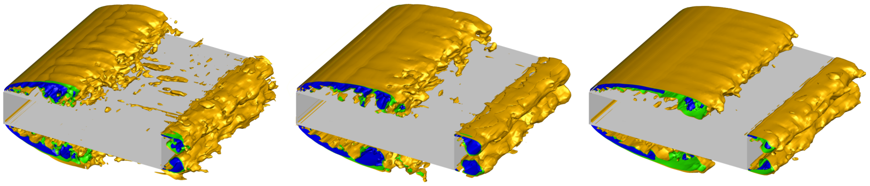
The increase of the rounding curvature radius produces an increased length of the main recirculation region on the cylinder sides, as can be seen in Fig. 3 by means of the time-averaged vortex indicator λ_2. It should also be noted that a very small corner rounding, i.e. $r/D = 0.0037$, is enough to significantly change the shear layer dynamics compared with sharp edges, $r/D = 0$, as can be seen in Figs. 4−6. First, for the simulations with roundings, the time and spanwise-averaged turbulent kinetic energy (see Fig. 4b,c) starts to be significant in the shear layers detaching from the usptream corners more downstream, while in the simulation $r/D = 0$ is starts to be high very close to the sharp corners (see Fig. 4a), i.e. in the latter case the turbulent fluctuations in the upstream part of the shear layers are much higher than



(a)

(b)

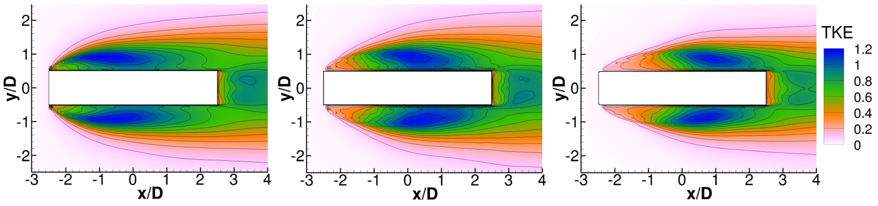
Fig. 2 Mean pressure coefficient (a) and standard deviation (b) on the lateral sides of the cross section for the different values of the corner roundings (both averaged in spanwise direction). A comparison is provided with the case with sharp corners [4], the ensemble statistics of the BARC experiments [1] and the experimental data in [5] (circles and triangles refer respectively to $Re = 56700$ and 112200).



(a) (b) (c)

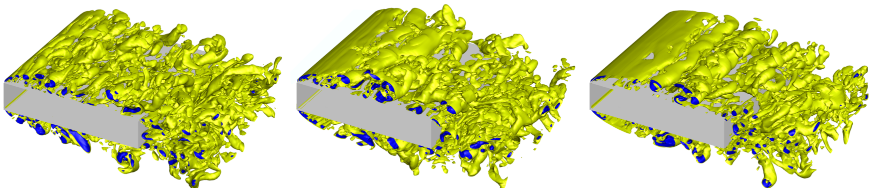
Fig. 3 Isosurfaces of the time-averaged vortex indicator λ_2: $r/D = 0$ (a) from [4], $r/D = 0.0037$ (b) and $r/D = 0.05$ (c).

for the simulations with roundings. This behavior is related to the dynamics of the vorticity contained in the shear layers. Indeed, from the analysis of the isosurfaces of the instantaneous vortex indicator λ_2 (see Fig. 5) and of its distribution in the plane section $z = 0$ (see Fig. 6) it is evident that increasing the corner roundings the detaching shear layers remain coherent up to a significantly more downstream position than the one obtained with sharp edges,in which they roll up in small vortical structures already near the upstream corners.



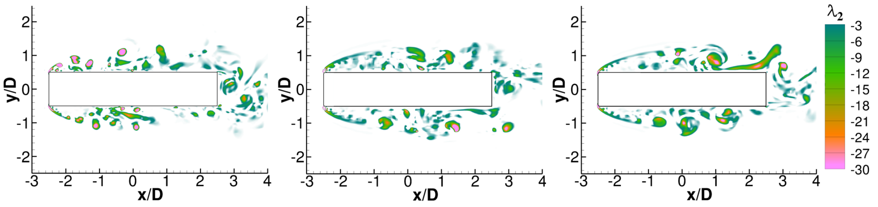
(a) (b) (c)

Fig. 4 Time- and spanwise-averaged turbulent kinetic energy: $r/D = 0$ (a) from [4], $r/D = 0.0037$ (b) and $r/D = 0.05$ (c).



(a) (b) (c)

Fig. 5 Isosurfaces of the instantaneous vortex indicator λ_2: $r/D = 0$ (a) from [4], $r/D = 0.0037$ (b) and $r/D = 0.05$ (c).



(a) (b) (c)

Fig. 6 Isosurfaces of the instantaneous vortex indicator λ_2 on the plane $z = 0$: $r/D = 0$ (a) from [4], $r/D = 0.0037$ (b) and $r/D = 0.05$ (c).

A very small value of the curvature radius of the corner roundings – which would be hard to be detected in experiments unless ad-hoc diagnostic techniques are employed – is enough to change the scenario and to significantly improve the agreement with the experiments. Indeed, a premature instability of the shear layers, leading to a too short mean recirculation zone, may be originated by small perturbations introduced by non-realistic perfectly sharp corners, which in highly-resolved LES are not damped by numerical or SGS dissipation. In this framework, a systematic analysis of the sensitivity of LES results to the upstream corner sharpness could be the object of future investigations and, to this aim, a stochastic approach could be suitable.

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