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CFD ANALYSIS OF BLOCKAGE EFFECT FOR RECTANGULAR CYLINDERS IN WIND TUNNEL FLOW

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Abstract: *The blockage effect, arising from the confinement of flow by solid walls in wind tunnel testing, can significantly influence the aerodynamics of bluff bodies. In this study, its impact is numerically investigated using 2D RANS simulations of flow around rectangular cylinders with a side ratio of 2:1 at various angles of attack. The simulations were performed in computational domains with different distances between the upper and lower boundaries to represent varying levels of blockage. Key aerodynamic quantities, including mean drag, lift, and moment coefficients, were evaluated. Results obtained in domains with significant blockage were corrected using the Maskell method and compared with reference simulations in domains where blockage effects are negligible.*

Keywords: U-profile, Blockage effect, RANS simulation, Aerodynamic characteristics, Maskell correction

1. Introduction

Experimental data obtained in wind tunnels can be affected by the blockage effect, which occurs when the presence of a bluff body reduces cross-sectional area of the tunnel. This phenomenon often leads to the increase of the local airflow velocity resulting in discrepancies in aerodynamic quantities and to the distortion of the flow characteristics. When the blockage ratio - defined as the ratio of the body's frontal area to the tunnel cross-section- exceeds a threshold (typically 5 %) the application of appropriate correction is recommended (cf. Koloušek et. al 1983). A widely adopted approach is the Maskell correction (Maskell, 1965)

$$\frac{C_{Ff}}{C_F} = \frac{1}{1+\varepsilon C_D S/A} \tag{1}$$

where C_{Ff} represents the corrected force (drag C_D, lift C_L or moment C_M) coefficient, C_F is uncorrected force coefficient, C_D is uncorrected drag coefficient, S is frontal area of the body, A is the tunnel cross section area and ε is the blockage correction parameter related to a shape of the body. In this study, the correction parameter $\varepsilon = 0.83$ valid for rectangular cross section with side ratio equal to 2 was adopted.

To systematically investigate the blockage effect, RANS k–ω SST simulations were carried out for two rectangles ($B \times D$ = 300 × 150 mm and 150 × 75 mm, where B denotes the width and D the height of the body). The simulations were performed in a computational domain replicating the dimensions of the Vincenc Strouhal climatic wind tunnel at the Institute of Theoretical and Applied Mechanics of the Czech

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Academy of Sciences (cf. Hračov and Macháček, 2023), as well as in an enlarged domain representing conditions with a negligible blockage ratio.

2. Computational settings

The simulations involved a 2:1 rectangles positioned at various angles of inclination (0°–12°) within the computational domain (cf. Figure 1a). The wall spacing of the domain, *w*, was varied: for the larger rectangle*, w* was set to 1.9 m (corresponding to the actual tunnel width) and 7.5 m (unconfined reference case); for the smaller rectangle*, w* was 1.9 m and 3.75 m. The blockage ratios, *S/A*, related to each analyzed case are summarized in Table 1.

Tab. 1: Blockage ratio for rectangular cylinders at different inclination in computational domains. (Values exceeding recommended value 5% are marked in bold.)

Width of domain w	**Angle of attack [°]**					
	0	2.5	5	7.5	10	12
1.9 m large rectangle	**7.9%**	**8.6%**	**9.2%**	**9.9%**	**10.5%**	**11.0%**
7.5 m large rectangle	2.0%	2.2%	2.3%	2.5%	2.7%	2.8%
1.9 m small rectangle	3.9%	4.3%	4.6%	4.9%	**5.3%**	**5.5%**
3.75 m small rectangle	2.0%	2.2%	2.3%	2.5%	2.7%	2.8%

A hybrid mesh was employed to ensure high near-wall resolution while maintaining a reasonable computational cost. Two computational meshes with different structures were used to verify mesh independence. The resulting aerodynamic coefficients showed only slight differences. The mesh structure used for all subsequent computations is described below. The boundary layer around the rectangular cylinder consists of 16 layers of quadrilateral elements with an expansion ratio of 1.23 and a first-layer thickness of 1×10^{-5} m and 5×10^{-6} m for the larger and smaller rectangles, respectively, ensuring that the dimensionless wall resolution remains below one over most of the perimeter. This boundary layer is followed by 13 layers of a structured quadrilateral mesh extending to a distance of 10 mm and 5 mm from the walls of the larger and smaller rectangles, respectively. Within this quadrilateral region, the ratio of the thickness of the first to the last element is 6, while the longer and shorter sides of the rectangle are discretized using 100 and 50 elements, respectively. The arrangement of the boundary layer and the quadrilateral mesh is illustrated in Figure 1d.

