MODELLING OF BUILDING EFFECTS IN ADMS

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In this document 'ADMS' refers to ADMS 5.2, ADMS-Roads Extra 4.1, ADMS-Urban 4.1 and ADMS-Airport 4.1. Where information refers to a subset of the listed models, the model name is given in full.

Summary

The building effects module calculates the near field dispersion of pollution from sources close to large buildings or groups of buildings represented as a single effective building.

The model has the following features:

(1) A complex of rectangular or circular buildings is replaced by a single block with equivalent crosswind and vertical dimensions. This is carried out separately for each source and met line.

(2) The disturbed flow field consists of a recirculating flow region in the lee of the building and a turbulent wake downwind.

(3) There is a uniform concentration within the well-mixed recirculating flow, which is calculated based upon the fraction of material entrained.

(4) Concentrations in the main wake are the sum of a ground-level plume from the entrained fraction and an elevated plume from the remainder.

(5) Wake decay reduces the height of elevated plumes. Plume spread within the wake is increased by the combined effects of the mean velocity deficit and excess turbulence in the wake.

The building effects module uses the underlying dispersion model concentration profiles with modified plume parameters.

CONTENTS

1. INTRODUCTION

A large bluff surface obstacle, such as an industrial building, has a significant impact on the boundary-layer flow in its vicinity and the dispersion of airborne pollution from nearby sources. Comprehensive accounts of building effects on dispersion are given by Hunt *et al.* (1978), Meroney (1982), Hosker (1984) and Foster and Robins (1985). The main features of the flow field which influence dispersion of released material and air concentrations are:

- flow stagnation and streamline impingement on the upwind face,
- streamline displacement and change of turbulence around the building,
- flow separation and recirculating flow;
- an extensive wake with high turbulence, net down-flow and reduced longitudinal velocity,
- vortices formed from the roll-up of shear layers and advected downwind.

The building effects module computes the dispersion of pollution from sources near isolated large buildings or an effective building representing a group of closely spaced buildings. For the module to be called into operation the source must lie within a building effects region whose size is related to the dimensions of the building (or the effective building).

The model for building effects is based on that of Hunt and Robins (1982), described in more detail by Apsley (1988) and Robins *et al.* (1997). The main features of this model are that it can:

- incorporate significant features of the flow field near a large building within a simple dispersion model;
- take full account of source position and admit complete or partial entrainment into the near wake recirculating flow; and
- model the influence on turbulent and mean velocity fields of an extensive downstream wake.

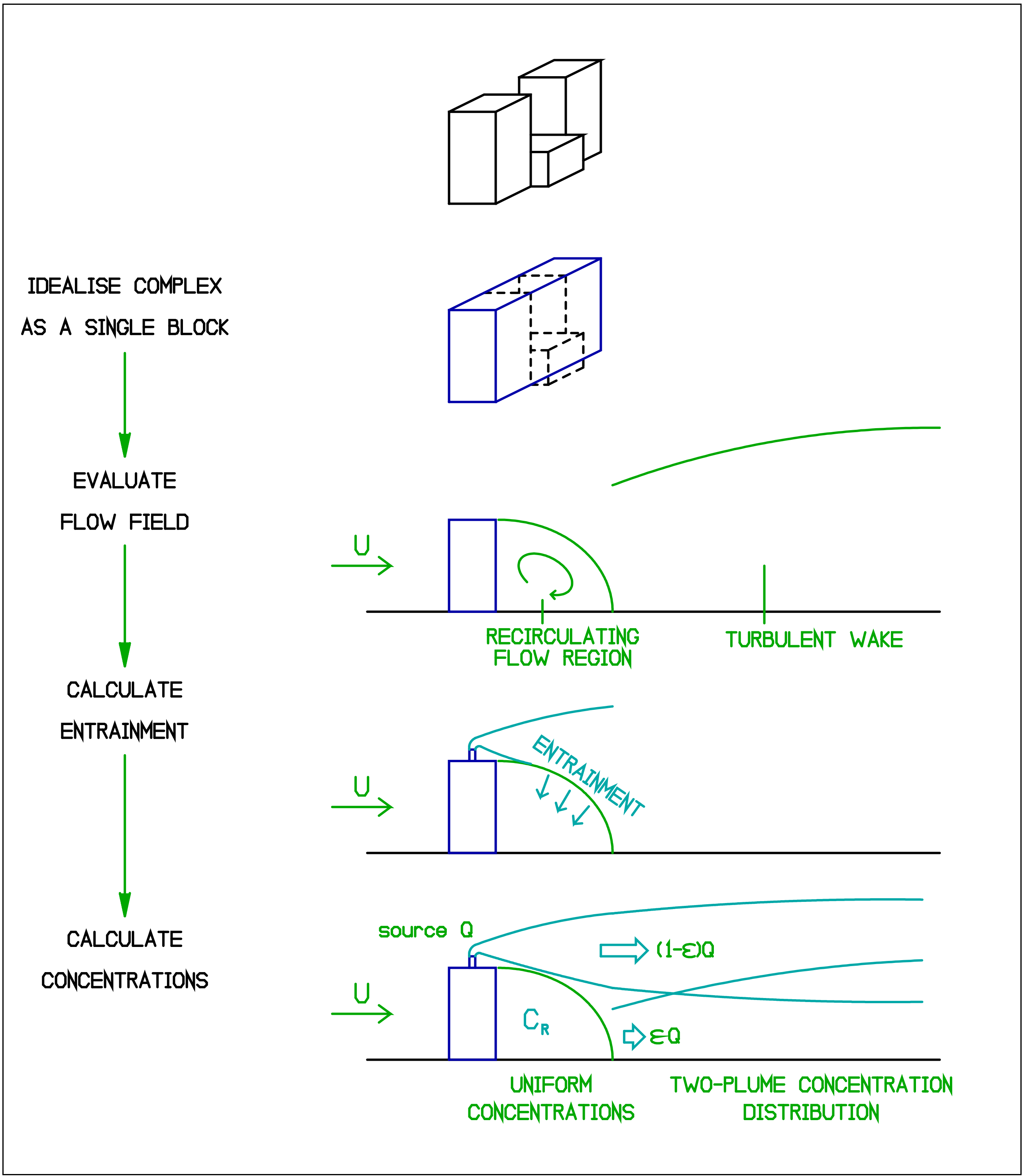

Figure 1. Stages in the analysis of dispersion at a complex site

The stages in the analysis, illustrated in Figure 1, are as follows.

(1) Building dimensions and positions are input through the user interface, either as cuboids or cylindrical buildings. A group of buildings may be specified in this manner and where this is done the first step in the analysis is to replace the group by an 'equivalent' single building. The alignment of this building (or that directly specified at the input stage) relative to the wind is recorded and the building then replaced by an effective building aligned with the flow. Some care is needed in selecting building input information as the size of the recirculating wake region and its effect on dispersion are sensitive to the dimensions of the effective building.

(2) A simplified flow field is defined, based on a well-mixed cavity or recirculating flow region and a downstream wake region with reduced momentum.

(3) The dispersion of released material is parameterised from the source to the downwind extent of the output grid. The release may undergo complete or partial entrainment according to source location and emission conditions. For partially entrained emissions the entrained and non-entrained components form a two-plume structure downwind. The elevated plume centreline follows a mean streamline of the perturbed flow field and alternative spread parameters describe dispersion inside and outside the downstream wake.

(4) Concentrations are calculated from a 'box' model in the recirculation region, and a two-plume Gaussian model downwind.

A perturbed flow field is defined within a region **B** whose extent is determined by the size of the idealised building. The building effects module is only invoked if the source lies within the confines of this region. Concentrations are calculated by the module for all distances downwind from the source.

