Materials Research Proceedings 69 (2026) 227-232 https://doi.org/10.21741/9781644904251-40

Blockage Effects in Wind Tunnel Experiments of Turbulent Wakes: A Numerical Study

Gianluca PORPORA[1,a *] and Andrea PALUMBO[1,b]

[1]Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza Università di Roma, Via Eudossiana 18, 00184 Roma, Italy

[a]gianluca.porpora@uniroma1.it, [b]andrea.palumbo@uniroma1.it

Keywords: Computational Fluid Dynamics, Separated Flows, Wind Tunnel Blockage

Abstract. In many industrial applications, turbulent flow past bluff bodies separates, causing aerodynamic forces unsteadiness, structural vibrations, and noise. Wind tunnel experiments are commonly used to study wake dynamics, evaluate aerodynamic coefficients and perform spectral analyses. However, wind tunnel walls may significantly alter the wake topology, thereby leading to biased measurements. Predictive formulae for the effect of confinement are mainly available for simple bodies, such as circular and square cylinders. This study investigates the influence of wall confinement on the turbulent wake behind a missile-shaped airfoil using unsteady Reynolds-averaged Navier–Stokes (URANS) simulations. The analysis is performed at moderate Reynolds numbers and for various blockage ratios. Results show that drag, lift fluctuations, and shedding frequency all increase monotonically with blockage ratio. These findings extend previous observations on laminar confined wakes to turbulent bluff-body wakes, underscoring the importance of designing proper wind tunnel experiments.

Introduction

Flow unsteadiness behind bluff bodies is a critical issue in aerospace applications, as the shedding of vortical structures can affect vehicle performance, structural integrity, and generate acoustic emissions. Those phenomena are often the effects of vortical structures generated in the separated region behind the body. Numerous passive and active flow-control strategies have been proposed, whose design requires accurate knowledge of the characteristic frequency and spatial pattern of the wake structures.

Wind tunnel experiments have been the main source of knowledge about separated flows behind bluff bodies. However, the physical significance of those studies may be questioned when the separated flow dynamics is strongly influenced by the bounding walls of the test section. As demonstrated in [1], lateral walls can strongly affect experimental measurements, as confinement modifies both the mean flow topology and the large-scale wake dynamics. Moreover, blockage effects may alter vortex shedding frequencies, distort aerodynamic forces, and even promote coherent structures that are absent in unconfined conditions. Those long standing issues have been the object of several studies, as recently reviewed by [2].

Extensive studies have been performed for canonical geometries such as circular [3, 4, 5] and square [6, 7, 8] cylinders. Those studies span a very wide range of flow conditions, from very low-Reynolds number laminar flows, to subcritical/supercritical turbulent flow regimes. All those studies do recognize a strong effect of blockage on aerodynamic coefficients and their characteristic frequency (which is properly scaled to form a non-dimensional group, known as Strouhal number). By contrast, other geometries as elongated or rectangular bluff bodies have received less attention, despite their relevance for practical aerodynamic design. Addressing the lack of research on this topic may be particularly important because accurate wind tunnel measurements must account for confinement effects while still satisfying similarity laws.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 license. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under license by Materials Research Forum LLC.

Materials Research Proceedings 69 (2026) 227-232 https://doi.org/10.21741/9781644904251-40

In this study, unsteady Reynolds-averaged Navier–Stokes (URANS) simulations are em ployed to characterize the influence of wall confinement on the turbulent wake past a D shaped cylinder in subcritical conditions. Fully resolved simulations as direct numerical simulations or wall-resolved large eddy simulations would be computationally prohibitive, and dedicated experimental facilities quite demanding. In this sense, URANS computations provide a low-fidelity tool, able to obtain the unsteady distributions of drag and lift coeffi cients in relatively short time and with good accuracy. Blockage ratio, defined as the ratio between the thickness of the body and the wind tunnel crosswise width, is varied between 2% and 25%. The present study allows a systematic assessment of confinement effects in turbulent bluff-body wakes and provides insights for the design and interpretation of wind tunnel experiments. Specifically, we aim at investigating confinement effects on the time averaged value of the drag, lift fluctuations variance, and Strouhal number.

