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.

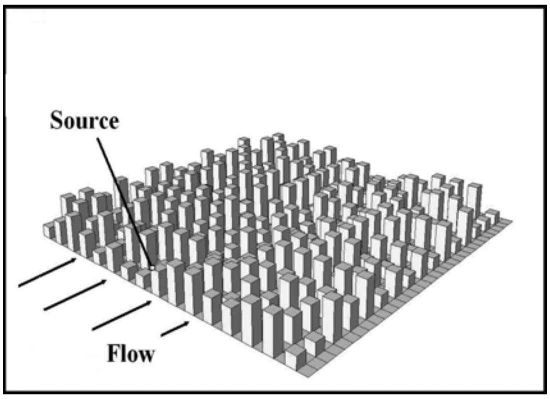

Figure 1: An example of one of the obstacle arrays

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.

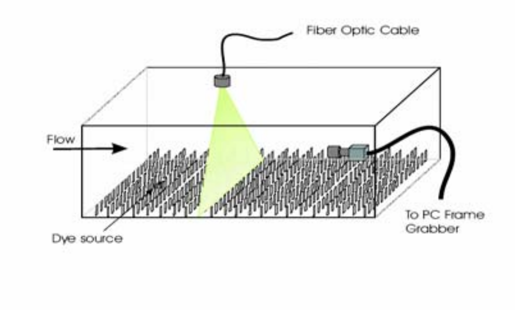

Figure 2: Schematic representation of the experimental setup, depicting the sheet of laser light intersecting the dispersing fluorescent dye in a surface layer flow with canopy objects.

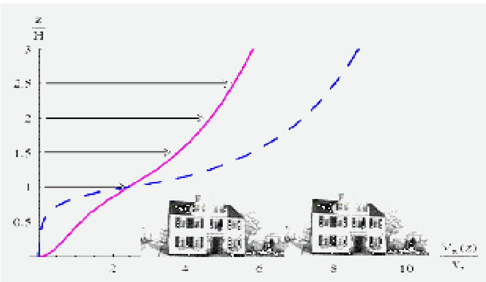

Figure 3: The calculated wind profile in sparse (solid line) and dense (dashed line) canopies based on the proposed model. The dashed line corresponds to the lower value of the parameter ε (dense canopy).

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):

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

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

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

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

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

where all parameters in this formula are determined by the canopy morphology (H is the canopy hight, 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 ($\varepsilon >> 1$) and dense ($\varepsilon << 1$) 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.

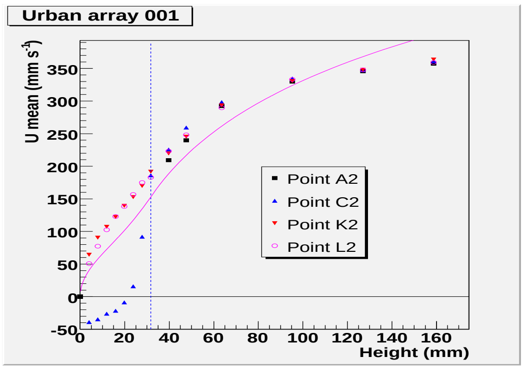

Figure 4: Measured velocity profiles for a simulated urban canopy at different positions relative to canopy objects.

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

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

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.

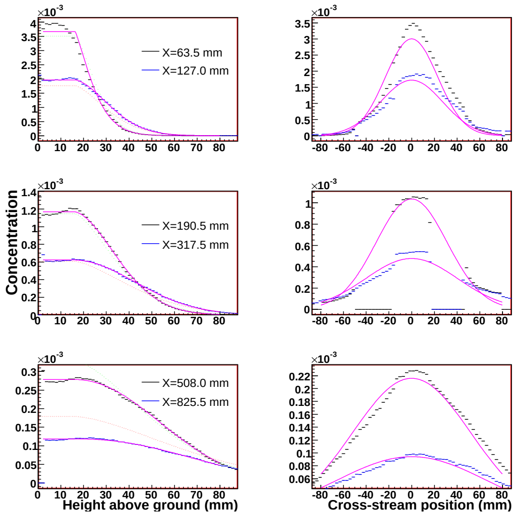

Figure 5: Concentration data fit in the "clipped" model ($C_{z,}$ for the left column and C_y for right column). Horizontal axis is the distance from the ground (left column) and from the centre of the channel (right column).