The building effects module works in the context of an underlying mean concentration model for undisturbed flow, which is assumed to be of the form:

$$C = (Q/U)C_y(y; y_p,\ \sigma_y)C_z(z; z_p,\ \sigma_z, h) \qquad (1.1)$$

where y_p and z_p are measures of plume location, σ_y and σ_z are measures of spread, h is the boundary-layer height, U is an advection velocity and Q is the plume strength. It is not necessary that the measures of spread are the standard parameters, nor that the crosswind and vertical profile functions are Gaussian, although this will often be the case. Profile functions C_y and C_z and the plume parameters $\left(y_p, z_p, \sigma_y, \sigma_z\right)$ are assumed to be known a priori as functions of downwind distance x in the absence of building effects. Except within the recirculating flow where concentrations are assumed uniform, the building effects module calculates concentrations for a unit source using the same profile functions for each plume but with modified plume parameters.

2. GEOMETRY AND FLOW

2.1 Building Geometry

The model is based on the assumption that for dispersion modelling purposes a complex of closely spaced buildings can be replaced by an ‘equivalent’ single rectangular block orthogonal to the approach flow. An effective orientation is specified separately to model appropriate downwash and related processes. There are obvious limitations implicit in these modelling assumptions and care is needed in the definition of building groups.

The user supplies the centre (x_i, y_i) and height H_i of each building, together with the side lengths S_{1i}, S_{2i}, and orientation θ_i for a rectangular building, or the diameter D_i for a circular building. For each wind direction the building effects module determines equivalent idealised building parameters:

H_B building height
W_B crosswind width
L_B along-wind length
θ_B orientation

Note that the idealised building is orthogonal to the flow. The 'orientation' θ_B is a parameter used to define some aspects of roof flow and near-wake behaviour.

The idealised building is derived by the following algorithm.

Circular buildings are converted to ‘equivalent’ square blocks, with the same centre as the input circular building and side length $D_i/\sqrt{2}$, oriented such that the wind is normal to the building face.

Any buildings of height less than a fraction $1/\alpha$ of the source height are ignored, where

$$\alpha = 1 + 2\text{x}\min(1, W_i/H_i)$$

where W_i is the crosswind width of building i.

Any buildings that are greater than a certain distance from the plume centreline in the crosswind direction are ignored. Specifically, a building will be ignored if all its vertices are greater than $0.5\sigma_y(|x|)$ from the plume centreline in the crosswind direction, where x is distance from the source in the alongwind direction, and $\sigma_y(x)$ is the horizontal plume spread (not including building effects) at distance x downwind of the source (see example in Figure 2).

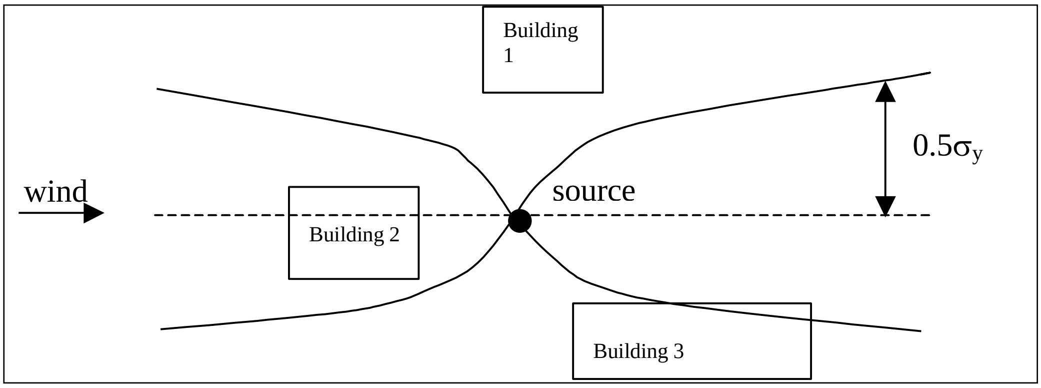

Figure 2. Example source and building configuration. Buildings 2 and 3 will be included in the effective building, but building 1 will not be included.

The user specifies which is the main building; H_B and θ_B are the height and orientation of this unit. Multiples of 90° are added or subtracted until -45°$< \theta_B \leq$ 45°. A different main building may be selected for each source. If the main building is not tall enough to be considered, according to (2) above, then no buildings are modelled for that source. If the main building is too far from the plume centreline, according to (3) above, then an alternative main building is automatically selected. The new main building will be that with its centre closest to the source, of those that are able to modelled according to (3).

A subset Σ is then defined by the main building plus all other buildings (a) that are at least $0.5H_B$ high and (b) whose projected crosswind and along-wind separations from another subset member do not exceed half the projected crosswind width of the main building.

Considering only buildings in Σ, W_B is the projected crosswind width and L_B is the along-wind projection from the furthest upwind mid-face to the furthest downwind mid-face, L_F unless Σ only includes one building, in which case $L_B = \min(L_F, L_D)$, where L_D is the alongwind length of the building, as seen when travelling along the wind direction (Figure 3).

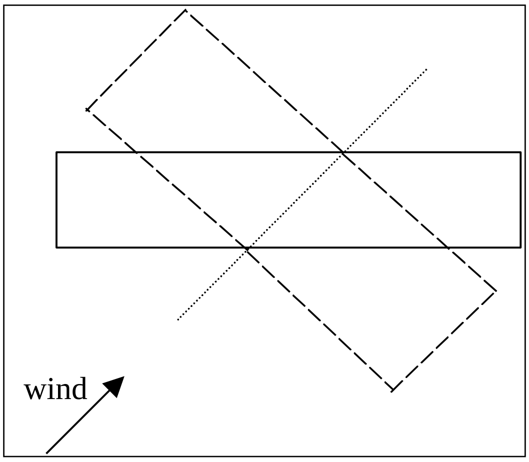

Figure 3. Effective building for case where Σ only includes one building. The user-input building is shown by the solid line, and the effective building by the dashed line.

It is impossible to give universal guidelines for the choice of the *main* building. It is a matter of the user's expertise and discretion to decide which unit should set the overall height of a complex. An example for a comparatively straightforward complex (typical of gas-cooled nuclear power plant) is illustrated in Figure 4.

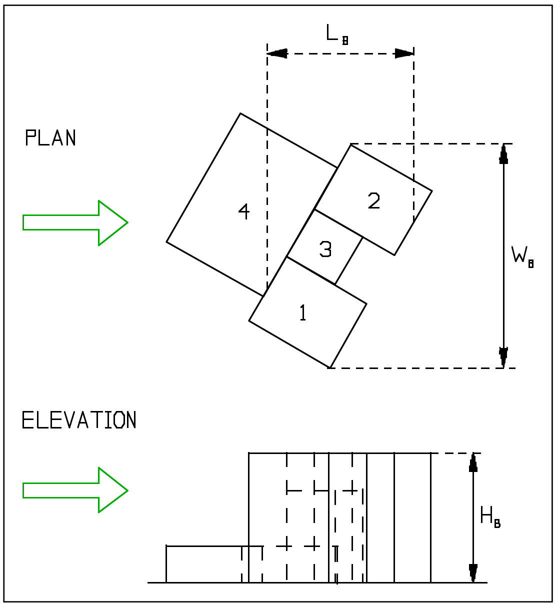

Figure 4. Example of an idealised building constructed from a set of orthogonal blocks

2.2 Coordinate Systems

Building and source locations are input to the module in terms of *user coordinates*, which form a fixed Cartesian system. These are converted internally into *module coordinates* which have origin at the ground centre of the idealised building and x-axis in the direction of the mean wind, as illustrated by Figure 5. Module coordinates will be assumed throughout the remainder of the paper.

