A MODEL FOR BUOYANT PUFF DISPERSION IN URBAN AREAS

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Abstract: The Urban Dispersion Model (UDM) is a Gaussian puff model that has been optimised for rapidly predicting the dispersion of hazardous material in urban areas. As part of an on-going development programme to enable the model to handle a wider variety of releases, modifications have been made to the code to model the complex process of buoyant puff rise in urban areas. Research conducted by Hall and Spanton has led to the development of a first order model for estimating buoyant puff rise effects. This model is based on developing the theory relating to thermals in still air to include advection by the wind and additional dispersion by atmospheric turbulence. The new model has been integrated into the UDM dispersion modelling framework, to predict buoyant puff rise taking account of dispersion due to atmospheric turbulence and isolated obstacle and urban array interactions. Testing of the model has verified that it provides a plausible prediction of the behaviour of buoyant puffs in neutral, stable and unstable meteorological conditions.

***Key words:** Buoyant gas rise, urban dispersion, Gaussian puff model.*

INTRODUCTION

The UDM is a Gaussian puff model that is optimised for rapidly predicting the dispersion of hazardous material in urban areas. The model was originally limited to handling the dispersion of ground-based releases of neutrally buoyant gases, but since its incorporation into the Defense Threat Reduction Agency's Hazard Prediction and Assessment Capability (HPAC) it has been the subject to an on-going programme of development to enable it to handle a wider variety of materials and releases. The most recent stage of the programme has led to the introduction of modifications into the model to account for the complex process of buoyant puff rise in urban areas.

In most circumstances the dispersion of hazardous material releases can be modelled by considering the material to disperse as either a neutrally buoyant or dense gas. In certain cases, however, due to either the input of heat or because of its intrinsic density, the released material may have significant buoyancy. This buoyancy can lead to plume or puff rising. This has a substantial effect on the evolution of the subsequent dispersion and the potential effects of the release. The dispersion model must therefore account for the physics associated with the buoyant puff rise process to produce accurate dispersion predictions.

The general philosophy in developing UDM has been to use existing models where possible. In the case of modelling buoyant puff rise however, research by Hall and Spanton failed to identify a simple model that could handle releases of arbitrary size and shape and height above the ground, and the effects of interactions with obstacles and urban arrays. Furthermore, their research revealed that not only was the literature devoid of a simple buoyant puff rise model, but also of systematic experimental information in general, and of buoyant puff or plume dispersion from within or just above the urban canopy in particular.

BASIS OF MODEL AND ASSUMPTIONS

The literature review conducted by Hall and Spanton concluded that the best approach to developing a simple buoyant puff rise model was through further developing the theory relating to atmospheric thermals in still air to include advection by the wind and additional dispersion by atmospheric turbulence. It was noted, however, that both Turner (1973) and Scorer (1978) remarked on the high level of variability in the behaviour of thermals even in tank experiments. This was supported by Hall et al (2001) who recorded similar highly variable behaviour in elevated puff experiments in a wind tunnel. Based on this evidence, it was considered impractical to accurately model the rise and dispersion of buoyant puffs within a fast response model such as UDM. The goal was therefore to construct a model that provided a first order prediction of the effects of buoyant puff rise.

The buoyant puff rise model developed is based on work described by Csanady (1973), Turner (1973), Scorer (1978) and Fannelop (1994) and is applicable to atmospheric thermals, which are essentially buoyant puffs. The first order approach adopted means that the model incorporates the following assumptions:

- There is no initial energy in the source apart from its buoyancy;
- The Boussinesq approximation holds (i.e. the density difference is small);
- The puff forms are self-similar at all heights;

- There is no initial vertical acceleration of the puff (i.e. it immediately develops its vertical velocity);
- The source buoyancy is preserved in its subsequent dispersion;
- The rate of lateral spreading is the same across both coordinates of the puff.