The second evaluated concentration model was based on allowing the variation of α with height to provide the best data fit i.e. $\alpha = \alpha(z)$**.** The rationale behind this framework was the known limiting values of α: $\alpha = 1 + 2m$ for $z > d$, and $\alpha = 2$ near $z << d$ (stagnation areas near ground in a deep canopy). As a reasonble approximation we proposed

$$\alpha = (1+2m)(1+\phi\exp(-z/d))$$

where

$$\phi = (1-2m)(1+2m)$$

is a function of the velocity profile parameter m and canopy parameter ε (since $d = d(\varepsilon)$).

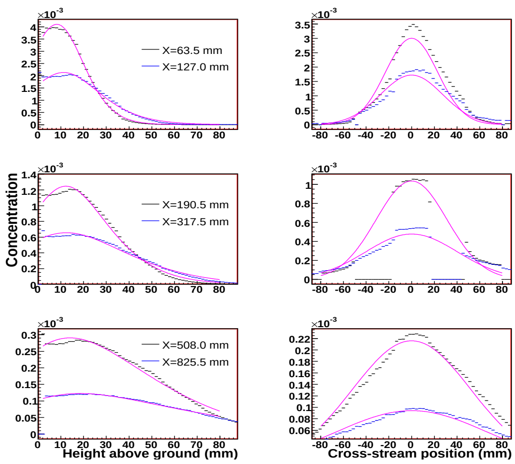

Figure 6: Concentration data fit in "variable α" model. All notations are as in **Fig 5**.

The data fit to the "variable α" model is presented in Fig 6 (left column). As in Fig 5, the right column is the lateral structure of the plume with a Gaussian fit.

In general we observed that both models are in good agreement with the experimental data. The data fits are nearly indistinguishable downstream of the source. Closer to the source the "variable α" model seems to be a better representation of the vertical plume structure. The better performance of the "variable α" model can be attributed to the more adequate description of the process of turbulent mixing in the canopy layer (i.e. mixing is changing within the canopy with height). The "clipped" model corresponds to the constant mixing in the canopy. For dense canopies with the stagnation flows near the ground changes with height are not so importation (Harman *et al* 2007) and both models produce very close results.

2.3. Concentration Fluctuations

The approach outlined above models the development of a "mean plume" within a complex environment. This is the time average behaviour of a real dispersing plume, or equivalently, the average pattern that would be seen if an identical release of material was performed many times. Model analysis of CBR events also requires the development of "concentration realisation" models that give a statistically sound representation of possible instantaneous patterns of plume dispersion. This is important to enable the investigation of uncertainty or risk in CBR hazard assessments, as well as to provide realistic synthetic environments for operational analysis studies.

A model of plume concentration fluctuations has been developed based on the so-called "fluctuating plume" approach, where overall fluctuations are represented as a combined effect of slowly oscillating plume meander and fast in-plume fluctuations. Thus, for the conditional Probability Density Function (PDF) of concentration in absolute frame f the following general representation was adopted (Gailis *et al* 2007):

$$f(C;\mathbf{x}) = \int f_r(C;\mathbf{x}-x_c)\, f_c(\mathbf{x};x_c)\, dx_c$$

where f_c is the PDF of centroid meander, f_r is the concentration PDF in relative frame (associated with plume centroid), $x_c(t)$ is the position of centroid.

Development of realistic models for f_r and f_c requires the application of rather complicated statistical methods and are described in detail in our other publications (see Gailis *et al* 2006, Gailis *et al* 2007, Skvortsov *et al* 2007). We have proposed a model where the PDF for vertical plume meander can be described by a Gamma distribution while the PDF for horizontal meander is always close to Gaussian. We have proposed the model for in-plume fluctuations in a recent paper (Borgas *et al* 2007) where we related the concentration fluctuation intensity

$$i^2 = \frac{< C^2 >}{(< C >)^2} - 1$$

with the flow parameters within and above the canopy. The important conclusion is that the statistical properties of the plume in the canopy can be parameterised with the flow parameters (m,ε), so a proposed two-parameter model of the velocity profile (1) also provides a consistent framework for concentration fluctuation modelling.

3. CONCLUSIONS

Physics based models of a plume in an urban canopy allow a simplified (but still adequate) analytical description of pollution transport in a complex environment, particularly useful for CBR applications. The proposed theoretical framework has been validated against our experimental data (water channel experiment) and provided a close match. The proposed framework can help to validate and justify some more empirically based and heuristic assumptions of operational dispersion models currently available to the ADF. Our modelling framework can thus be used as a valuable performance check of such models, or is in a form available for extension to an operational model prototype, able to be linked to larger modelling systems. With the development of enhanced CBR defensive capabilities now seen as a priority within the ADF, the model described here is an important contribution to this larger scale effort.

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