Available online at www.sciencedirect.com

ScienceDirect

Atmospheric Environment 41 (2007) 5848–5862

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

A simple network approach to modelling dispersion among large groups of obstacles

David Hamlyn[a,*], Trevor Hilderman[b], Rex Britter[a]

[a]*Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ, UK*
[b]*Coanda Research and Development Corp., 110A-3430 Brighton Ave, Burnaby, British Columbia, Canada V5A 3H4*

Received 5 September 2006; received in revised form 15 March 2007; accepted 19 March 2007

Abstract

A simple network approach has been developed to simulate the movement of pollutant within urban areas. The model uses estimates of pollutant exchange obtained from velocity measurements in experiments with various regular obstacle arrays. The transfer of tracer material was modelled using concepts of advection along streets, well-mixed flow properties within street segments and exchange velocities (akin to aerodynamic conductances) across side and top facets of the street segments.

The results predicted both the centreline concentration and lateral dispersion of the tracer with reasonable accuracy for a range of packing densities and wind directions. The basic model's concentration predictions were accurate to better than a factor of two in all cases for the region from two obstacle rows behind a source located within the array to around eight rows behind, a range of distances that falls into the so-called "neighbourhood-scale" for dispersion problems. The results supported the use of parameterized rates of exchange between regions of flow as being useful for fast, approximate dispersion modelling. It was thought that the effects of re-entrainment of tracer back into the canopy were of significance, but modelling designed to incorporate these effects did not lead to general improvements to the modelling for these steady-state source experiments.

The model's limitations were also investigated. Chief amongst these was that it worked poorly among tall buildings where the well-mixed assumption within street segments was inadequate.

Keywords: Urban canopy; Box model; Exchange velocity; Re-entrainment

1. Introduction

This paper describes the development of a simple network approach for modelling dispersion at the neighbourhood scale (i.e. several streets downstream of a source). This model, while remaining fast to run, aims to take account of the important advective and diffusive flow processes within the obstacle arrays, rather than representing the obstacles simply as a spatially averaged roughness. The model might be particularly attractive for assessing pollutant spread from hotspots such as busy intersections to surrounding parts of a city, or to assess potential danger areas after an accidental or intentional release of hazardous material. The model has been developed and tested against

*Corresponding author. Tel.: +44 1223 332869.
E-mail address: dpdh2@eng.cam.ac.uk (D. Hamlyn).
URL: http://www.coanda.ca (T. Hilderman).

1352-2310/$ - see front matter
doi:10.1016/j.atmosenv.2007.03.047

a range of experiments using regular obstacle arrays, which provided basic flow data for model development and dispersion data for model testing.

Flow among arrays of cubes has been examined in experiments (e.g. Davidson et al., 1995, 1996; Mavroidis and Griffiths, 2001). These studies commented on the relevance for dispersion of obstacle wakes and longitudinal channelling along streets. Computational studies by Kim and Baik (2004) and Hamlyn and Britter (2005) have also examined the form of the flow structures, finding a range of large recirculatory structures present in the gaps between obstacles, with the form of these structures dependent on the wind direction and obstacle array packing density.

The model concept is that a series of short streets form a network of boxes that comprise the canopy space. Tracer material is advected along the streets and is assumed to be well mixed within each box, or "cell" due to vigorous mixing from recirculatory structures and locally generated turbulence around the obstacles. The transfers of tracer between cells, and transfers between the canopy and the air above are governed by the magnitude of the resistance to transfer (via advection or turbulent diffusion) between the cells, or between the canopy and the air above. The model is designed to capture the important flow physics in a simple, fast-to-run approach applicable to the neighbourhood scale and requiring only very limited inputs regarding flow velocities. Techniques and references are suggested for estimation of these inputs. The network model approach reflects that taken by Soulhac's model SIRANE (2000) but the methods of parameterizing exchanges differ, as does our more simplified approach of assuming local in-canopy vertical homogeneity.

Computational fluid dynamics (CFD) simulations by Hamlyn and Britter (2005) focused on quantifying the exchanges within simple obstacle arrays. The concept of "exchange velocity", u_E was described by Bentham and Britter (2003) and in essence is a characteristic velocity relating the momentum flux across a plane to spatially averaged reference velocities either side of the plane. The fluxes that contribute to momentum exchange across the canopy top are turbulent and advective fluxes, the latter often referred to as dispersive stresses. For pollutant exchange, the same exchange velocity concept may be applied to quantify the exchange of pollutant mass across the canopy top.

The introduction of an exchange velocity has come from the realization that parameterizations like surface roughness length z_0 and displacement height d are of limited usefulness when dealing with flow near and within an urban canopy. They only have meaning in the context of boundary layer flow over a very long, statistically homogeneous fetch. The exchange velocity directly addresses the aspect of the flow that is of direct importance in the urban environment, the ventilation of the urban canopy. Thus, it could be interpreted as the dominant link in any network model of the urban canopy. It should not be confused with various mass, momentum or heat conductances that connect surface variables with variables within the canopy or above it. The exchange velocity is not a particularly novel concept (it is similar to the concept of aerodynamic conductances e.g. see Monteith and Unsworth, 1990) but, for its importance, it has been very little studied or parameterized in the urban context when compared with the efforts on z_0, d and conductances between surfaces and the air.

The exchange velocity is probably best parameterized in terms of the friction velocity u_* and Bentham and Britter (2003) developed a simple analysis to connect the two. However u_* is not an easily determinable parameter in the urban context. Unrealistically (see Cheng and Castro, 2002a) long fetches that have statistical homogeneity are required if the velocity profile is to be used to determine u_*, z_0 and d. Additionally, the considerable sensitivity of the determined u_*, d and z_0 to the velocity profile is reflected in the relative insensitivity of the wind speed at a particular height to a (consistent) set of estimates for u_*, d and z_0. The determination of the friction velocity from measurements of the Reynolds stress is also quite problematic in an urban context from measurements within or above the roughness sub-layer for a variety of reasons. Consequently, the wind speed at a particular height, measured, calculated or estimated, can be a preferable reference velocity to the more fundamentally correct variable, the friction velocity, u_*. For this reason, we choose a reference velocity towards the top of the roughness sub-layer, at 2.5 times the average obstacle height, H.

It might be considered that in obstacle arrays, knowledge of the canopy-top exchange velocities $u_{E\text{top}}$, and a mean in-canopy exchange velocity between sheltered and unsheltered regions of flow $u_{E\text{side}}$ could be sufficient to produce a simple model