ARTICLE IN PRESS

International Journal of Heat and Fluid Flow xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Direct numerical simulations of a wall-attached cube immersed in laminar and turbulent boundary layers

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ARTICLE INFO

Keywords:
Wall-attached cube
Boundary layer
Turbulence
Strouhal number

ABSTRACT

A wall-attached cube immersed in a zero pressure gradient boundary layer is studied by means of Direct Numerical Simulations (DNS) at various Reynolds numbers Re_H (based on the cube height and the free-stream velocity) ranging from 500 to 3000. The cube is either immersed in a laminar boundary layer (LBL) or in a turbulent boundary layer (TBL), with the aim to understand the mechanisms of the unsteady flow structures generated downstream of the wall-attached cube. The mean locations of the stagnation and recirculation points around the cube immersed in a TBL are in good agreement with reference experimental and numerical data, even if in those studies the cube was immersed in a turbulent channel. In the TBL simulation, a vortex shedding can be identified in the energy spectra downstream of the cube, with Strouhal number of . However, the frequency of the vortex shedding is different in the LBL simulations, showing a significant dependence on the Reynolds number. Furthermore, in the TBL simulation, a low frequency peak with $St = 0.05$ can be observed far away from the boundary layer, at long streamwise distances from the cube. This peak cannot be identified in the LBL simulations nor in the baseline TBL simulation without the wall-attached cube.

1. Introduction

The turbulent flow around a wall-attached solid cube represents an interesting and complex problem from a fundamental point of view. Additionally, this flow configuration is a simple model for the interaction between a boundary layer and complex bodies immersed in it. For instance, the wall-attached cube may represent a typical protuberance on the surface of aerodynamic vehicles, such as aircraft or vessels. The flow around low and high aspect-ratio square cylinders is also very important for environmental applications, since it can model the air movement around simplified buildings.

In the last few decades, there has been extensive research on the turbulent flow around wall-attached obstacles with high aspect ratios $H/L \gg 1$ (where H is the obstacle height and L accounts for the base side). Early experiments on the mean-flow characteristics and vortex shedding of high aspect ratio wall-attached circular and square cylinders were performed in the 70's and 80's. Corke et al. (1979) studied the flow near a building model in order to examine the response of the flow field to variations in the characteristics of the boundary layer. Measurements of the vortex-shedding frequency behind a vertical rectangular prism and a vertical circular cylinder attached to a plane wall were performed by Sakamoto and Arie (1983) to investigate the effects of the aspect ratio of these bodies and the boundary-layer characteristics on the vortex-shedding frequency. Kawamura et al. (1984) performed flow visualization experiments and measurements of surface pressure around a finite circular cylinder on a flat plate, in order to study the main flow features close to the immersed objects. More recently, experimental research on the finite-length effects of wall-attached circular and cylinders using hot-wire anemometry was carried out by Park and Lee (2000). Additionally, the Particle Image Velocimetry (PIV) experiments of Wang and Zhou (2009); Monnier et al. (2010); Wang et al. (2014a) provide further insight on the flow structures generated by wall-attached circular and square cylinders. The wind tunnel experiments of Wang et al. (2006) studied the effect of the inflow conditions on the interactions between a boundary layer over a flat plate and flow around a wall-mounted finite-length cylinder. Finally, the research of McClean and Sumner (2014); Sumner et al. (2015), 2017) focused on the effect of the aspect ratio and the incidence angle of wall-attached objects in a low-speed wind tunnel using PIV.

Direct Numerical Simulations (DNS) of square cylinders were performed by Saeedi et al. (2014) with a study of the turbulent wake behind a wall-mounted square cylinder with aspect ratio 4. Vinuesa et al. (2015) assessed the effect of inflow conditions by considering a fully turbulent zero pressure gradient boundary layer and a laminar boundary layer. The evolution of various flow structures

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.09.015
Received 4 May 2017; Received in revised form 24 September 2017; Accepted 25 September 2017

Table 1
Summary of the simulation parameters (the momentum thickness is θ and the displacement thickness is δ^*) for the present investigation.

	Re_θ	Re_{δ^*}	$n_x \times n_y \times n_z$	$\frac{L_x}{H} \times \frac{L_y}{H} \times \frac{L_z}{H}$	$\Delta y_{wall}/H$	$\Delta y_{top}/H$	$\Delta t U_\infty/H$	T/H
$Re_H = 500$ LBL	68	175	357 × 129 × 192	35 × 15 × 8	0.02	0.68	0.007	10,000
$Re_H = 600$ LBL	81	210	357 × 129 × 192	35 × 15 × 8	0.02	0.68	0.007	10,000
$Re_H = 750$ LBL	101	263	357 × 129 × 192	35 × 15 × 8	0.02	0.68	0.007	10,000
$Re_H = 1100$ LBL	149	385	357 × 129 × 192	35 × 15 × 8	0.02	0.68	0.007	10,000
$Re_H = 1700$ LBL	230	596	357 × 193 × 192	35 × 15 × 8	0.015	0.41	0.005	10,000
$Re_H = 3000$ LBL	406	1051	513 × 385 × 256	35 × 15 × 8	0.007	0.22	0.002	3000
$Re_H = 3000$ TBL	750	1105	4, 097 × 513 × 256	320 × 27 × 10	0.0033	0.833	0.001	750

associated with finite length cylinders immersed in a low Reynolds number boundary layer such as wakes, tip vortices, base vortices and horse-shoe vortices were discussed by Saha (2013). A square rectangular tall building was considered by Li et al. (2014) to investigate the effects of turbulence integral length scale and turbulence intensity on the building by means of Large Eddy Simulation (LES). Numerical investigation of the turbulent flow around a surface-mounted square cylinder of aspect ratio 4 were performed by Wang et al. (2014b) to get detailed information about the flow structures around such a cylinder and to establish a suitable turbulent model that could yield accurate and reliable results for practical industrial applications.

