

Chemical, Biological and Radiological Hazard Assessment: A New Model of a Plume in a Complex Urban Environment

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Keywords: pollutant, plume, urban canopy, mean concentration profile, model, comparison

EXTENDED ABSTRACT

There has been a growing interest in recent years in the modelling of hazards arising from the atmospheric dispersion of chemical, biological and radiological (CBR) agents in the environment, and the threat that they pose to the population and military forces. This is a particularly challenging problem in an urban setting. Dispersion of CBR agents in an atmospheric boundary layer (ABL) over a heterogeneous (urban) canopy is a complex process to be described by advanced methods of fluid dynamics, turbulence theory, diffusion and statistics. Using comprehensive modelling is computationally intensive and too time consuming when applied to operational problems when reliable outcome has to be produced within a limited time frame. Plume characterisation requires the development of simplified analytical models of turbulent dispersion based on physical assumptions and “first principles” physics considerations. These models must still be simple enough to be easily treated numerically in an operationally viable way. Such models can also provide a theoretical foundation for “backtracking” problems, i.e. finding a CBR source in a complex canopy under various meteorological conditions. The purpose of this paper is to summarise the recent research conducted by DSTO (HPPD) in the development of such models.

There undoubtedly exists a vast amount of literature dedicated to the simplified models of tracer dispersion (for instance see an extensive literature review and references in our recent publications: Gailis *et al* 2006, Gailis *et al* 2007). The main goal of our study was the extension of the celebrated fluctuating plume model of tracer dispersion to two cases: namely, a simple sheared boundary layer and a large array of regular obstacles (model of urban canopy, Fig 1). We tried to incorporate these cases based on the physical models of the associated advection-diffusion process in turbulent flow, rather than based on ad-hoc empirical relationships.

We present a new mathematical model of CRB plume dispersion in an urban environment. The model uses parameters that explicitly take into account turbulent flow close to the ground and the urban canopy parameters enabling an analytic calculation of the plume concentration profiles. Model predictions are compared with some recent experimental data, showing a close match. The model developed can be used as an analytical tool for predicting CBR plume behaviour in complex urban environments, or as a prototype and performance check for a new generation of dispersion models. This will lead to a set of improved tools for planning and support of military operations in CBR threat environments.

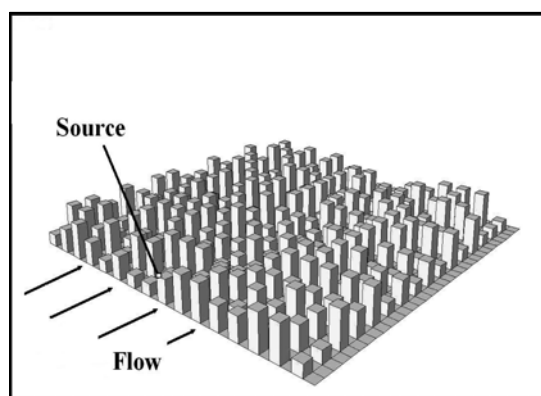


Figure 1: An example of one of the obstacle arrays

1. INTRODUCTION

Since air flow in the ABL is a key driver for CBRN pollutant advection and dispersion, the development of a high fidelity model of this flow is a crucial step in the modelling of the whole turbulent dispersion process. The fluctuations are presented as a composition of two distinct components (large-scale plume centroid meandering and fine-scale internal plume fluctuations) allowing reasonable analytical predictions.

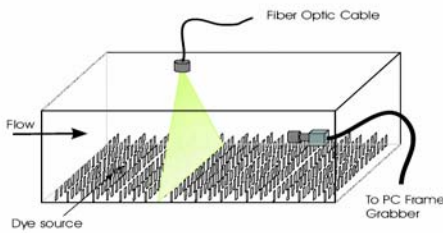


Figure 2: Schematic representation of the experimental setup, depicting the sheet of laser light intersecting the dispersing fluorescent dye in a surface layer flow with canopy objects.

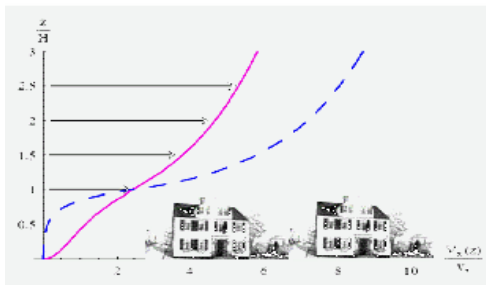


Figure 3: The calculated wind profile in sparse (solid line) and dense (dashed line) canopies based on the proposed model. The dashed line corresponds to the lower value of the parameter ε (dense canopy).

2. A NEW MODELLING FRAMEWORK

2.1. Mean Flow in a Complex Canopy

The flow model in surface layer within and above the canopy should correctly describe the average (i.e. non-fluctuating) velocity field. It has been known for a long time (dating back to Prandtl, see Monin and Yaglom 1978) that the ABL mean velocity profile can be fairly approximated by a power-law function (see Fig 1):

$$(1) \quad U = aV_* \left(\frac{z-d}{z_0} \right)^m,$$

where $U(z)$ is the horizontal velocity, z is distance from the ground, V_* is the friction velocity, a and m are constants (m is a main parameter from the theory), z_0 is the roughness height and d is the so-called displacement height. Both d and z_0 should be considered as fitting parameters of the ABL flow over the canopy.

