A Model for Buoyant Puff Dispersion in Urban Areas

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Introduction

• The Urban Dispersion Model (UDM) was developed to satisfy an MOD requirement for prediction of toxic contaminants in urban areas from 10 m to 10 km.

• A Gaussian puff model combined with wind tunnel data approach was adopted to:
  – Provide **rapid** predictions of urban dispersion;
  – Enable a wide variety of releases to be simulated: instantaneous, continuous, static or moving.
Introduction

• UDM is a component of the Hazard Prediction and Assessment Capability, and has been continuously developed to handle a wider range of sources.

• A first-order buoyant puff model has now been developed.

• The model enables UDM to predict the dispersion of material with significant buoyancy resulting from:
  – The density of the material;
  – Heat input.
Basis of Model

• A literature review by Hall and Spanton showed:
  – No simple model existed for predicting the buoyant rise of puffs of arbitrary size and shape;
  – There was no data from systematic experiments on buoyant puff-rise;
  – There was no data on the dispersion of buoyant puffs or plumes within or just above the urban canopy.
• They concluded a model could be developed from theory relating to atmospheric thermals in still air\(^1\).

\(^1\)Developed by Csanady (1973), Turner (1973), Scorer (1978) and Fannelop (1994).
Model Assumptions

• The first-order approach assumes the following:
  – There is no initial energy apart from the buoyancy;
  – The Boussinesq approximation holds;
  – The puff forms are self-similar at all heights;
  – There is no initial vertical acceleration of the puff;
  – The source of buoyancy is preserved;
  – The rate of lateral spreading is equal across both coordinates of the puff.
Puff-rise in Open Terrain

- The model predicts puff spread ($\sigma$) and vertical velocity ($w$).
- Puff shapes are assumed to vary linearly between the extremes of axisymmetric and line forms:

  \[
  \text{Axisymmetric puff : } \frac{\sigma_x}{\sigma_y} = 1 \quad \text{, line puff : } \frac{\sigma_x}{\sigma_y} < 0.1 \quad \text{or} \quad \frac{\sigma_x}{\sigma_y} > 10
  \]

- The puff spread is given by:

  \[
  \frac{d\sigma}{dz} = F(\alpha) \quad \text{where } F(\alpha) \text{depends upon the puff shape}
  \]
Puff-rise in Open Terrain

• The buoyancy forces for axisymmetric and line thermals are $F_0$ and $F_L$ respectively:

$$F_0 = \frac{g}{\pi} \frac{\Delta \rho}{\rho} V \quad \text{and} \quad F_L = \frac{g}{\pi} \frac{\Delta \rho}{\rho} V$$

where $\rho$ is density and internal volume $V$ depends upon puff shape.

• The vertical velocity is given by:

$$w = C \left( g \frac{\Delta \rho}{\rho_0} R \right)^{0.5} \quad \text{where} \ C \ \text{is a constant and} \ R \ \text{the lateral spread}$$
Puff-rise in Open Terrain

- The common form for all puffs derived by Hall and Spanton is:

\[ w = F(\beta) \left( \frac{F(\gamma)Q}{\sigma_x \sigma_y} \right) \]

- \( F(\beta) \) = constant depending on puff shape,
- \( F(\gamma) \) = volume scale factor = \( \frac{0.74 \min(\sigma_x, \sigma_y)}{\sigma_z} \)
- \( Q \) = initial heat release in MJ, and \( F_0 = 8.9Q \)
Merging Buoyant Puff-rise with Dispersion by Turbulence

• UDM merges turbulence and array dispersion components by summing in quadrature:

\[ \sigma_{total}^2 = \sigma_{turbulence}^2 + \sigma_{array}^2 \]

• The interaction between buoyant puff-rise and spread by turbulent dispersion is accounted for by using:

\[ \sigma(t + \Delta t) = \sigma(t) + \left( \Delta\sigma_b^2 + \Delta\sigma_{total}^2 \right)^{0.5} \]
Example output

Rapid rise initially

Axisymmetric Line

Heat release, $Q = 10$ MJ
Windspeed at 10m = 2 m s$^{-1}$
$z_0 = 0.3$ m
Source area = 10 m$^2$
Over-lapping puffs

- When puffs over-lap during simulations, their varying densities must be accounted for.
- Buoyancy enhancement is assumed proportional to the additional concentration of over-lapping puffs.
- Puff buoyancy is enhanced by the factor $F(\delta)$:

$$F(\delta) = \frac{C_{\text{total}}}{C_{\text{max}}}$$

Where $C_{\text{total}}$ is total cumulative concentration at the puff centre, and $C_{\text{max}}$ the concentration at the puff centre.
Interaction with Isolated Obstacles

- Experiments on plumes by Hall et al. have shown that buoyant plumes will lift-off:

Neutral buoyancy

High buoyancy
Interaction with Isolated Obstacles

- Interactions are accounted for by development of the puff partitioning in UDM to incorporate buoyant puffs:
Conclusions

- A simple first-order model has been developed for thermal plume and buoyant puff-rise:
  - Its behaviour is in accordance with observations;
  - It integrates the prediction of buoyant puff-rise with dispersion due to turbulence;
  - It accounts for changes in puff-rise velocity due to changes in puff depth and over-lapping puffs;
  - It models interactions with urban arrays and obstacles.
Questions?