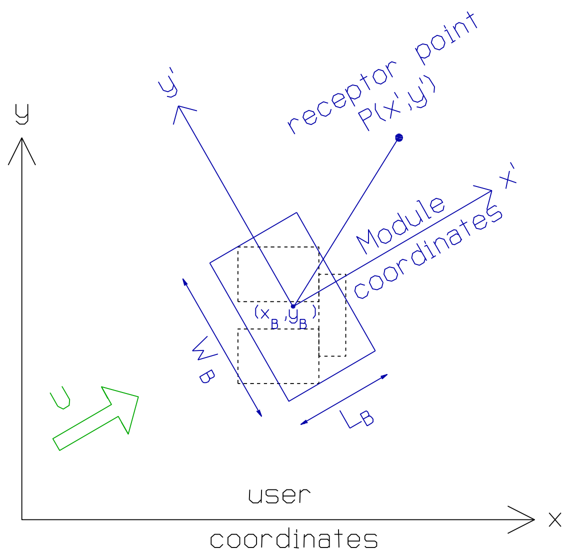

Figure 5. Definition of Module and user coordinates

2.3 Regions of the Flow

The size of the perturbed flow region **B** is determined by the dimensions of the idealised building (H_B, W_B, L_B). The building-affected dispersion model will only be invoked if the source lies within **B.** This region is subdivided, as shown in Figure 6, into the recirculating flow region **R**, wake **W**, and three 'external' sub-regions: **U** directly upwind, **A** the remainder of the perturbed flow around the building and **E** the region external to the wake. For convenience, **U**, **A** and **R** are lumped together as the 'near wake' and **W, E** as the 'main wake'.

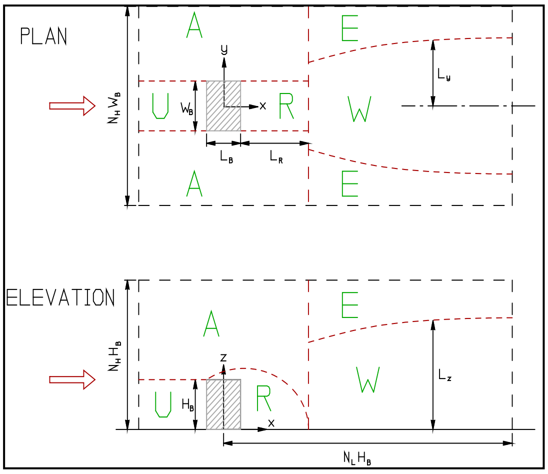

Figure 6. Regions of the flow

The upwind boundary is set on the assumption that building effects can be ignored if a plume's dimensions (evaluated at the upwind face) are larger than the building dimensions. The height and width of **B** are based on extensive wind tunnel studies primarily concerning the sensitivity of building effects to source height. The downwind extent is taken to infinity (in practice, the farthest downstream output point).

The upwind limit of **B**, $x = -x_{min}$, is that at which the lateral or vertical spread from a ground-level source would become equal to the building half-width or height, respectively, of the upwind face; i.e. x_{min} is the smaller of the two values:

$$\sigma_y\left(x_{\min} - \left(\frac{L_B}{2}\right)\right) = \frac{W_B}{2}; \sigma_y\left(x_{\min} - \left(\frac{L_B}{2}\right)\right) = \frac{H_B}{2} \tag{2.1}$$

As noted above no downwind limit is applied. When the flow perturbations become negligible, far downstream, the dispersion behaviour in the module returns to that of the undisturbed flow.

The vertical and crosswind limits of region **B** are given by a modified '3 times rule'.

$$y_{\max} = N_H(W_B/2), z_{\max} = N_H H_B \tag{2.2}$$

where:

$$N_H = 1 + 2\min(1, W_B/H_B) \tag{2.3}$$

The following sub-sections define the recirculating flow and wake regions in more detail.

2.3.1 Near Wake Region

The recirculating flow region **R** is modelled as a volume of uniform cross-section across the width of the building, as illustrated in Figure 7.

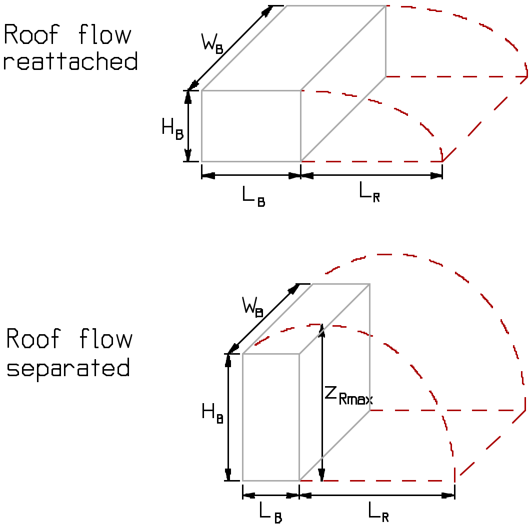

Figure 7. Recirculating flow region

The cavity length L_R and mean residence time T_R in neutral and stable conditions have been derived empirically by Fackrell and Pearce (1981):

$$L_R = \frac{AW_B}{1 + BW_B/H_B}$$
$$A = 1.8\left(\frac{L_B}{H_B}\right)^{-0.3}, B = 0.24 \tag{2.4}$$

where if $L_B/H_B < 0.3$ then $A = A(0.3)$, or if $L_B/H_B > 3$ then $A = A(3)$;

$$T_R = \frac{a(W_B/H_B)^{3/2}}{1 + b(W_B/H_B)^{3/2}}\frac{H_B}{U_H}$$
$$a = 11.0,\ \ b = 0.6 \tag{2.5a}$$

U_H is the approach flow mean wind speed at building height. In convective conditions, T_R is modified to account for the convective turbulence, as follows:

$$T_R = H_B \left\{ \left(U_H \frac{\left(1 + b(W_B/H_B)^{3/2}\right)}{a(W_B/H_B)^{3/2}} \right)^2 + 0.4 {w_*}^2 \right\}^{-1/2} \qquad (2.5b)$$

The upper limit of the region **R** may be described by a function $z_R(x) = z_{R\max} f(x)$ such that $z_R(x = x_R = L_B 70/2 + L_R) = 0$ and $z_R(x_{\text{sep}}) = H_B$, where x_{sep} is the downwind rooftop separation point. The recirculating flow region is formed from the shear layer separating from the leading or trailing edge of the roof, depending on whether the former reattaches. We write:

(a) $L_B \geq \min(H_B, 0.5W_B)$ - roof flow reattaches:

$$z_{R\max} = H_B; \quad x_{\text{sep}} = \frac{L_B}{2} \qquad (2.6)$$

(b) $L_B < \min(H_B, 0.5W_B)$ - roof flow remains separated:

$$z_{R\max} = H_B \left[1 + 0.7 \left(1 - \exp\left\{ \frac{-(W_B - 2L_B)}{H_B} \right\} \right) \right]$$
$$x_{\text{sep}} = \frac{-L_B}{2} \qquad (2.7)$$

Equation (2.7) is an empirical fit to data in Fackrell (1982). For computational purposes $f(x)$ is assumed to be elliptical:

$$f(x) = \left[1 - \left\{ \frac{(x - x_{\text{Rmax}})}{(x_{\text{R}} - x_{\text{Rmax}})} \right\}^2 \right]^{1/2} \qquad (2.8)$$

with the effective volume, needed to calculate recirculation region concentrations, given by:

$$V_R' = \left(\frac{\pi}{4}\right) z_{R\max} L_R W_B \qquad (2.9)$$

2.3.2 Cuboids

Wind tunnel studies have shown how plume heights and concentration fields just downwind of the recirculating region behind a block-shaped obstacle respond to changes in building orientation. The weakest effects arise when the building is normally aligned to the approach flow, and the strongest when 'diagonally' aligned.