PUFF RISE MODEL FOR DISPERSION IN OPEN TERRAIN

Experimental observations by Scorer (1973) showed that buoyant puffs may be considered to exhibit self-similarity with height. Equation (1) is Scorer's result for the growth of a thermal with height, *z*, above the source, in which θ is a constant of proportionality and *R* the lateral radius of an axisymmetric thermal, or half-width of a line thermal.

$$z = \theta R \tag{1}$$

The theory presented by Scorer and others, leading to equations for the vertical velocity of axisymmetric or line thermals in still air is based on dimensional analysis. The work of various researchers was consolidated by Scorer, who summarised the results for axisymmetric and line thermals in a common format. Equation (2) is Scorer's common format result for the vertical velocity, where *C* is a constant of proportionality, $\Delta\rho$ the initial puff density difference from ambient, ρ the ambient air density and *g* the acceleration due to gravity.

$$w = C\left(g\frac{\Delta\rho}{\rho_0}R\right)^{0.5} \tag{2}$$

Given that the buoyancy forces for axisymmetric and line thermals, F_0 and F_L respectively, are given by:

$$F_0 = \frac{g}{\pi}\frac{\Delta\rho}{\rho}V \quad \text{and} \quad F_L = \frac{g}{\pi}\frac{\Delta\rho}{\rho}V \tag{3}$$

The internal volume, V, of the thermal is given by equation (4).

$$V = mR^n \tag{4}$$

Where *n*=3 for an axisymmetric thermal and *n*=2 for a line thermal, and *m* is a substitute for the volume of a sphere or cylinder respectively that accounts for the slightly oblate form of the thermal.

The need for UDM to be able to handle puffs of arbitrary form is addressed by defining the dimensions of the puff in terms of the spreads, so the radius of the puff, or length of a finite line source are replaced by R=σ, and L=2σ respectively, and by defining axisymmetric and line puffs to exist within the limits given in equation (5) below.

$$\text{Axisymmetric puff}: \frac{\sigma_x}{\sigma_y} = 1 \quad , \ \text{line puff}: 0.1 > \frac{\sigma_x}{\sigma_y} > 10 \tag{5}$$

In practice, *m* in equation (4) effectively gives the depth of axisymmetric and line thermals as 0.72R and 0.76R respectively. For application in the current model it was assumed that an average of the two values was consistent with the approach, and that the puff depth should be based on the smallest lateral dimension. The puff depth is then given by:

$$\sigma_z = 0.74\min\left(\sigma_x, \sigma_y\right) \tag{6}$$

With the assumption that puffs of arbitrary forms may be defined by linearly interpolating between the extremes represented by axisymmetric and line puffs, Hall and Spanton derived common forms for the equations (1) and (2) to represent all puffs. These forms are shown in equations (7) and (8), in which F(α) and F(β) are appropriate constants for puffs varying in shape between axisymmetric and line.

$$\frac{d\sigma}{dz} = F(\alpha) \tag{7}$$

$$w = F(\beta)\left[\frac{Q}{\sigma_x \sigma_y}\right] \quad (8)$$

In equation (7) the initial heat release in MJ, Q, is substituted for the buoyancy force based on the relationship shown in equation (9), as this may be determined more easily for many releases. This is given by:

$$F_0 = 8.9Q \quad (9)$$

Equations (7) and (8) depend only upon local puff parameters, which enable ground or elevated releases to be handled without reference to their height above the ground.

MERGING OF BUOYANT PUFF RISE WITH DISPERSION BY TURBULENCE

Following the approach adopted in AERMOD and other models, the components of dispersion in UDM are summed in quadrature. This is illustrated by equation (10), which shows the summation of turbulence and urban array induced components of dispersion.

$$\sigma_{total}^2 = \sigma_{turbulence}^2 + \sigma_{array}^2 \quad (10)$$

The effect of puff rise cannot be simply added into equation (10) as there is a direct interaction between the buoyant puff rise and spread and puff dispersion by atmospheric turbulence. This is because atmospheric dispersion increases the puff size and thus reduces its upward velocity. This interaction effect is accounted for by incrementing the dimension of the puff on any coordinate in the way shown in equation (11). In which $\Delta\sigma_b^2$ is the increment due to vertical buoyant puff rise and growth, and $\Delta\sigma_t^2$ is the increment due to atmospheric dispersion which automatically accounts for the effects of atmospheric stability.

$$\sigma(t + \Delta t) = \sigma(t) + \left(\Delta\sigma_b^2 + \Delta\sigma_t^2\right)^{0.5} \quad (11)$$

The form of equation (11) means that the final increment in spread is dominated by the larger of $\Delta\sigma_b$ and $\Delta\sigma_t$. This ensures that the spread is consistent with descriptions of the initial stages of buoyant puff and plume dispersion in which the initial path is observed to be close to vertical, but then becomes horizontal.