The flow around a wall-attached object with $H = L$ is an important classical benchmark for simulations and experiments of bluff bodies. However, there is only a limited number of fundamental studies on the turbulence physics of this flow configuration. The investigation of Castro and Robins (1977) is among the first exhaustive experimental studies on the turbulent flow around a wall-attached cube. The authors compared the effect of uniform and sheared turbulent incoming streams at different Reynolds numbers. Since then, this flow configuration has been revisited, for instance, by the experimental work of Martinuzzi and Tropea (1993) at $Re_H = 40,000$, by Meinders et al. (1999) with $2750 < Re_H < 4970$ and by the Direct Numerical Simulation (DNS) of Yakhot et al. (2006b) at $Re_H = 1870$. The scalar concentration field behind a wall-attached cube has been studied experimentally by Ogawa et al. (1983), Li and Meroney (1983) and Mavroidis et al. (2003) at high Reynolds numbers and computationally by Rossi et al. (2010) at $Re_H = 5000$, using DNS and Reynolds-Averaged Navier Stokes (RANS) simulations. The recent study of a wall-attached cube by Hearst et al. (2016), at $Re_H = 1.8 \times 10^6$, suggested that different inflow conditions at high Reynolds numbers may not modify the main shedding frequency or the mean position of the stagnation and reattachment points but seem to affect the length of the turbulent wake behind the cube.

The presence of a wall-immersed object in a boundary layer can modify the flow properties in a noticeable way, even with a small blockage ratio. Its turbulent wake induces a momentum loss which results in a rapid increase of the boundary layer thickness. Moreover, despite of its relatively small size, the effect of a wall-attached body on the energy spectra of the flow can persist at long distance from the immersed object. However, there is little fundamental work published on the influence of a wall-attached cube further downstream of its position and on the far-field fluctuations that it generates. On the other hand, the far field dynamics generated by circular and square cylinders are slightly better documented in literature, in particular by the recent works of Becker et al. (2008), King and Pfizenmaier (2009), Porteous et al. (2013) and Moreau and Doolan (2013). An exhaustive review on the far-field dynamics has been recently compiled by Porteous et al. (2014).

The present numerical study investigates the downstream signature of a wall-attached cube, comparing situations where the cube is immersed in a laminar and in a turbulent boundary layer. In particular, we focus on the various peaks found in the energy spectra inside the boundary layer but also at large distances from the wall and far away downstream of the cube. Data in the near-field of the cube are also validated against the reference data of Martinuzzi and Tropea (1993) and Yakhot et al. (2006b).

2. Computational setup

The results presented here have been obtained from high fidelity Direct Numerical Simulations (DNS) of zero-pressure gradient laminar and turbulent boundary layers (LBL, TBL, respectively), with a solid cube immersed in the computational domain. The baseline simulation of the TBL case, which uses the same numerical domain without the immersed wall-attached cube, was introduced and validated in a fundamental investigation on the wall shear-stress fluctuations by Diaz-Daniel et al. (2017). The local Reynolds number of the TBL covers the range $Re_\theta = 270 - 2200$, based on the momentum thickness θ and free-stream velocity U_∞.

The computational flow solver, Incompact3d (Laizet and Lamballais, 2009; Laizet and Li, 2011), uses sixth-order finite difference schemes, with a spectral treatment for the pressure equation and a semi-implicit time advancement for the viscous terms. The validation results of the TBL in Diaz-Daniel et al. (2017) include the computation of the budget terms of the mean turbulence kinetic energy equation. The balance of the steady budget terms stays under 1% of the mean dissipation rate in the entire computational domain. The statistics of velocity and wall shear-stress are in excellent agreement with the reference data of Schlatter and Örlü (2010) and Jiménez et al. (2010) at equal Reynolds numbers.

The computational parameters of the present simulations are included in Table 1. The cube height is represented by H and the coordinate variables in the streamwise, wall-normal and spanwise directions are x, y, z, respectively. The coordinate system is shifted to a streamwise position such that $x = 0$ is located at the front plane of the cube. The computational domain is stretched in the wall normal direction using the metric described by Laizet and Lamballais (2009). In the baseline TBL simulation, the mesh resolution, in wall viscous units (at $Re_\theta = 1470$) is: $\Delta x^+ = 10.2, \Delta z^+ = 5.1, \Delta y^+ = 0.42$ at the wall and $\Delta y^+ = 108.8$ at the top of the domain. The stretching function parameters guarantee that the wall-normal node spacing inside the boundary layer is lower than $\Delta y^+ = 12$ at the maximum Reynolds number $Re_\theta \approx 2200$.

The inflow boundary condition in our simulations is a Blasius laminar boundary layer profile prescribed at the inlet plane. In the TBL simulation, the transition to turbulence is triggered via the random-forcing method described in Schlatter and Örlü (2012). A streamwise convective equation is solved at the outlet and a no-slip condition is imposed at the bottom wall. Periodic boundary conditions are used in the spanwise direction, effectively modelling an infinite array of cubes, and an homogeneous Neumann condition is imposed at the top boundary.

The solid cube, of size H, is modelled with an immersed boundary method (see Laizet and Lamballais (2009) for the details). In the simulation with an incoming TBL, the height of the cube, H, is equal to 0.42δ, where δ is the local boundary layer thickness, and the Reynolds