Methodology

The two-dimensional turbulent wake behind a thick flat plate in a confined wind tunnel is numerically analyzed by means of URANS simulations. The flow configuration under study is sketched in Fig. 1. It consists of an elongated D-shaped cylinder with aspect ratio $A = c/H = 10$, where *c* is the chord length and *H* is the trailing edge thickness. The longitudinal axis of the body lies along the mid-plane of a two-dimensional plane channel. The leading edge of the body is rounded in the form of a semi-ellipse, transitioning into a thick flat plate that terminates with a blunt trailing edge. This setup mimics the longitudinal mid-plane of a wind tunnel configuration, where the test model spans the full tunnel width in the spanwise direction.

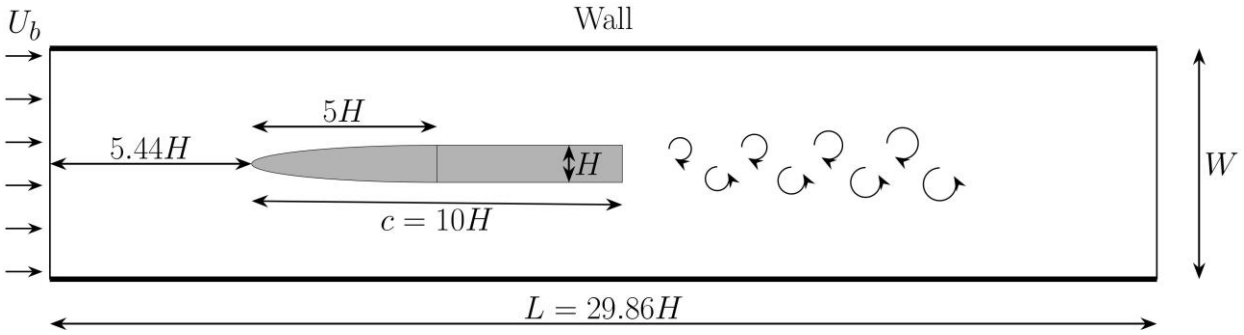


Figure 1: Sketch of the numerical setup and main notation used in this study.

The computational domain extends for a $L = 29.86H$ length in the streamwise direction, while the transverse width W is varied to analyze blockage effects. The plate leading edge is placed $5.44H$ downstream from the inflow section, where a uniform velocity profile is imposed. The governing equations considered in this work are the incompressible Navier-Stokes equations, made dimensionless using the bulk velocity U_b and the plate thickness H. This configuration is completely characterized by two non-dimensional parameters, namely the Reynolds number $Re = U_b H/\nu$ and the blockage ratio $B = H/W$. A fixed Reynolds number of $Re = 32000$ is considered in this work, with blockage ratios varying in the range $2\% < B < 25\%$ ($W/H \in [4,50]$). The present numerical setup allows direct comparison with the previous work [9], which investigated the same configuration, at the same Reynolds numbers for a single blockage ratio $B \approx 0.16$.

Simulations are performed with the OpenFOAM solver *pimpleFoam* [10] using the $k-\omega$ SST model [11]. Body-fitted meshhed are generated with the native OpenFOAM mesher *snappyHexMesh*. Fig. 2 shows the numerical mesh used to investigate the confined flow at $B = 0.16$. The figure highlights the wake refinement and the prismatic layers introduced on the body and the wind tunnel lateral walls. Near-wall mesh clustering ensures resolutions of $y^+ \approx 1$ on the

Materials Research Proceedings 69 (2026) 227-232 https://doi.org/10.21741/9781644904251-40

lateral walls and $y^+ \approx 0.5$ on the body. Within this framework, governing equations are spatially discretized using second-order schemes for p and U, whereas turbulent quantities are discretized using first-order upwind schemes. Time integration is performed with a second-order implicit scheme. Pressure-velocity coupling is handled with the PIMPLE algorithm, which merges the SIMPLE (semi-implicit method for pressure linked equations) and PISO (pressure implicit with split operator) [12]. At the inlet, a uniform velocity is prescribed, whereas the turbulent variables are obtained by fixing the inflow turbulence intensity to 2%.

