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Wind tunnel investigation on the retention of air pollutants in three-dimensional recirculation zones in urban areas

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Abstract

The article discusses an experimental investigation of turbulent dispersion processes in a typical three-dimensional urban geometry, in reduced scale, in neutrally stable conditions. Wind tunnel experiments were carried out for characterizing the flow and the dispersion of a pollutant around a scaled model (1:400) of a group of eight 10-floor buildings surrounding a square. The situation corresponded to the dispersion of fine inertialess particles released from a line source positioned upstream of the urban geometry. After the sudden interruption of the source generation, the particles persisted in the recirculation cavity between the buildings, with the concentration decaying exponentially with time. This is in accordance with previous works on the dispersion process around bluff bodies of different shapes [e.g., Humphries and Vincent, 1976. An experimental investigation of the detention of airborne smoke in the wake bubble behind a disk. Journal of Fluid Mechanics 73, 453–464; Vincent, 1977. Model experiments on the nature of air pollution transport near buildings. Atmospheric Environment 11, 765–774; Fackrell, 1984. Parameters characterizing dispersion in the near wake of buildings. Journal of Wind Engineering and Industrial Aerodynamics 16, 97–118]. The main parameter in the investigation was the characteristic time constant for the concentration decay. The measurements of the variation in the concentration of the fine particles were performed by means of a photo-detection technique based on the attenuation of light. The velocity fields were evaluated with the particle image velocimetry (PIV) technique. The dimensionless residence time H for the particles ($H = \tau U/L$, where τ is the time constant for the concentration decay, U the free-stream velocity, and L is a characteristic dimension for the urban geometry, as defined by Humphries and Vincent [1976. An experimental investigation of the detention of airborne smoke in the wake bubble behind a disk. Journal of Fluid Mechanics 73, 453–464] was determined for various locations in the scaled model, in the range of Reynolds numbers (Re) between 8000 and 64,000. H was found to be 6.5 ± 1.0.

Keywords: Atmospheric pollution; Urban areas; Residence time; Bluff bodies; Wind tunnel experiments

1. Introduction

Atmospheric pollution has become an important issue in the last decades and an increasing number of studies have been performed for investigating the

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generation and dispersion of pollutants in urban environments. As an example of that, it is possible to list several studies addressing the atmospheric flow and the dispersion process near buildings (Hunt and Castro, 1984; Fackrell, 1984; Hosker, 1984; Hall et al., 1996; Santos, 2000; Mavroidis and Griffiths, 2001; Mavroidis et al., 2003). At long distances from the source, where the plume cross-section becomes large compared to the dimensions of individual obstacles, conventional dispersion models are used to simulate the flow and dispersion patterns (e.g., Carruthers et al., 1994). Closer to the source, where the interaction between the plume and structures dominates the process, field trials and wind tunnel experiments are usually required, either for providing direct information on the dispersion process or for serving in the validation and evaluation of more complex numerical codes.

Both numerical and physical models are important instruments for assessing the dispersion of a pollutant in the atmosphere. A large number of commercial and research numerical models are currently available. The evaluation of the code accuracy and the definition of the optimal model set-up (numerical grid resolution, simplifying hypothesis, sub-models, and so on) are very important tasks. Experiments in reduced models are very useful for developing, improving, and testing such numerical codes.

In Schatzmann and Leitl (2002), field measurements were repeated in a boundary-layer wind tunnel under carefully controlled conditions. The comparisons between field and wind tunnel concentration results were generally fair. The authors employed these data for investigating the performance of commercially available urban dispersion models.

The transport of pollutants in moving air near a bluff body is of great importance to many areas of science and engineering and several previous studies have been performed on the subject. More specifically, this study is related to the transport of fine (virtually inertialess) particles or gaseous pollutants in environmental flows around a cluster of bluff objects which may represent a typical urban geometry.

The flow around bluff body systems involves highly distorted and recirculating structures formed by the separation of the flow. If there is a source of pollutants (aerosols or gases) nearby, they may entrain in such recirculation regions and persist there for a long period, even after cessation of the source generation. The recirculation zone then starts playing the role of a secondary source of pollutants for the adjacent and downwind locations. The identification and quantification of the important parameters governing such transport (e.g., some characteristic residence time for the pollutant in the recirculation cavities) is an essential requirement in the development of models by which we might, for example, predict the transport of pollutants in urban geometries. This paper represents a contribution towards such understanding.

The investigation of the dispersion of a pollutant on the downwind side of bluff bodies is more complicated than in the case of the upstream flow. The flow separation and the generation of shear layers and turbulence introduce considerable experimental and theoretical difficulties. One relevant body of work concerned studies on the transport of small particles into and out of the near wake regions of bluff bodies of simple shape, both axisymmetric (e.g., disks, triangles, squares) and two-dimensional (e.g., flat plates and cylinders), surface-mounted fences and blocks (e.g., Humphries and Vincent, 1976; Vincent, 1977, 1978; MacLennan and Vincent, 1982; Gomes et al., 1997), as well as laboratory scale buildings (Hunt and Castro, 1984; Fackrell, 1984).

Most of these studies employed a "tracer-decay" technique in a wind tunnel to determine the characteristic residence time (τ, time constant for the concentration decay process) of fine fog particles introduced into the near wake regions of bluff bodies. Changes in the concentration of particles in the near wakes were monitored by means of an optical system operating on the principles of light extinction or light scattering. The decay of the concentration of the tracer material in the near wake, following the sudden interruption of the source generation, was found to be invariably exponential, even for quite complex bluff body systems. The dispersion was also characterized by a dimensionless residence time H ($H = \tau U/L$, where U and L are the characteristic velocity and characteristic length of the system, as it was first suggested by Humphries and Vincent, 1976).

The present experiments, which were concerned only with neutrally stable atmospheres, were performed in a wind tunnel with the purpose of characterizing the flow and the dispersion of a pollutant around a bluff body system. This was composed by a group of eight solid blocks around an open space representing a reduced model for a cluster of eight 10-floor buildings surrounding a square.