The process of merging buoyant puff spread with that due to atmospheric turbulence will generally result in the puff shape diverging from the self-similar form for puff depth assumed in equation (6). This would affect the total mass on which the buoyant force acts, and alter the puff rise. This effect is removed by introducing an additional function F(γ) to scale the volume of air in the puff, and equation (8) is modified to the form:

$$w = F(\beta)\left[\frac{F(\gamma)Q}{\sigma_x \sigma_y}\right] \quad \text{where} \quad F(\gamma) = \frac{0.74\,\min(\sigma_x, \sigma_y)}{\sigma_z} \quad (12)$$

OVER-LAPPING PUFFS

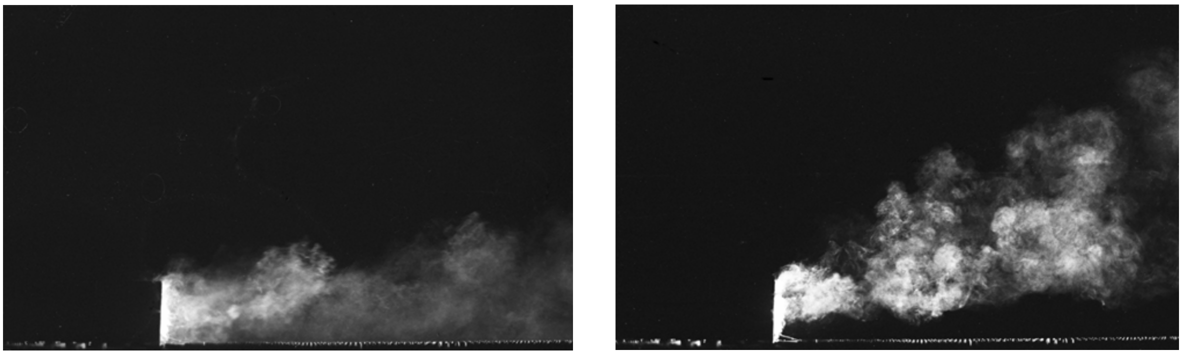
The fundamental basis of UDM is that atmospheric dispersion may be simulated by using multiple puffs. This is straightforward when the puffs are neutrally buoyant as they may be assumed to disperse independently, even when they overlap. When the puffs are not neutrally buoyant and of varying densities then if they overlap they will interact, and this must be accounted for. The approach adopted in the model is to assume that the relative density of the puff is proportional to the concentration of the buoyant material. This means that the buoyancy enhancement is directly proportional to the additional concentration due to over-lapping puffs. The individual puff buoyancy is enhanced by the factor F(δ), defined as:

$$F(\delta) = \frac{C_{\text{total}}}{C_{\text{max}}} \quad (13)$$

In equation (13) C_{total} is the total cumulative concentration at the puff centre due to over-lapping puffs, and C_{max} the concentration at the puff centre.

INTERACTION OF BUOYANT PUFFS WITH ISOLATED OBSTACLES

Work by Hall et al (1980) on plumes of varying buoyancy dispersing from an obstacle wake showed that complex wake/buoyant plume interactions took place. Experiments with plumes of varying density showed that a sufficiently buoyant plume would lift-off as shown in Figure 1. However, the literature search conducted failed to discover any systematic experimental data on buoyant plume rise interaction with either urban arrays or isolated obstacles. The interaction model adopted is therefore based on knowledge of the interaction of neutrally buoyant puffs with wakes, urban arrays and isolated obstacles.



a b

Figure 1. Flow visualisation of plume discharges from building wake with (a) neutral and (b) high buoyancy (Hall et al 1980).

The approach adopted was to further develop the partitioning process for neutrally buoyant puffs developed by Hall and Spanton (2008) to handle buoyant puffs. This means that when a buoyant puff that interacts with an obstacle: 1) the puff is partitioned and buoyancy proportionately attributed to the partitioned puffs which may then travel around or over the obstacle; 2) buoyant puff mass is entrained into a building wake. Two puff fractions are then calculated for the puff to be released from the wake at each timestep. One fraction is calculated following the usual procedure for a neutrally buoyant puff, but in addition, the rise of the whole puff in the obstacle wake is determined. The fraction of the puff that then sits above the wake is assumed to detrain. The masses of the two fractions are then summed to create a single puff which is detrained by calculating its rise and horizontal travel during the simulation timestep. Further puffs are detrained from the wake at subsequent timesteps until a minimum concentration threshold is reached.