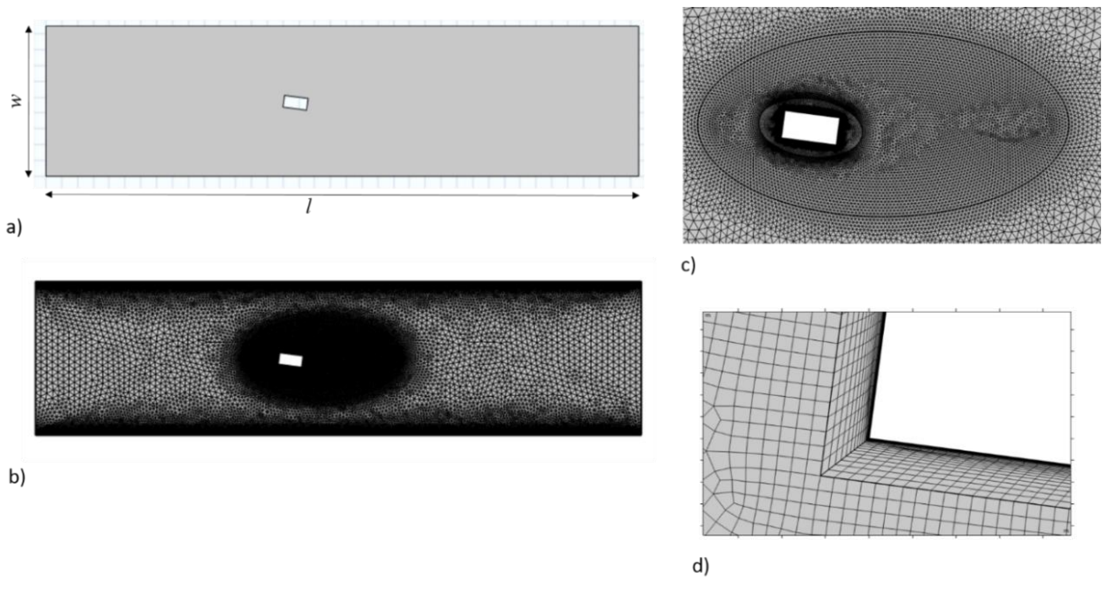

Fig. 1: a) Rectangle 2:1 in the computational domain, b) computational mesh, c) detail of the meshed wake, d) boundary layer on the walls of rectangle.

Two auxiliary ellipses were employed in the mesh generation process, with semi-axis lengths of 0.28 m and 0.205 m for the smaller ellipse, and 1 m and 0.5 m for the larger ellipse. Within the smaller ellipse, an unstructured quadrilateral mesh with a maximum element size of 0.01 m was used, transitioning into a triangular mesh with a maximum element size of 0.02 m in the larger ellipse, thereby ensuring adequate resolution of the wake behind the rectangle (cf. Figure 1c). The length of the finely resolved wake corresponds to four times the characteristic length of the rectangle, *B*. A boundary layer consisting of six layers with an expansion ratio of 1.23 and a total thickness of 0.02 m was applied near the top and bottom walls of the computational domain, while the remaining regions were discretized using a coarser triangular mesh, as shown in Figure 1b. Regarding the boundary conditions, a no-slip condition was applied to all solid surfaces, including both the model and the confining wind tunnel walls. A zero-pressure condition was prescribed at the outlet, while a uniform inlet velocity of $v = 14$ m/s (corresponding to $Re=1.4x10^5$) and a turbulence intensity of 1% were imposed, corresponding to the parameters used in the reference experiments (Hračov and Macháček, 2023).