The main output of the work ist o quantify blockage effects on the aerodynamic force coefficients, namely the aerodynamic drag coefficient $C_D = 2D/(\rho U_B^2 H)$ and the aerodynamic lift coefficient $C_L = 2L/(\rho U_B^2 H)$. Those quantities are obtained as the projection oft he aerodynamic force along the x and y axes. In this work, we mainly refer to the time-averaged drag coefficient $\overline{C_D}$, the lift coefficient root-mean square C_L' and their characteristic Strouhal number $S_t = fH/U_b$. The aerodynamic coefficients are sampled once the flow have reached a saturated vortex-shedding regime, and the Strouhal number is obtained as the peak of the lift frequency spectra.

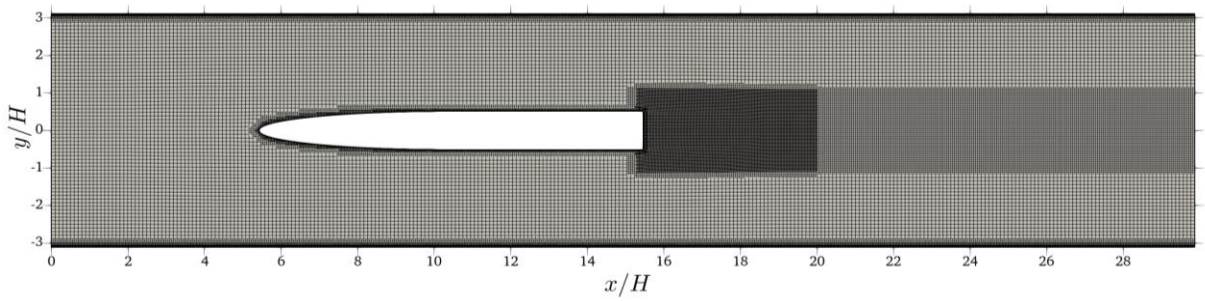


Figure 2: Mesh employed for the numerical analysis. Blockage ratio B=0.16.

Results

Fig. 3 shows the variation of the mean drag coefficient $\overline{C_D}$, with blockage ratio. We can distinguish two different trends as B is increased. For low blockage ratios ($B < 0.04$), $\overline{C_D}$ remains nearly constant. Outside of this range, the drag coefficient start deviating from its unconfined value, with an increasing slope as B increases. The present trend appears to be in very good agreement with the previous simulation by [9] in the same flow conditions.

The difference between the confined and the unconfined drag coefficient value exceed 3% for $B > 6\%$. Similar results have been reviewed by [2] for circular and square cylinders in both laminar and turbulent regimes. Hence, the present geometry appears to follow the same trend shown in those cases. However, for the thick D-shaped plate the viscous contribution to $\overline{C_D}$ should be larger than in the circular cylinder case making a direct quantitative comparison non readily available.

Materials Research Proceedings 69 (2026) 227-232 https://doi.org/10.21741/9781644904251-40

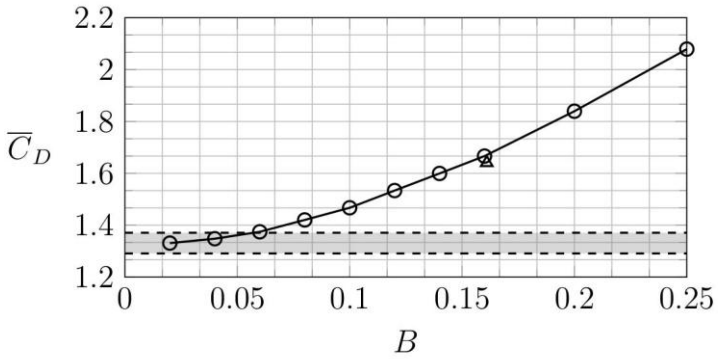


Figure 3: Time-averaged drag coefficient as function of blockage ratio B. Dashed lines represent ±3% difference band with respect to $\overline{C_D}$ at B=0.02. A triangle mark denotes the URANS results by [9] at B=1/6.2.

