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Turbulent wake and vortex shedding for a stack partially immersed in a turbulent boundary layer

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Abstract

The effect of the jet-to-cross-flow velocity ratio, R, on the turbulent wake and Kármán vortex shedding for a cylindrical stack of aspect ratio $\mathrm{AR} = 9$ was investigated in a low-speed wind tunnel using thermal anemometry. The cross-flow Reynolds number was $\mathrm{Re}_D = 2.3 \times 10^4$, the jet Reynolds number ranged from $\mathrm{Re}_d = 7.6 \times 10^3$ to 4.7×10^4, and R was varied from 0 to 3. The stack was partially immersed in a flat-plate turbulent boundary layer, with a boundary layer thickness-to-stack-height ratio of $\delta/H = 0.5$ at the location of the stack. From the behaviour of the turbulent wake and the vortex shedding, the flow around the stack could be classified into three regimes depending on the value of R, which were the downwash ($R<0.7$), cross-wind-dominated ($0.7 \leqslant R < 1.5$), and jet-dominated ($R \geqslant 1.5$) flow regimes. Each flow regime had a distinct structure to the mean velocity (streamwise and wall-normal directions), turbulence intensity (streamwise and wall-normal directions), and Reynolds shear stress fields, as well as the variation of the Strouhal number and the power spectrum along the stack height.

1. Introduction

Stacks are used to reduce the ground-level concentration of an exhaust gas by emission of the exhaust gas at greater heights. For a stack mounted on a building rooftop, the local velocity field, the origin and development of the rooftop boundary layer, the proximity of other buildings and structures, the stack exit temperature and velocity, and the wind velocity and direction, are major factors that affect the rise and dispersion of the stack jet or plume (Wilson, 1979; Schulman and Scire, 1991). Engineering design guidelines for rooftop-mounted stacks are well established (ASHRAE, 1999, 2001) and the behaviour of stack jets and buoyant plumes has been extensively studied (Briggs, 1984).

In addition to the behaviour of the jet or plume, many of the same factors mentioned above also influence the local flow field of the stack itself. In order to understand the local flow field around a rooftop stack, which has not been extensively reported in the literature, there is need to study the jet and its interaction with near field of the stack. In the present study, the turbulent wake of a short cylindrical stack is investigated experimentally in a low-speed wind tunnel, to provide more insight into the near-field behaviour of the flow under different jet flow conditions. In addition, the effects of the jet on Kármán vortex shedding from the stack are also examined.

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2. Background

The local flow field of a stack involves three fundamental yet complex flows: the plane wall boundary layer flow on the ground plane, the separated flow field and wake of a finite circular cylinder (representing the simplest possible stack geometry), and the development of an elevated round jet in cross-flow (representing the exhaust jet exiting the stack). The flow field of a stack of uniform cylindrical shape, with external diameter, D, internal diameter, d, and height, H, is shown schematically in Fig. 1. In Fig. 1(b), the stack is shown partially immersed in a turbulent flat-plate boundary layer on the ground plane, with freestream velocity, U_∞, boundary layer mean velocity profile, $\bar{U}(z)$ (where z is the wall-normal coordinate), and boundary layer thickness, δ. Also identified in Fig. 1(b) are the stack and jet wakes, as well as the rise, $h(x)$ (where x is the streamwise coordinate), of the elevated turbulent jet after it exits the stack (where U_e is the average jet exit velocity).

The flow around the stack and along its height is influenced by the stack Reynolds number, $\mathrm{Re}_D = \rho_\infty U_\infty D/\mu_\infty$ (where ρ_∞ and μ_∞ are the density and dynamic viscosity of the approach flow, respectively), the stack aspect ratio, $\mathrm{AR} = H/D$, and the relative thickness of the flat-plate boundary layer at the location of the stack, δ/H. The behaviour of the round jet exiting the stack is governed by the jet Reynolds number, $\mathrm{Re}_d = \rho_e U_e d/\mu_e$ (where ρ_e and μ_e are the density and dynamic viscosity of the jet, respectively). If the jet is nonbuoyant, $\rho_\infty = \rho_e$ and $\mu_\infty = \mu_e$, and its interaction with the cross-flow is influenced primarily by the jet-to-cross-flow velocity ratio, $R = U_e/U_\infty$ and to a lesser extent by the diameter ratio, d/D. For buoyant jets (or plumes), the main parameter of influence is the momentum flux ratio, $R_m = (\rho_e U_e^2)/(\rho_\infty U_\infty^2)$.