Although there are quite important case-to-case variations, experiments with cubic obstacles suggest that in the 'strong' case (orientation $\theta_B = 45°$) the effective height of a roof level emission is reduced to zero, whereas there is no loss of height in the 'weak' case (orientation $\theta_B = 0°$). Emissions above a certain height, here taken to be the upper limit for the perturbed flow region, **B**, are not affected by the building. Although the equivalent building in the dispersion model is implicitly normally aligned to the wind, we assume a downwards flow speed above the recirculating flow region, **R**, which depends on the orientation parameter θ_B:

$$\frac{w}{U_H} = \frac{1}{3}\left(\frac{dz_R}{dx}\right)\left[\frac{z_{\max} - z}{z_{\max} - z_R(x)}\right]\left(\left|\frac{\theta_B}{45}\right|\right) \tag{2.10}$$

The horizontal velocity is assumed to be U_H.
The plume trajectory is horizontal for normal alignment but follows the boundary to **R** to an extent depending on source height and the magnitude of θ_B for oblique wind incidence. For non-passive releases we solve the plume trajectory equation:

$$\frac{dz_p}{dx} = \frac{w}{U_H} + \left(\frac{dz_p}{dx}\right)^{\text{Plume Rise}} \tag{2.11}$$

2.3.3 General Formulation

Relating the maximum mean streamline deflections over the near-wake to the building height is clearly inappropriate for tall buildings, where a zero deflection limit is to be expected for all wind directions as the building side to height ratio tends to zero. Rewriting the algorithm to achieve this, whilst still providing the observed level of downwash over cuboids, is straightforward. A downwash scaling factor, δ, is introduced:

$$\delta = \min\left(H_B, \left\{\frac{H_B(L_B + W_B)}{2}\right\}^{1/2}\right)/H_B \tag{2.12}$$

and is used both to define the level of plume downwash and the plume height range over which it decreases to zero. Equation (2.10) is replaced by:

$$\frac{w}{U_H} = \frac{\delta}{3}\left(\frac{dz_R}{dx}\right)\left[\frac{z'_{\max} - z}{z'_{\max} - z_R(x)}\right]\left(\left|\frac{\theta_B}{45}\right|\right) \tag{2.13}$$

where

$$z'_{\max} = H_B + \delta(z_{\max} - H_B) \tag{2.14}$$

Reduced plume downwash also results in reduced entrainment into the near-wake as the plume centreline remains further from the near-wake boundary. However, the assumption that material is well mixed throughout the near-wake region may overestimate the extent to which material is brought down to the surface for elevated sources, resulting in some overestimation of near ground concentrations in the near-wake for these cases, in particular for elevated sources and tall thin buildings.

2.4 Main Wake Model

The main wake model rests heavily on theory developed for two dimensional wakes (Counihan *et al.*, 1974), which bases the prediction of the wake structure on an eddy viscosity model, with the eddy viscosity defined by the upwind flow conditions. The properties of the approach flow influence wake development through the eddy viscosity and, additionally, the concentration field through the undisturbed spreading rates. Although the eddy viscosity assumption is in itself debatable, the most important limitation of the theory is that it treats only one aspect of wake development, the so-called 'momentum wake' where momentum is reduced and turbulence increased. Equally important, is the 'vortex wake' component that arises as a consequence of the streamwise vortices that are generated in the flow over the building (e.g. the roof vortex system). There is no useful theory for vortex wakes. Mean streamline displacements in the main wake region occur because of the decay of the momentum wake, which produces a secondary flow into the wake centre, and because of flows induced by the streamwise vortex system. The former are calculated, but not the latter. The overall effect of the vortex wake is represented empirically by the algorithm for mean streamline displacements around the building and its near-wake.

2.4.1 Flow Field

Downstream of the recirculating flow, in regions **W** and **E**, a small-deficit wake model is used to describe the perturbed *mean* flow. The model is a simplified 3-dimensional version of that derived by Counihan, Hunt and Jackson (1974). It assumes self-preserving profiles, a uniform approach flow $U = U_H$, and constant eddy-viscosities, $D_{y,z} \propto u_* H_B$. A similar model, but with slightly different crosswind velocities, was used by Apsley (1988). The mean velocity components are:

$$u = U_H \left\{1 - \hat{u} \left[\frac{W_B}{2\lambda_y}\right] \left[\frac{H_B}{\lambda_z}\right]^2 g(\xi) h(\eta)\right\} \tag{2.15a}$$

$$v = -U_H \, \hat{u} \left[\frac{W_B}{2(x - x_0)}\right] \left[\frac{H_B}{\lambda_z}\right]^2 g(\xi) h(\eta) \eta / 2 \tag{2.15b}$$

$$w = -U_H \, \hat{u} \left[\frac{H_B}{(x - x_0)}\right] \left[\frac{W_B}{2\lambda_y}\right] \left[\frac{H_B}{\lambda_z}\right] [g'(0) - g'(\xi)] h(\eta) \tag{2.15c}$$

where:

$$\eta = \frac{y}{\lambda_y} \quad \xi = \frac{z}{\lambda_z} \tag{2.16a}$$

$$\begin{gathered} g(\xi) = \left(\frac{\xi}{2}\right) \exp\left(\frac{-\xi^2}{4}\right) \\ h(\eta) = \left(\frac{1}{2\sqrt{\pi}}\right) \exp\left(\frac{-\eta^2}{4}\right) \end{gathered} \tag{2.16b}$$

The model directly provides the analytical solution for u given in equation (2.15); the expressions for v and w have been derived from this so as to satisfy continuity. The conserved property for the wake is the moment of momentum deficit flux; i.e.:

$$\frac{d}{dx} \int_0^{\infty} \int_{-\infty}^{\infty} z U_H (u - U_H) \, dy \, dz = 0 \tag{2.17}$$

which can be related to the couple on the obstacle and the added pressure couples on the surface near the obstacle. Counihan *et al.* (1974) suggest that in many cases the added couples are negligible for cuboid-shaped obstacles.

The horizontal and vertical crosswind length scales are:

$$\begin{gathered} \lambda_y(x) = \left\{\frac{D_y (x - x_0)}{U_H}\right\}^{1/2} \\ \lambda_z(x) = \left\{\frac{D_z (x - x_0)}{U_H}\right\}^{1/2} \end{gathered} \tag{2.18}$$

where D_y and D_z are eddy viscosities and x_0 is a virtual origin. The eddy viscosities in stable and neutral conditions are given by:

$$D_y = \kappa u_* H_B \quad D_z = 2\kappa u_* H_B \tag{2.19a}$$

and in convective conditions are given by:

$$D_y = \kappa u_* H_B \left(1 + \frac{0.3}{4.0}\left(\frac{w_*}{u_*}\right)^2\right)^{1/2} \tag{2.19b}$$

$$D_z = 2\kappa u_* H_B \left(1 + \frac{0.4}{(4.0 \times 1.3^2)}\left(\frac{w_*}{u_*}\right)^2 \left(T_{WC}(H_B)\right)^2\right)^{1/2}$$

where

$$T_{WC}(z) = 2.1\left(\frac{z}{H}\right)^{1/3}\left(1 - 0.8\frac{z}{H}\right)$$

as in the boundary layer structure technical specification (P09/01).

Mixing length arguments for the perturbation shear stress, or modelling of the effects of extra rates of strain on the eddy viscosity, lead to the expression for D_z (Counihan *et al.*, 1974). D_y is not affected in this way and is simply the eddy viscosity at height $z = H_B$ in the wall layer. The virtual origin, x_0, is set so that the longitudinal velocity remains positive through the main wake region, thus ensuring that streamlines and plume trajectories, which are calculated from equation (2.15), are well behaved. This implies:

$$u > 0 \quad \text{for} \quad x \geq x_R$$

Clearly, there is room for optimising the choice of x_0, though not the data to undertake the exercise. The pragmatic choice is made:

$$u = 0 \quad \text{at} \quad x = \frac{L_B}{2}$$

The magnitude of the perturbation, $\hat{u}$, could also be optimised, but a control volume analysis (Counihan *et al.*, 1974, Apsley, 1988) shows that for cuboids it is related to the non-dimensional couple acting on the body:

$$\hat{u} = \frac{C_G}{\sqrt{\pi}} \quad C_G \approx 0.8 \tag{2.20}$$

There is insufficient experimental data to specify any dependence of C_G on building geometry and flow conditions.

