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Cylinder wake dynamics in turbulent channel flow at high friction Reynolds number

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SUMMARY:
This study investigates the wake dynamics of spanwise-oriented cylinders embedded in a fully turbulent channel flow at $Re_\tau \approx 3000$. Although fundamental in nature, this research is relevant to numerous wind-engineering applications, e.g., cylindrical towers and buildings, and bridge cables. Experiments were conducted in nine configurations across three cylinder diameters and three wall-normal positions, spanning from the logarithmic to the outer region of the boundary layer. Each configuration was characterized by a single cylinder exposed to a cross-flow. Time-resolved hot-wire anemometry was used for assessing instantaneous velocity fluctuations downstream of the cylinder. The mean streamwise velocity profiles show that wake geometry depends on the cylinder wall-normal position, with wakes becoming more vertically spread as the cylinder is positioned closer to the wall. The streamwise turbulence intensity exhibits a distinct outer-layer peak associated with the wake, absent in the unperturbed plane channel. Both the wake shape and turbulence intensity vary systematically with cylinder diameter and wall-normal height, indicating sensitivity to local turbulence conditions and geometric effects. These findings provide new experimental insight into the wake-turbulence interaction in wall-bounded flows, with implications for predicting flow-induced vibrations, aerodynamic loads and fatigue on cylindrical structures in boundary layer flows.

Keywords: cylinder wake, turbulent channel flow, hot-wire anemometry

1. INTRODUCTION

The interaction between turbulent boundary layers and bluff-body wakes is a fundamental topic in fluid mechanics, with practical significance in wind engineering. Classic studies have established wake behaviour behind cylinders in laminar or uniform flows, where vortex shedding and mean velocity profiles are well understood (Roshko, 1954; Williamson, 1996). When a cylinder is immersed in a turbulent boundary layer, however, the wake characteristics are significantly modified by the surrounding shear and turbulence, and depend on the wall proximity of the cylinder. The existing studies on this topic have been conducted at relatively low-to-moderate friction Reynolds numbers, Re_τ (Bearman and Zdravkovich, 1978; Marumo et al., 1978; Ouro et al., 2019; Torres De Jesus et al., 2024). Despite the practical and theoretical importance, experimental studies of cylinder wakes in fully developed turbulent channel flow at high Re_τ remain scarce. The present study addresses this research gap by examining the wake characteristics of spanwise-oriented cylinders in a channel flow at $Re_\tau \approx 3000$, across a range of wall-normal positions and cylinder diameters. The aim is to clarify the effects of local characteristics of the turbulent boundary layer on the wake structure, and to establish an experimental reference that supports future modelling and simulations.

2. EXPERIMENTAL SETUP

The experiments were conducted in a fully turbulent channel facility at The University of Melbourne, Australia. The boundary layer thickness, $\delta = 50$ mm, is defined as half the channel height. The flow was set at a constant U_c/ν, where U_c is the centreline velocity and ν is the kinematic viscosity, with the corresponding friction Reynolds number $Re_\tau \approx 3000$. Friction Reynolds number is defined as $Re_\tau = u_\tau \delta/\nu$, where u_τ is friction velocity.

Cylinders were positioned horizontally and tensioned in the spanwise direction, resulting in a cross-flow configuration. All cylinders extended across the full width of the channel (1.2 m), generating a nominally two-dimensional wake. A total of nine configurations were investigated, combining three cylinder diameters ($D = 4.76$ mm, 3.18 mm and 2.25 mm or $D/\delta = 0.095$, 0.064, 0.045, respectively) and three wall-normal positions ($z/\delta = 0.15$, 0.36, 0.58). The blockage ratio of the test section remained below 5% in all experiments, which is regarded as an acceptable limit for minimizing blockage effects (Holmes and Bekele, 2021).

The Reynolds number based on the local mean velocity and the cylinder diameter is defined as $Re_D = UD/\nu$, where U is the mean velocity at the cylinder axis position measured in the channel without the cylinder. In the present study, Re_D is in the 2700 to 6800 range.

Time-resolved single-component hot-wire anemometry was used to measure streamwise velocity fluctuations at the channel mid-span, 1.5δ downstream of the cylinder. Signals were sampled at 50 kHz for 150 s to ensure statistically converged velocity data.

The experimental setup is shown in Figure 1.

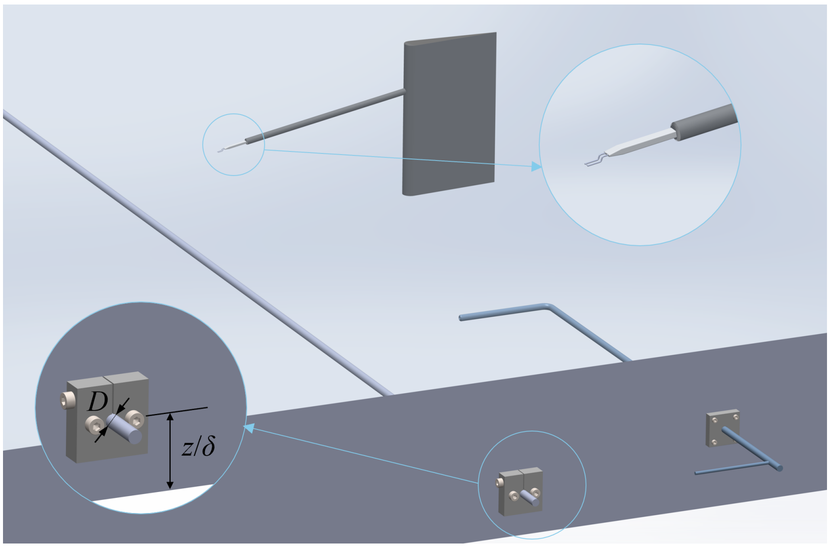

Figure 1. Experimental setup for hot-wire measurements

3. PRELIMINARY RESULTS

The initial results of the hot-wire measurements provide an overview of how the turbulent channel flow influences the wake structure for different cylinder configurations. The preliminary analysis focuses on the mean velocity profiles and turbulence intensity downstream of the cylinders. For brevity, only the results for the largest cylinder diameter are shown here, as the other cases exhibit similar trends.