2.1. Flow around a finite circular cylinder

The simplest stack geometry can be represented by a uniform circular cylinder of finite height mounted normal to a plane wall or ground plane. Flow around the base of the cylinder and over the free end causes the flow field to become

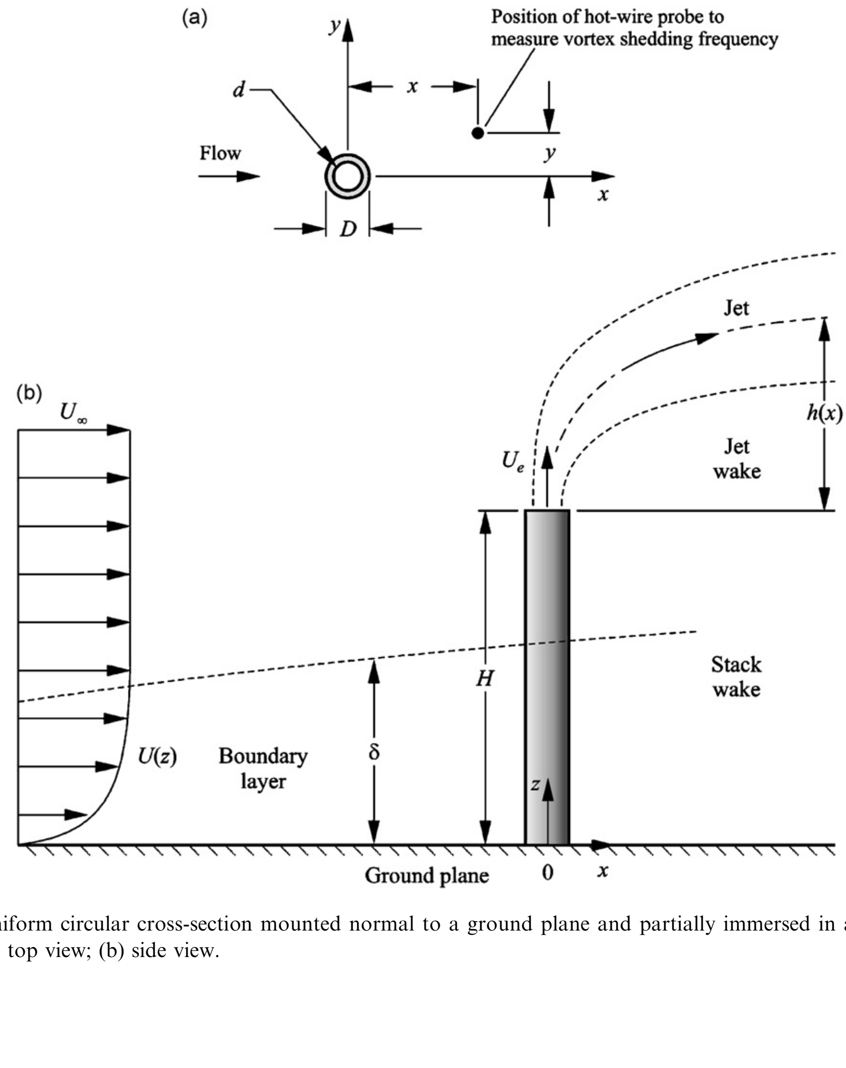

Fig. 1. Stack of uniform circular cross-section mounted normal to a ground plane and partially immersed in a turbulent flat-plate boundary layer: (a) top view; (b) side view.