2.4.2 Wake Averaging

While an analytical expression is used for the mean velocity field throughout regions **W** and **E**, turbulence levels are only enhanced by a bulk measure of the excess turbulence within the central wake region **W**. The limits of **W**, $y = \pm L_y = \pm \mu \lambda_y$ and $z = L_z = \mu \lambda_z$, and the mean velocity deficit, Δu, such that $u = U_H - \Delta u$, are derived by a process of *wake-averaging* which requires that these produce the same mean and mean-square velocity deficits as the analytical velocity profile:

$$L_y L_z (\Delta u) = \int_0^\infty dy \int_0^\infty dz \, |u - U_H| \tag{2.21a}$$

$$L_y L_z (\Delta u)^2 = \int_0^\infty dy \int_0^\infty dz \, |u - U_H|^2 \tag{2.21b}$$

From this we find that:

$$\mu = 2\sqrt{2} \tag{2.22}$$

$$\frac{\Delta u}{U_H} = \frac{1}{2} \hat{u} \left(\frac{W_B}{2L_y} \right) \left(\frac{H_B}{L_z} \right) \left(\frac{H_B}{\lambda_z} \right) \tag{2.23}$$

(with a proviso that L_z is not allowed to exceed the inversion height h). **W** is constrained to be at least as wide as the idealised building, i.e. a minimum value of $W_B/2$ is imposed on L_y. In order that (2.23) is limited to be less than unity, the following formulation is adopted by the model:

$$\frac{\Delta u}{U_H} = \begin{cases} Eq(2.23), & \text{if} \dfrac{\Delta u}{u_H} \le \mathrm{B_p} \\ \mathrm{B_p} + (1 - \mathrm{B_p}) * \left[1 - \exp\left(\mathrm{B_p} - \dfrac{\Delta u}{u_H} \right) \right], & \text{if} \dfrac{\Delta u}{u_H} > B_p \end{cases} \tag{2.23a}$$

in which B_P is an empirical parameter set to 0.75. Equation (2.23a) ensures that the velocity u remains positive in the region **W**.

Linearising in small perturbations, the integral momentum balance:

$$L_y \Delta \tau = \frac{d}{dx} \int_0^\infty dy \int_0^\infty dz (u^2 - U_H^2) \tag{2.24}$$

leads to a wake-averaged surface shear stress:

$$\Delta\tau = U_H \Delta u \left\{\frac{L_z}{(x - x_0)}\right\} \tag{2.25a}$$

In stable conditions, (2.25a) is modified to account for the stable wind profile, as follows:

$$\Delta\tau = U_H \Delta u \left\{\frac{\ln(H_B/z_0)}{\ln(H_B/z_0) + \alpha H_B/L_{MO}}\right\}\left\{\frac{L_z}{(x - x_0)}\right\} \tag{2.25b}$$

Here z_0 is the roughness length and L_{MO} is the Monin-Obukhov length. The constant α takes the value 5.2, which is obtained from expanding the expression for Ψ in the boundary layer structure technical specification paper (P09/01) to first order and looking at the coefficient of z/L_{MO}.

The turbulent velocity variances are assumed to increase in proportion to the surface shear stress:

$$\Delta\sigma_v{}^2/\sigma_v{}^2 = \Delta\sigma_w{}^2/\sigma_w{}^2 = \Delta\tau/u_*^2 \tag{2.26}$$

3. DISPERSION

The velocity field information derived in Section 2 is taken as the basis for dispersion calculations. The wake-averaged model is used for calculating the turbulence levels and concentration field. Plume trajectories are defined by the full velocity solution, equation (2.15).

The main features of the Hunt-Robins dispersion model are:

- uniform concentrations within the well-mixed recirculating flow region;
- a double plume concentration profile in the main wake; and
- altered plume spread coefficients in main wake regions **W** and **E**.

For many sources not all the release will be swept into the recirculating flow downwind of the building but dispersion may still be significantly affected by the distorted flow field. The assumption of either low level fully-entrained or elevated point source behaviour alone is inadequate. The model described here allows for a fraction of the released material being entrained into the recirculating flow and subsequently re-emitted as a ground-level plume, and the remainder behaving as an elevated release. A two-plume concentration distribution is then seen in the main wake. Only sources releasing directly into the recirculating flow are regarded as fully entrained.

For sources outside the recirculating flow region, the concentration within **R** is taken to be the average of that which would arise from the non-entrained plume on the boundary of **R** (Puttock and Hunt, 1979). The rate of incorporation of material into **R**, which, in the steady state, is equal to the effective source strength from this region, is then determined from the mean volume of **R** and the residence time. For wide buildings (here taken as $W_B > 3H_B$) an *effective* recirculation region $\mathbf{R}'$ is used for dispersion, since emissions cannot be assumed to be well-mixed across the whole width. This is defined more precisely in Section 3.3.

For passive plumes outside the recirculating flow, the plume centreline $(y_p(x), z_p(x))$ is a streamline of the idealised mean flow field. Cross-streamline transport occurs when the plume possesses excess momentum or buoyancy (Section 3.5). The longitudinal rate of change of dispersion parameters σ_y and σ_z is governed by the local turbulence levels and, in the wake, by the convergence or divergence of mean streamlines. Undisturbed flow values are used for σ_y and σ_z in the near wake, region **A**, but in the main wake region there are two sets $(\sigma_y^{(\mathrm{W})}, \sigma_z^{(\mathrm{W})})$ and $(\sigma_y^{(\mathrm{E})}, \sigma_z^{(\mathrm{E})})$ for dispersion inside and outside **W**. A summary of the dispersion model for different source locations is set out in Table 1.

Source region	Dispersion region			
	Upwind	Recirculation region, **R**	Around **R**	Main wake
U	Undisturbed	Uniform concentration	Elevated plume	Elevated + ground-level plumes
A	Undisturbed	Uniform concentration	Elevated plume	Elevated + ground-level plumes
R	---	Uniform concentration	Ground-level plume	Ground-level plume
E, **W**	---	---	---	Elevated plume

Table 1. Dispersion model features according to location and source

In the table, the term 'elevated plume' is used to describe any plume that is not fully entrained into the recirculation region, which includes ground level emissions in regions **U**, **A** and **W**.

3.1 Source Conditions

The following source parameters are required by the building effects module:

x_s, y_s, z_s	source location
(U_s, V_s, W_s)	emission velocity
D_s	source diameter
ρ_s	emission density

The standard ADMS correction for stack downwash is modified to ensure the adjusted source location is not inside one of the user-defined buildings.

The condition of full entrainment at the source is tested by the following three steps:

(1) If $\mathbf{x_s} \notin \mathbf{R}$, the release is not fully entrained at source.

(2) Otherwise, an estimate is made of the rise that results from the initial momentum and buoyancy fluxes. The components, $\Delta z_s{}^{\mathrm{Buoy}}$ and $\Delta z_s{}^{\mathrm{Mom}}$, are calculated from:

$$\Delta z_s^{\mathrm{Buoy}} = 1.3\left[\left(\frac{3}{2\beta^2}\right)\frac{F_B H_B^2}{U^3}\right]^{1/3} \tag{3.1a}$$

$$\Delta z_s^{\mathrm{Mom}} = 1.8\left[\left(\frac{3}{\beta^2}\right)\frac{F_M H_B}{U^2}\right]^{1/3} \tag{3.1b}$$

where $\beta = 0.6$ is an entrainment parameter, F_B and F_M are the buoyancy and momentum fluxes, defined as:

$$F_B = g'Q_v; \quad F_M = \alpha W_s Q_v; \quad Q_v = A_s W_s/\pi \tag{3.2}$$

where α is the ratio of the emission and ambient densities, $g' = g(1\text{-}\alpha)$ and A_s is the source area. The plume is assumed to be trapped and hence fully entrained when:

$$z_R(x_s) - z_s \geq \Delta z_s^{\mathrm{Buoy}} + \Delta z_s^{\mathrm{Mom}} \tag{3.3}$$

where the left hand side is the height difference between the source and the edge of the recirculation region. These estimates have been specified so as to be broadly consistent with ‘lift-off’ criteria derived from wind tunnel experiments of plumes released into building wakes (e.g. see Robins, 1994, 1997).