3. Results

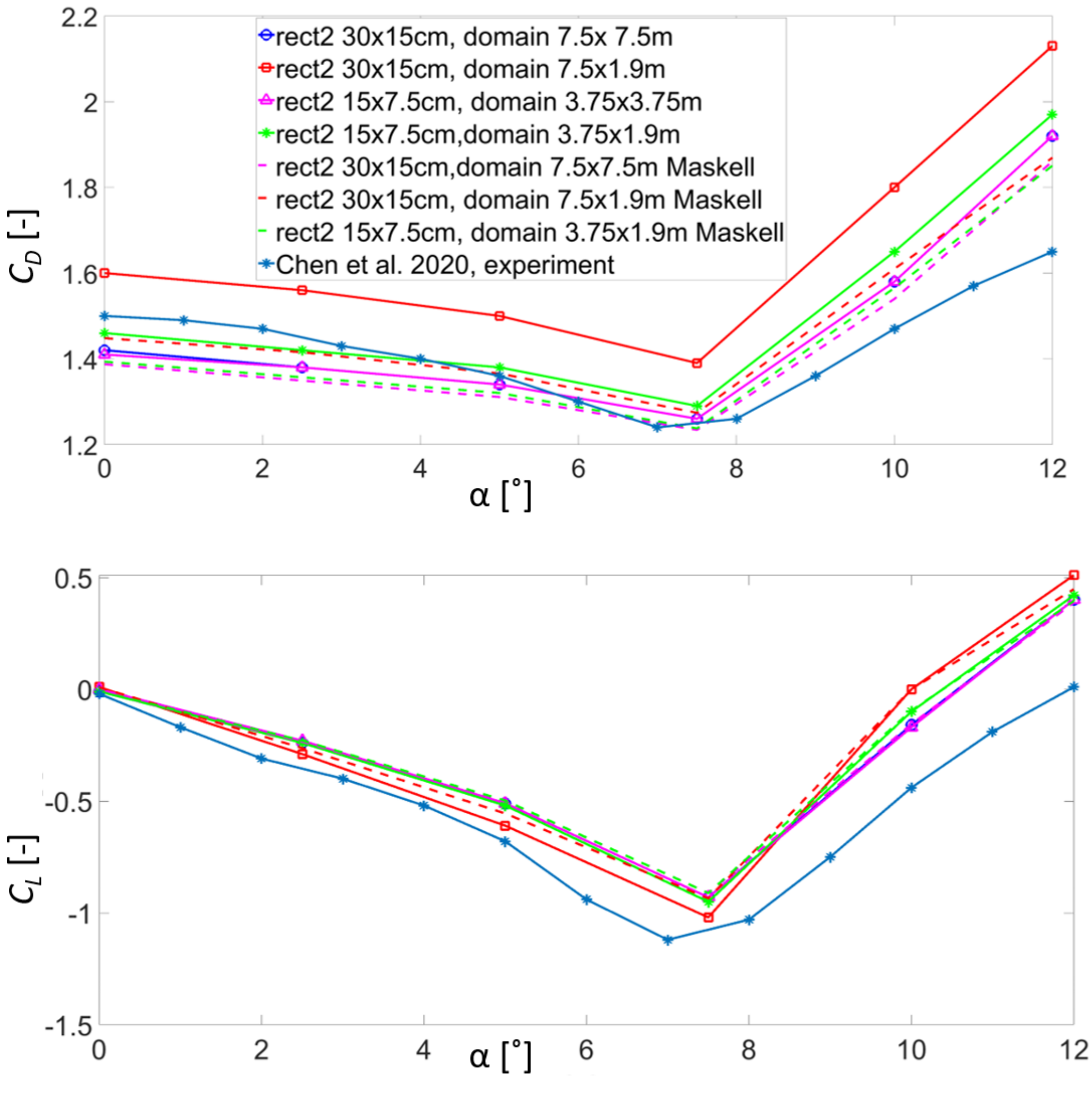

Fig 2: Drag and lift coefficients vs. angle of wind attack under different blockage conditions, before and after Maskell correction.

The aerodynamic characteristics, including the mean drag, lift, and moment coefficients (C_D, C_L and C_M) were evaluated for both rectangle scales and various computational domain widths. As illustrated in Figure 2, the mean aerodynamic coefficients for the larger and smaller rectangles show no significant deviation in domains where the blockage effect is below 3%. This consistency confirms the scalability of the numerical approach under unconfined flow conditions. To compare calculated values with experiment, experimental drag and lift coefficient data, obtained by Chen et al. (2020) for a rectangle 12x6 cm within a 1.2 m wide tunnel at Re=6x10^4, are also plotted in Figure 2.

The application of the Maskell correction method (dashed curves in Figure 2) to cases with non-negligible blockage ratios resulted in values approaching those obtained for domains with negligible blockage, cf. Table 2.

Tab. 2: Relative error of the drag coefficient for selected angles of attack. Reference values consist of aerodynamic coefficients for small rectangle in unconfined domain (uncorrected for columns 1–2; adjusted by Maskell's correction for columns 3–4).

	Large rect. non corrected	Small rect. non corrected	Large rect. Maskell	Small rect. Maskell
0˚	13.4%	9.6%	5.1%	1.1%
5˚	11.9%	8.9%	4.1%	0.7%
10˚	13.9%	8.8%%	3.2%	1.6%

4. Conclusions

This study presents a numerical investigation of the wind tunnel blockage effect on the aerodynamic characteristics of sharp-edged rectangular cylinders with a 2:1 aspect ratio. By comparing results across different domain widths, it was demonstrated that inaccuracies due to blockage effects become significant when the blockage ratio exceeds approximately 5%, in accordance with established aerodynamic theories.

Following the application of the Maskell correction, the corrected drag and lift coefficients showed improved agreement with results obtained from unconfined domains, confirming the method's reliability for adjusting global aerodynamic forces.

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