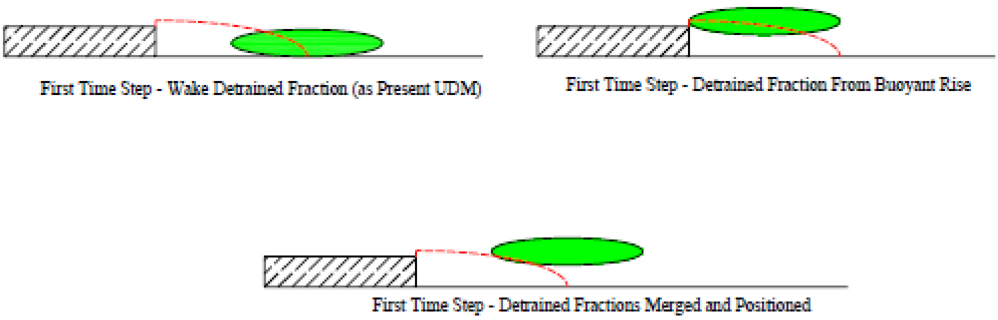


Figure 2. Schematic of model for buoyant puff detrainment from a building wake.

INTERACTION OF BUOYANT PUFFS WITH URBAN ARRAYS

The key feature of UDM is its modelling of the dispersion through urban arrays, and the buoyant puff model must support this. This is achieved by determining the initial spread rate and puff rise as if the puff was in open terrain. In subsequent timesteps, however, the advection velocity, rise and spread are calculated in accordance with equations (7) (8) and (11), except that the turbulence component in equation (10) is enhanced through calculating the quadrature sum of the array and atmospheric turbulence components. If the release is not made at ground level, then the effect of this on the array component and advection velocity is accounted for using the elevated puff model derived by Hall and Spanton (2012).

RESULTS AND DISCUSSION

Examination of the buoyant puff model outputs has shown that there is a marked reduction in puff rise due to the additional dispersion from atmospheric turbulence as might be expected. The outputs also show that the puff eventually loses its memory of the source characteristics, and that all initial puff shapes evolve towards the axisymmetric form over time, and the initial puff velocities have a marked dependence on Q. Plume experiments on buoyant rise from the ground or in contact with buildings made by Hall et al (1995) and Hall and Walker (2002), showed that increasing the puff surface area or distributing it across the wind considerably inhibited the buoyant rise. This characteristic is reproduced by the model, and the initial puff size and shape are consistent with measurements of buoyant plume rise from the ground made by Hall et al (1995) and Hall and Walker (2002).

The behaviour of puffs in still air as thermals is fairly well documented for the two limit cases of axisymmetric and line thermals but not intermediate forms. Very limited experimental data on buoyant puff releases in boundary layer flows exists, and virtually none on interactions with obstacles or arrays. It has not been possible to validate (or calibrate) the model with any experimental data. Based on the information available, however, the model produces plausible predictions of the behaviour of buoyant puffs in neutral, stable and unstable meteorological conditions.

Due to the simple approach adopted the model is not applicable to complex source terms where other thermodynamic effects occur such as liquid fraction boiling or latent heat releases. For example, gases stored under pressure or at low liquefaction temperatures. However, the model is equally valid for dense gas releases, and has therefore been integrated into the existing UDM dense gas model.

CONCLUSIONS

A simple first order model has been developed for thermal plume and buoyant puff rise that accounts for the effects of area sources, and surface obstacle interactions. This model has been integrated into the UDM dispersion modelling framework. This means that the prediction of buoyant puff rise is integrated with the prediction of dispersion due to atmospheric turbulence, accounting for changes in puff rise velocity due to changes in puff depth and over-lapping puffs.

Modifications have been incorporated into the isolated obstacle and urban array interaction modelling in UDM to allow for the presence of buoyant puffs. The interaction of buoyant puffs with obstacles leads to the detrainment of rising puffs from the wakes, while bulk urban array interactions are simply handled by modifying the component of turbulent dispersion.

Testing of the model has verified that the predicted dispersion behaviour is in accordance with the observations made in buoyant plume experiments. Testing has also verified that the model provides a plausible prediction of the behaviour of buoyant puffs in neutral, stable and unstable meteorological conditions. However, a lack of systematic experimental data means that it has not been possible to validate (or calibrate) the model.

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