Fig.4 shows the standard deviation of the lift coefficient, C_L', which quantifies the intensity of unsteady lift fluctuations induced by vortex shedding, as a function of the blockage ratio B. For small blockage ratios $B < 0.04$, the variation of fluctuating lift coefficient remains weak, whereas at higher blockage ratios the growth becomes stronger, reflecting the increasing influence of wall confinement. The growth is monotonic, indicating that confinement amplifies the strength of the periodic vortex shedding, thereby increasing the unsteady aerodynamic loads on the body. This result is in very good agreement with turbulent wakes at subcritical Reynolds number (as reported in [2]) and, as expected, in contrast with laminar wakes and turbulent wakes in supercritical conditions.

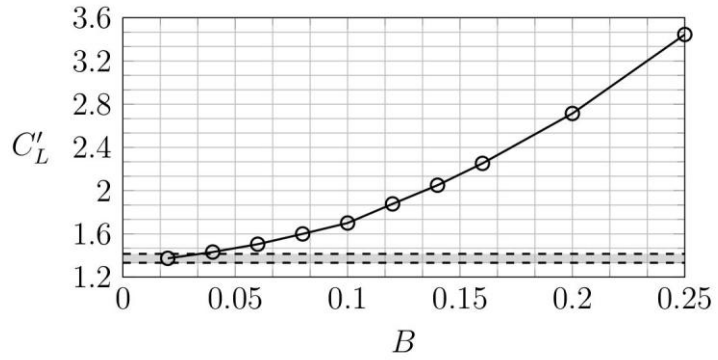


Figure 4: Lift coefficient root-mean-square C_L' as a function of blockage ratio B. Dashed lines represent ±3% difference band with respect to C_L' at B=0.02.

The dependence on B of the Strouhal number St is illustrated in Fig.5. The value of the Strouhal number is in excellent agreement with the experimental value found by [9] using particle image velocimetry (triangle mark in Fig.5). The present results show that St increases monotonically with B. Specifically, for very low blockage ratios $B < 0.1$, St is weakly influenced by confinement, consistent with observations summarized in [2]. The overall observed trend in Strouhal number well conforms with previous findings from circular and square cylinders in both laminar and turbulent regimes.

Finally, Fig. 6 shows an instantaneous snapshot of the vorticity field for $B = 0.16$. The classical vortex shedding is still visible, however their trajectory is closer to the x axis if compared with unconfined flow. A large amount of vorticity is also observed next to the wind tunnel walls, which is connected to boundary layer thickening and instantaneous lift-off of fluid from the near-wall region.

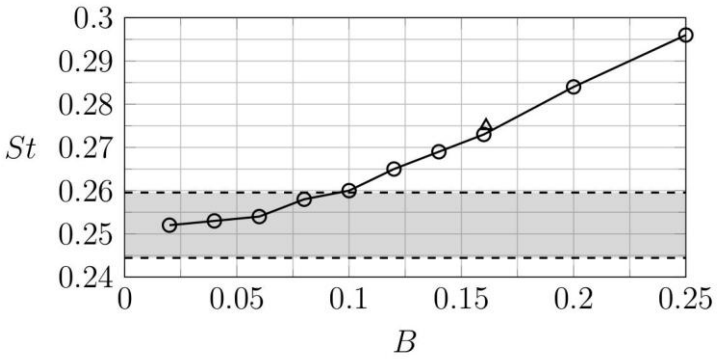


*Figure 5: Stouhal number as a function of blockage ratio **B**. Dashed lines represent ±3% difference band with respect to St at B=0.02. The triangle marker reports the experimental value of the Strouhal number obtained by [9].*