The mean streamwise velocity profiles reveal the effect of the wall-normal position on the cylinder wake. When the cylinder is closer to the wall (z/δ = 0.15), the wake shows greater vertical spread, and it becomes narrower when the cylinder is placed higher in the flow (z/δ = 0.58) (Figure 2). This demonstrates that the local turbulence and shear directly control the vertical redistribution of the momentum in the wake.

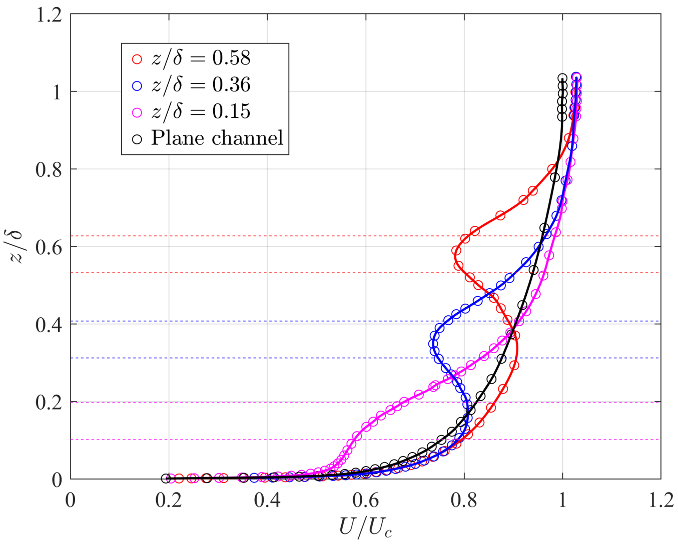

Figure 2. Normalized mean streamwise velocity profiles for the largest cylinder diameter (4.76 mm) at three wall-normal positions, compared to the plane channel flow

The streamwise turbulence intensity profiles show an outer-layer peak associated with the wake, absent in the plane channel flow (Figure 3). The location and magnitude of the peak vary systematically with the cylinder diameter and wall-normal position, confirming that the incoming turbulent boundary layer affects turbulent production in the wake. The results show that the larger diameters yield stronger wakes with more pronounced turbulence peaks, compared to smaller diameters.

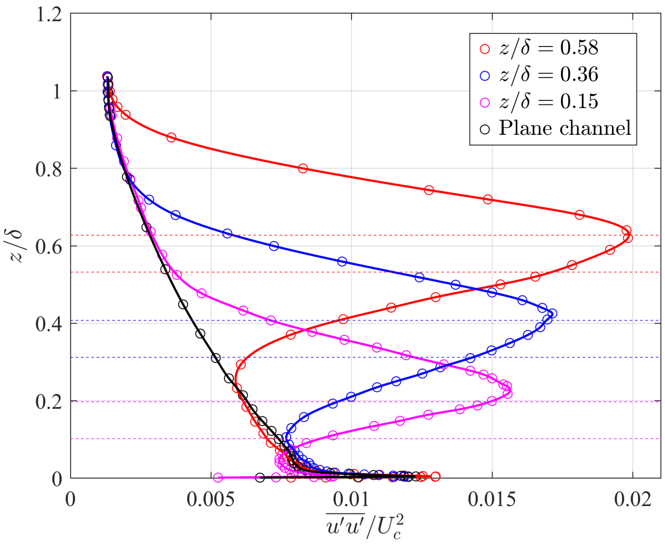

Figure 3. Normalized streamwise turbulence intensity for the largest cylinder diameter (4.76 mm) at three wall-normal positions, compared to the plane channel flow

4. DISCUSSION

These results indicate that the wake is not self-similar as in the uniform flow, but instead evolves in response to the spatially varying turbulence in the turbulent boundary layer. The shape of the wake and the distribution of turbulence intensity are controlled by both the cylinder geometry and the local boundary layer conditions. This demonstrates how the incoming turbulence influences wake development in wall-bounded flows, particularly in high Re_τ flows where the discrepancies between the small- and large-scale eddy structures are substantial.

Ongoing work focuses on further processing of the time-resolved hot-wire data to examine spectral information and vortex-shedding frequencies. In parallel, planar PIV measurements downstream of the cylinder are performed to assess the spatially resolved statistics, enabling further analysis of wake dynamics.

5. CONCLUDING REMARKS

This work moves beyond prior low-to-moderate Re_τ wind-tunnel and computational studies of cylinder wakes by providing experimental data in fully turbulent channel flow at $Re_\tau \approx 3000$. The results show that the wake formation and characteristics depend strongly on the wall-normal position and cylinder diameter. The preliminary results and ongoing work will clarify how the turbulent boundary layer affects the wake structure, providing insight into the wake-turbulence interaction in realistic wall-bounded flows and creating a dataset for future wall-bounded flow simulations.

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