(3) All other releases are fully entrained.

Note that the rise correction is used only to establish whether there is initial entrainment. For partially-entrained releases the plume rise module integrates the rise equations from the source location corrected only for stack downwash.

3.2 Concentrations Upwind of the Building

Concentrations upwind of the building and on the upwind face (following Hunt and Mulhearn, 1973) are assumed equal to those in the absence of building effects. Thus, for sources in the regions **U** and **A**, when $x_s < x \leq -L_B/2$:

$$C = Q/U_p C_y(y; y_p, \sigma_y) C_z(z; z_p, \sigma_z, h) \tag{3.4}$$

where U_p is the velocity at the mean plume height and the profile functions C_y and C_z are determined by the underlying dispersion model.

3.3 Concentrations in the Near Wake

The recirculating flow region is assumed well-mixed over a maximum width $W_B' = \min(W_B, 3H_B)$. If $W_B \leq 3H_B$ the effective well-mixed region (denoted $\mathbf{R}'$) is the same as **R**, the recirculation region. Otherwise $\mathbf{R}'$ is located within **R**, according to the lateral location of the source, y_s, as illustrated in Figure 8. The effective volume, V_R', is set equal to the volume of **R**, reduced in proportion to W_B'/W_B.

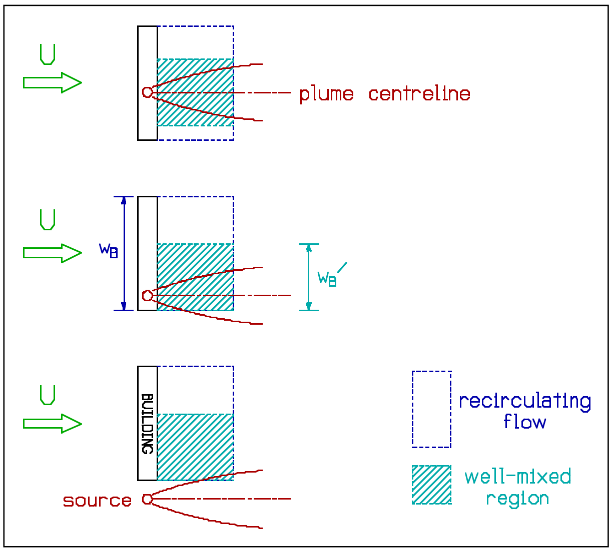

Figure 8. Well-mixed region for wide buildings

Concentrations within the well-mixed region $\mathbf{R}'$ take the uniform value C_R. There are two possibilities:

The release is fully entrained. C_R is determined by the volume of the well-mixed region and by the cavity mean residence time, and a simple flux balance gives:

$$C_R = QT_R/V_R' \tag{3.5}$$

The release is not fully-entrained. C_R is equated to the *average* concentration that would exist on the surface of **R** in the absence of entrainment

$$C_R = \frac{\iint_S C_0 dA}{\iint_S dA} \tag{3.6}$$

The *entrained fraction* ε is then given by

$$\varepsilon = \frac{C_R}{Q}\frac{V_R'}{T_R} \tag{3.7}$$

If dry deposition is modelled, Q is unaffected, but C_R is decreased to account for depletion due to deposition within **R**. This is achieved by multiplying the plume strength by $\left(1\text{-}\left(\nu_d\, L_R W_B'\, C_R/Q\right)\right)$ where ν_d is the dry deposition velocity. The emission rate from the virtual source representing the recirculation region is reduced by the same factor.

Concentrations outside **R** are given by the underlying dispersion model, C_0:

$$C_0 = \frac{Q}{U_p} C_y\left(y: y_p, \sigma_y\right) C_z(z; z_p, \sigma_z, h) \tag{3.8}$$

If the release is fully-entrained then the plume parameters used with equation (3.8) take the uniform values:

$$y_p = \begin{cases} y_s & \text{if } \left(|\, y_s| + \dfrac{W_B'}{2}\right) \le \dfrac{W_B}{2} \\ \operatorname{sign}(y_s)\, \dfrac{W_B - W_B'}{2} & \text{otherwise} \end{cases} \tag{3.9}$$

$$z_p = 0$$

$$\sigma_y = \left(1/\sqrt{3}\right)(W_B'/2),\ \sigma_z = \left(1/\sqrt{3}\right) H_B \tag{3.10}$$

corresponding to the ground-level plume from the recirculating flow region. These expressions, equations (3.9) and (3.10), also define the initial conditions for dispersion calculations in the main wake.

If the release is not entrained then σ_y and σ_z are the same as in undisturbed flow but the plume trajectory $\left(y_p, z_p\right)$ follows the streamlines of the flow given in Section 2.4 with some cross-streamline transport due to plume momentum or buoyancy:

$$\frac{dy_p}{dx} = 0$$
$$\frac{dz_p}{dx} = \frac{w}{U_H} + \left(\frac{dz_p}{dx}\right)^{Plume\ Rise} \tag{3.11}$$

If the release is partially-entrained the concentration is calculated as a weighted combination of the two cases described above, with the weighting between the two cases depending on the entrainment fraction, ε, and distance downstream within the near wake.

3.4 Concentrations in the Main Wake

Downwind of the recirculating flow there is an extensive wake where the region of velocity deficit and excess turbulence gradually expands in cross-section but the magnitude of the velocity deficit decreases. In this model the downstream cross-section is subdivided, according to the position of y_p and z_p, as shown in Figure 9 into the central wake region $\mathbf{W} = \mathbf{WW}$ and external region **E** the union of **WE**, **EW** and **EE**. The whole is capped by an inversion at $z = h$.

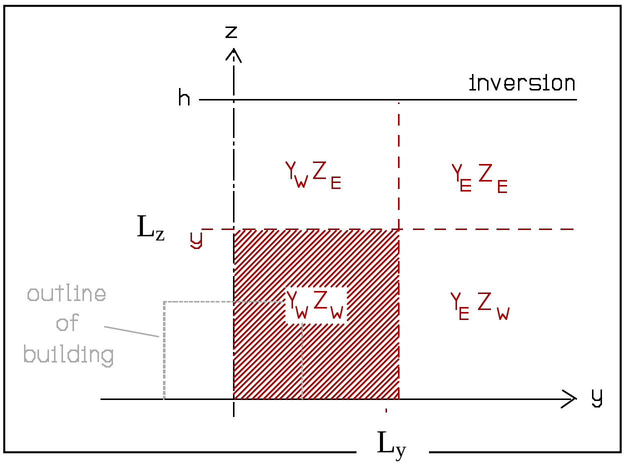

Figure 9. Main wake cross-section

The concepts behind the model for the concentration field are:

(i) plume spread in **W** is calculated from the wake-averaged predictions of mean flow and turbulence,

(ii) plume spread in **E** follows the underlying dispersion model,

(iii) plume trajectories in both **W** and **E** are based on the full, three dimensional, mean velocity field,

(iv) Gaussian concentration distributions are used in both **W** and **E**, with appropriate plume spreads,

(v) values of lateral and vertical spread used in the Gaussian distributions are chosen according to the position of the plume centre and the flow regions where they apply,

(vi) the concentration field is continuous on the boundaries between regions.

As an example if the plume centre is within **WW** then the plume is modelled with the central part of a 'broad' plume modelled in **W**, matched to the outer parts of 'narrow' plumes in **E**, in such a way that concentrations are continuous on the boundaries and the external spread parameters define how the concentration field decays away from **W**.

If a plume initially in **E** above **W** subsequently enters **W**, then it is modelled as described above except that increased plume spreading rates only commence from the point at which $z_p = L_Z$. It is therefore the rates of plume spread that are expressed in the model.