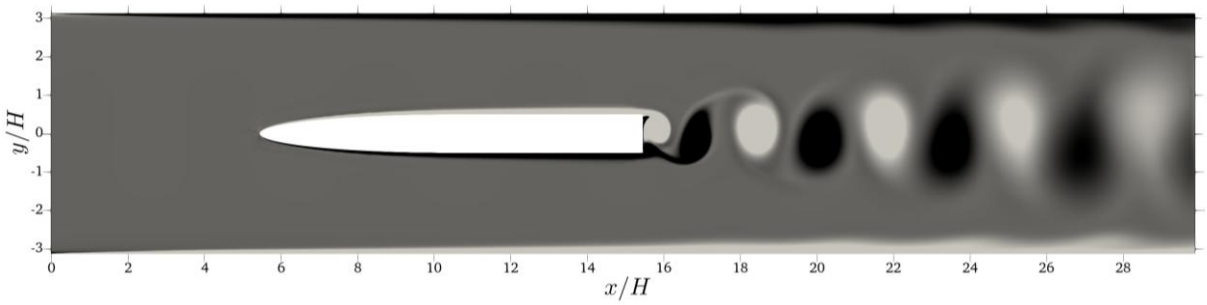


Figure 5: Instantaneous snapshot of flow vorticity for the B=16% case (extrema of the color map are 1.5, black and -1.5, white).

Conclusions

The present study quantified the influence of wall confinement on the turbulent wake past a missile-shaped airfoil using URANS simulations. The mean drag coefficient, lift coefficient and fluctuations, and Strouhal number all increase monotonically with blockage ratio. For low blockage ratios ($B < 0.1$), mean drag and shedding frequency remain within a $\pm 3\%$ band, indicating negligible confinement effects. At higher blockage ratios ($B > 0.1$), the aerodynamic coefficients and Strouhal number are markedly affected by the wind tunnel walls. These results provide a practical reference for estimating the influence of confinement in wind tunnel experiments of non-canonical bluff bodies in turbulent channels.

References

[1] G.S. West, C.J. Apelt, The effects of tunnel blockage and aspect ratio on the mean flow past a circular cylinder with Reynolds numbers between 104 and 105, Journal of Fluid Mechanics, 114 (1982) 361-377 https://doi.org/10.1017/S0022112082000202

[2] R. Mondal, M.M. Alam, Blockage effect on wakes of various bluff bodies: A review of confined flow, Ocean Engineering, 286 (2023) 115592 https://doi.org/10.1016/j.oceaneng.2023.115592

[3] J.-H. Chen, W.G. Pritchard, and S.J. Tavener, Bifurcation for flow past a cylinder between parallel planes, Journal of Fluid Mechanics, 284, 23-41, 1995 https://doi.org/10.1017/S0022112095000255

[4] M. Sahin and R.G. Owens, A numerical investigation of wall effects up to high blockage ratios on two-dimensional flow past a confined circular cylinder, Physics of Fluids, 16(5), 1305-1320, 2004 https://doi.org/10.1063/1.1668285

[5] S. Singha, K.P. Sinhamahapatra, Flow past a circular cylinder between parallel walls at low Reynolds numbers, Ocean Engineering, 37(8-9) (2010) 757-769 https://doi.org/10.1016/j.oceaneng.2010.02.012

[6] M. Breuer, J. Bernsdorf, T. Zeiser, F. Durst, Accurate computations of the laminar flow past a square cylinder based on two different methods: lattice-Boltzmann and finite volume, International Journal of Heat and Fluid Flow, 21(2) (2000) 186-196 https://doi.org/10.1016/S0142-727X(99)00081-8

[7] S. Turki, H. Abbassi, S. Ben Nasrallah, Effect of the blockage ratio on the flow in a channel with a built-in square cylinder, Computational Mechanics, 33(1) (2003) 22-29 https://doi.org/10.1007/s00466-003-0496-2

[8] Patil, P. P. and Tiwari, S., Effect of blockage ratio on wake transition for flow past square cylinder, Fluid Dynamics Research, 40(11-12), 753, 2008 https://doi.org/10.1016/j.fluiddyn.2008.04.001

[9] M. Carini, C. Airiau, A. Debien, O. Léon, J.O. Pralits, Global stability and control of the confined turbulent flow past a thick flat plate, Physics of Fluids, 29(2) (2017) https://doi.org/10.1063/1.4974069

[10] OpenFOAM web page: www.openfoam.org

[11] F.R. Menter, Two-equation eddy-viscosity turbulence models for engineering applications, AIAA Journal, 32 (8) (1994) 1598-1605 https://doi.org/10.2514/3.12149

[12] R.I. Issa, Solution of the implicitly discretised fluid flow equations by operator-splitting, Journal of Computational Physics, 62 (1) (1986) 40-65 https://doi.org/10.1016/0021-9991(86)90099-9