The profile described by Eq (1), being algebraically simpler than the celebrated log-law profile, has been used merely as a convenient engineering approximation, but recently it has attracted much attention since it has been shown that it can be justified based on a self-similarity property of the ABL flow (see Barenblatt et al 2002). For the boundary layer over a flat smooth surface it has been rigorously shown that

$$m = \frac{3}{2 \ln \text{Re}},$$

where Re is the Reynolds number of the flow. Observed values of m in the atmosphere range from nearly 0 in very unstable conditions, representing perfect mixing and a uniform velocity profile, to nearly 1 in very stable conditions, approaching the Couette linear profile of laminar motion over a plane surface. For neutral conditions $m = 1/7$ (Monin and Yaglom 1978). The value of m also depends on surface roughness: roughness promotes mixing near the surface, which reduces the velocity gradient at small z and thus leads to larger variation in m .

Based on the so-called distributed drag approach it has been recently shown (see Harman *et al* 2007) that the entire influence of the canopy on the ABL flow (1) can be described by only one parameter that describes the ratio of the canopy surface area to the total area. For an array of identical cylinders (similar to Fig 1) this parameter is approximately equal to

$$(2) \quad \varepsilon = \frac{2H}{\pi r_0} \left(\frac{1 - \lambda_p}{\lambda_p} \right),$$

where all parameters in this formula are determined by the canopy morphology (H is the

canopy height, r_0 is the radius of the cylinders and λ_p is the packing density of canopy elements). The limiting values of ε correspond to sparse ($\varepsilon \gg 1$) and dense ($\varepsilon \ll 1$) canopies.

We have developed a consistent theoretical framework that allows us to derive a “modified” velocity profile $U(z)$ (1) for a given value of ε , i.e. for a given canopy. Our framework is based on “smooth” matching of the two solutions of momentum balance (below and above the canopy) near the canopy top. We have derived general functions for $d(\varepsilon)$, $z_0(\varepsilon)$ and $U(z)$ within the canopy.

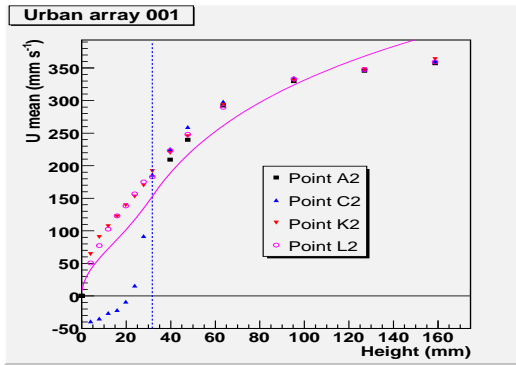


Figure 4: Measured velocity profiles for a simulated urban canopy at different positions relative to canopy objects.

We found that for a large ε function $d(\varepsilon) \rightarrow H$, $z_0(\varepsilon) \rightarrow 0$ as a power law (i.e. rather slowly) and $d(0) = z_0(0) = 0$ if $H = 0$. It should be emphasized that in the proposed framework, the entire morphological variety of canopies manifests itself only in different values of parameter ε .

Examples of calculated velocity profiles are presented in Fig 3. In Fig 4 we show our experimental data from a water channel experiment (Gailis *et al* 2007). The urban canopy was modelled by an array of cubic obstacles that were packed in regular or random patterns (see Fig 1 and Fig 2). The velocity measurements were conducted in various positions within a canopy cell (including wake areas). The solid line in Fig 4 is our model prediction, which represents an average velocity profile for the whole cell. This is to be compared to the individual point measurements of velocity within each cell, which vary significantly from point to point. The point C_2 corresponds to the position straight behind the obstacle (wake area) with a clear visible reverse flow (negative velocity). Our simplified models attempt to capture the averaged behaviour. For a variety of obstacle array configurations, we observed a reasonably

good agreement between our model and the measured velocity profiles.

2.2. Mean CBRN Concentration Profiles

For the derived velocity profile in and above the canopy we computed the mean concentration field from the advection-diffusion equation. For the power-law profile the mean concentration can be modelled by the well-known stretched exponential solution (see Monin and Yaglom 1978)

$$C = C_y(y, x)C_z(z, x),$$

where x is downstream distance, y is the distance from the plume centroid in the lateral direction, C_y is the lateral concentration profile (Gaussian function of y) and

$$(3) \quad C_z = B \exp\left(-\left(\frac{z}{\sigma}\right)^\alpha\right)$$

is a stretched exponential profile. The functions $B(x)$ and $\sigma(x)$ are determined by source intensity and downstream position, and the parameter $\alpha = 1 + 2m$ is determined only by the velocity profile parameter m .

The profile (3) is valid above the canopy top (i.e. $z > d$) and should be matched with the pollutant concentration modelled within the canopy.

Two models of the concentration profile within the canopy were validated. The first model was a “clipped” profile, when we simply assumed a constant value of concentration for $z < d$. The justification for such a model is the strong process of turbulent mixing that occurs within the canopy that should “smooth out” all concentration gradients. The data fit to the “clipped” model for different downstream positions is presented in Fig 5. The left column is the vertical concentration profile and the right column is the lateral structure of the plume with a Gaussian fit. The concentration is normalised to the known pollutant at the source rate. This removes source strength as a free parameter and enforces conservation of pollutant material at each downstream position.