For partially-entrained releases there is a two-plume concentration distribution. The centre-line, spread parameters and crosswind distribution are separately evaluated for each plume and the contributions combined according to the amount of material entrained:

$$C = Q[\{1-\varepsilon\}C_1^{\mathrm{NonEnt}} + \varepsilon C_1^{\mathrm{Ent}}] \tag{3.12}$$

where ${C_1}^{\mathrm{NonEnt}}$ and ${C_1}^{\mathrm{Ent}}$ represent concentrations from unit strength elevated and ground-level plumes and ε is the entrained fraction.

In the idealised velocity field, the mean flow is given by a linearised, small deficit wake model throughout, but the turbulence is only modified in the central region $\mathbf{W} = Y_W Z_W$. The plume centreline is determined by the mean flow field and plume rise:

$$dy_p/dx = v/u \tag{3.13}$$

$$dz_p/dx = w/u + (dz_p/dx)^{\mathrm{PlumeRise}} \tag{3.14}$$

The full set of plume spread combinations is set out in Table 2, as a function of the model region, i.e. the output or receptor location.

Model Region			
WW	**WE**	**EW**	**EE**
$\sigma_Y = \sigma_{YW}$ $\sigma_Z = \sigma_{ZW}$	$\sigma_Y = \sigma_{YW}$ $\sigma_Z = \sigma_{ZE}$	$\sigma_Y = \sigma_{YE}$ $\sigma_Z = \sigma_{ZW}$	$\sigma_Y = \sigma_{YE}$ $\sigma_Z = \sigma_{ZE}$

Table 2. Plume spread parameters in main wake

The external spread parameters are as in the underlying model, whilst the wake parameters are modified by the competing effects of streamline convergence, reduced mean wind speed and enhanced turbulence if the plume centreline is within the **WW** region. Streamline convergence reduces plume spreading rates, relative to the undisturbed case, whilst excess turbulence increases them.

If the plume centreline is outside of the **WW** region then:

$$\frac{d\sigma_{YW}}{dt} = \frac{d\sigma_{YE}}{dt} \tag{3.15a}$$

$$\frac{d\sigma_{ZW}}{dt} = \frac{d\sigma_{ZE}}{dt} \tag{3.15b}$$

If the plume centreline is within the **WW** region then the basic relationships are:

$$\frac{d\sigma_{YW}}{dt} = v' = \sigma_V \left(1 + \frac{\Delta\sigma_V^2}{\sigma_V^2}\right)^{1/2} \tag{3.16a}$$

$$\frac{d(\sigma_{ZW})}{dt} = w' = \sigma_W \left(1 + \frac{\Delta\sigma_W^2}{\sigma_W^2}\right)^{1/2} \tag{3.16b}$$

leading to:

$$\frac{d\sigma_{YW}}{dx} = \left(\frac{\sigma_{YW}}{2}\right)\frac{d(\Delta u/U_H)}{dx} + \left[\left\{\left(1 + \frac{\Delta\sigma_V^2}{\sigma_V^2}\right)^{1/2}\right\} / \left(1 - \frac{\Delta u}{U_H}\right)\right]\frac{d\sigma_{YE}}{dx} \tag{3.17a}$$

$$\frac{d\sigma_{ZW}}{dx} = \left(\frac{\sigma_{ZW}}{2}\right)\frac{d(\Delta u/U_H)}{dx} + \left[\left\{\left(1 + \frac{\Delta\sigma_W^2}{\sigma_W^2}\right)^{1/2}\right\} / \left(1 - \frac{\Delta u}{U_H}\right)\right]\frac{d\sigma_{ZE}}{dx} \tag{3.17b}$$

where Δu, $\Delta{\sigma_v}^2$ and $\Delta{\sigma_w}^2$ are wake-averaged quantities, defined in Section 2.5. Use has been made of the relationships:

$$(U_H - \Delta u)\frac{d\sigma_{YW}}{dx} = \frac{d\sigma_{YW}}{dt};\;\; U_H\frac{d\sigma_{YE}}{dx} = \frac{d\sigma_{YE}}{dt} \tag{3.18a}$$

$$(U_H - \Delta u)\frac{d\sigma_{ZW}}{dx} = \frac{d\sigma_{ZW}}{dt};\; U_H\frac{d\sigma_{ZE}}{dx} = \frac{d\sigma_{ZE}}{dt} \tag{3.18b}$$

and only the first order terms have been retained.

The mean concentration is written as:

$$\frac{C}{Q} = \left(\frac{q_{\alpha\beta}}{U_H}\right) C_Y\left(y; y_p, \sigma_{y\alpha\beta}\right) C_Z(z; z_p, \sigma_{z\alpha\beta}, h) \tag{3.19}$$

where the suffixes (α, β) refer to the output or receptor location, such that:

$$\alpha = W \text{ if } |y| \leq L_y \qquad \alpha = E \text{ if } |y| > L_y \tag{3.20}$$

$$\beta = W \text{ if } z \leq L_z \qquad \beta = E \text{ if } z > L_z$$

The values of $\sigma_{y\alpha\beta}$ and $\sigma_{z\alpha\beta}$ are then given by Table 2. C_Y and C_Z are the concentration profiles of the underlying dispersion model. The coefficients $q_{\alpha\beta}$ are chosen to make C continuous and conserve the flux of material; i.e. to satisfy:

$$\iint_{\mathbf{WW+EW+WE+EE}} C\mathrm{u}_{\alpha\beta} dydz = \iint_{plume} C\mathrm{u}_{\alpha\beta} dydz = Q \tag{3.21}$$

where $\mathrm{u}_{\alpha\beta} = U_H$ except in **WW** where $\mathrm{u}_{\alpha\beta} = U_H - \Delta\mathrm{u}$. This leads to:

$$q_{\alpha\beta} = \alpha_{\alpha\beta} q \tag{3.22}$$

with:

$$\begin{aligned} \frac{1}{\mathrm{q}} = \left(\frac{u_{\mathbf{WW}}}{U_H}\right) \int_{\mathbf{W}} C_Y\left(y; y_p, \sigma_{Y\mathbf{W}}\right) dy \int_{\mathbf{W}} C_Z\left(z; z_p, \sigma_{Z\mathbf{W}}, h\right) dz \\ + A_Z \int_{\mathbf{W}} C_Y\left(y; y_p, \sigma_{Y\mathbf{W}}\right) dy \int_{\mathbf{E}} C_Z\left(z; z_p, \sigma_{Z\mathbf{E}}, h\right) dz \\ + A_Y \int_{\mathbf{E}} C_Y\left(y; y_p, \sigma_{Y\mathbf{E}}\right) dy \int_{\mathbf{W}} C_Z\left(z; z_p, \sigma_{Z\mathbf{W}}, h\right) dz \\ + A_Y A_Z \int_{\mathbf{E}} C_Y\left(y; y_p, \sigma_{Y\mathbf{E}}\right) dy \int_{\mathbf{E}} C_Z\left(z; z_p, \sigma_{Z\mathbf{E}}, h\right) dz \end{aligned} \tag{3.23}$$

where:

$$A_Y = \frac{C_Y(L_Y; y_p, \sigma_{Y\mathbf{W}})}{C_Y(L_Y; y_p, \sigma_{Y\mathbf{E}})} \tag{3.24a}$$

$$A_Z = \frac{C_Z(L_Z; Z_p, \sigma_{Z\mathbf{W}}, h)}{C_Z(L_Z; Z_p, \sigma_{Z\mathbf{E}}, h)} \tag{3.24b}$$

and

$$a_{\boldsymbol{WW}} = 1 \text{ , } a_{\boldsymbol{EW}} = A_y \text{ , } a_{\boldsymbol{WE}} = A_z \text{ , } a_{\boldsymbol{EE}} = A_y A_z \tag{3.25}$$

3.5 Matching Dispersion in the Undisturbed Flow

In earlier versions of ADMS the building effects region, **B**, was terminated far downstream and subsequent dispersion calculations were carried out with the underlying (undisturbed flow) model. Matching conditions were introduced to determine virtual origins for use with the underlying model. This approach has been replaced by extending **B** as far downwind as necessary and using the building effects module for all calculations. However, some modifications to the modelled concentration distributions described in Section 3.4 are necessary to ensure that the dispersion characteristics tend naturally to those of the underlying model at large x.

The spreading rates described by equations (3.17) behave correctly at large x, where Δu, $\Delta\sigma_v$ and $\Delta\sigma_w$ tend to zero. However, to ensure matching with the underlying dispersion model, equation (3.19) is replaced by:

$$\frac{C}{Q} = \left(\frac{q_{\alpha\beta}}{U_p}\right) C_Y\left(y; y_p, \sigma_{y\alpha\beta}\right) C_Z(z; z_p, \sigma_{z\alpha\beta}, h) \tag{3.26}$$

where U_p is the undisturbed flow velocity at the mean plume height, z_m; i.e:

$$U_p = U(z = z_m) \tag{3.27}$$

where $U(z)$ is the velocity profile of the undisturbed flow. Then, in equation (3.21), $u_{\alpha\beta}$ in region **WW** is written as $u_{\alpha\beta} = U_p - \Delta u'$ and the wake-averaged perturbation, $\Delta u'$, is defined so as to maintain the predicted wake-averaged mean velocity within **WW;** i.e. so that:

$$U_p - \Delta u' = U_H - \Delta u \tag{3.28}$$

Equations (3.22) to (3.25) then remain as written.

In fact, U_p, although a slowly changing function of x, is unlikely to depart greatly from U_H in the region where wake effects are important. Equation (3.10) defines the plume spread at commencement of the main wake, giving $z_m \approx 0.45H_B$ and hence $U_p \approx 0.85U_H$ for typical mean velocity profiles. Wake effects are generally negligible beyond about $x = 30H_B$, at which distance the mean plume height may well have grown to $O(3H_B)$, implying $U_p \approx 1.3U_H$. This rather modest change in U_p is acceptable in terms of the theoretical model for wake development.

3.6 Plume Rise

In general, the trajectory of a plume deviates from a streamline of the mean flow because of buoyancy or cross-stream momentum. In ADMS the effective cross-streamline velocity is determined by an integral plume rise model. For releases not entrained at source, the plume rise module is initialised in the usual way from the source parameters; any material subsequently entrained into the cavity is treated as passive. For *primary* plumes emanating from the cavity the plume rise module is reinitialised with a mass flux equivalent to that of fluid in the cavity $(\rho_a V_R{}'/T_R)$ and no velocity excess. However, the integrated plume heat flux is not changed.

The plume rise module also allows for initial spread due to a finite source diameter D_s. If the plume rise module is not evoked because the release is passive then there is some initial spread $\sigma_y = \sigma_z = D_s/4$.

3.7 Dispersion in Calm and Near-Calm Conditions

As described in the technical specification paper P10/01&P12/01, in calm or near-calm conditions the concentration predicted by ADMS 5 is a combination of the standard Gaussian solution and a radial solution. The buildings module requires a reliable wind direction measurement in order to set up the effective building, the flow field perturbation due to the building and the recirculation region. In very calm conditions, reliable wind direction measurements are not usually available. Hence in calm or near-calm conditions, when buildings are modelled, the concentration predicted by ADMS 5 is a combination of the standard Gaussian solution including the effects of buildings, and a radial solution that does not take the buildings into account. In ADMS-Roads, ADMS-Urban and ADMS-Airport, low wind speeds are increased to a minimum value of 0.75 m/s at 10 m, where the Gaussian solution remains valid, so a calm solution is not required.

4. NOMENCLATURE

Regions

B	building effects region
A, **E**, **R**, **U**, **W**	regions of the flow
$\mathbf{R}'$	well mixed region
WW, **WE**, **EW**, **EE**	sub-regions of the main wake

Variables

A, B	parameters describing length of recirculation region
A_Y, A_Z	parameters of the main wake dispersion model
a, b	parameters describing residence time
$a_{\alpha\beta}$	coefficients in the main wake dispersion model
B_P	building parameter (= 0.75)
D_s	source diameter
D_y, D_z	perturbation eddy viscosities
C	mean concentration
C_1	concentration for unit source strength
C_G	moment coefficient for block-shaped building
C_0	concentration from the underlying ADMS dispersion model
C_R	mean concentration in recirculation region
C_y, C_z	crosswind and vertical concentration profiles in underlying ADMS dispersion model
F_M, F_B	momentum and buoyancy fluxes
f(x)	shape function of recirculation region boundary
g	acceleration due to gravity
g'	modified gravity, $g(1-\alpha)$
$g(\xi)$, $h(\eta)$	wake velocity profile functions
h	boundary-layer height
H_B	idealised building height
H_i	height of individual building in complex
L_B	idealised building length (along-wind)
L_R	length of recirculating flow region
L_y, L_z	effective wake width and height
N_H	factors determining vertical and lateral limits of building effects
Q	plume strength

Q_v	volume emission rate
q, $q_{\alpha\beta}$	coefficients of the main wake dispersion model
S_{1i}, S_{2i}	sides of individual building in building complex
T_R	recirculating flow region residence time
t	time
U	mean wind speed in approach flow
U_H	approach flow mean wind speed at building height
U_p	velocity at plume mean height
u, v, w	mean velocity
$\hat{u}$	parameter defining main wake strength
U_s, V_s, W_s	emission velocity components
u_*	friction velocity
v', w'	rms total turbulent intensities
V_R	volume of recirculating flow region
V_R'	volume of well-mixed region
W_B	idealised building width
W'_B	width of well-mixed region
x, y, z	module coordinates: x along-wind, y crosswind, z vertical; origin at ground centre of building
x_B, y_B	centre of idealised building
x_i, y_i	centre of individual building in building complex
x_m	position of recirculating flow maximum height
x_{min}, x_{max}	upwind and downwind limits of building effects
x_R	end of recirculation region
x_s, y_s, z_s	source location
x_{sep}	roof-top flow separation point
x_0	virtual origin of self-preserving wake profiles
Y_α, Z_β	coordinate divisions of the main wake cross-section
y_{max}	lateral limit of building effects
y_p, z_p	plume centreline location
z_m	mean plume height
z_{max}	vertical limit of building effects
z'_{max}	effective limit of building effects in the near wake
$z_R(x)$	cavity envelope
z_{Rmax}	maximum height of cavity
α	ratio of emission and ambient densities

β	entrainment parameter
$\Delta\tau$	wake-averaged shear stress perturbation
Δu	wake-averaged velocity deficit; $u = U_H - \Delta u$
$\Delta u'$	wake-averaged velocity deficit; $u = U_H - \Delta u'$
Δz_s	plume rise above source
$\Delta\sigma_v$, $\Delta\sigma_w$	wake averaged excess rms turbulent velocities
δ	downwash scaling factor
ε	entrained fraction
γ	source strength parameter for plumes in region **U**
η, ξ	similarity coordinates in main wake velocity profile
θ_B	building roof orientation parameter for flow calculations
θ_i	orientation of individual building in complex
κ	von Karman's constant (0.4)
λ_y, λ_z	wake cross-section length scales
μ	wake scale ratio
ρ	density
$\sigma_{v,w}$	rms lateral and vertical turbulent velocities
σ_y, σ_z	lateral and vertical plume spread

Subscripts

a	ambient
B	idealised building
E	external region
R	recirculating flow region
s	source
W	wake region
α, β	region indicators = **W**, **E**
1,2	plume indicator

Superscripts

Buoy	buoyancy induced
E	external region
Ent	entrained fraction
Mom	momentum induced
NonEnt	non-entrained fraction
PlumeRise	plume rise component

Stack	stack downwash component
W	wake region

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