HSE
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Dispersion near buildings

Application of simple modelling

Prepared by **WS Atkins Consultants Ltd**
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The analysis of major accidental hazards often requires an assessment of the dispersion of toxic or flammable vapours in the atmosphere. Whilst there are many models which deal with dispersion in unobstructed terrain, most realistic releases are likely to occur in the vicinity of buildings. In order to assess the effects of buildings on gas dispersion, the HSE commissioned WS Atkins to investigate such situations using computational fluid dynamics (CFD) techniques. Phase 1 of the study reviewed the current situation with regard to both CFD modelling and appropriate validation data. In undertaking this review, some simple models for wake concentration were identified, and it was concluded that it would be useful to determine the extent to which simpler models could be used.

The second phase of this work then involved an in-depth study of the application of CFD modelling to dispersion around buildings. This included validation against wind tunnel and full scale data sets, as well as application to a typical industrial site. This has been reported fully by Hall et al.(1996)

In parallel, further work on simple modelling was undertaken and is presented in this report. It summarises the simple methods currently employed in major hazard analysis for assessing building wake effects, and goes on to identify some modifications and models which are not currently used, but which appear to be improvements, based on the available data and CFD modelling results. The study is focussed upon particular applications of wake modelling, primarily relating to non-normal wind incidence and the effects of high density on the wake structure and hence on gas concentration.

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1.0 INTRODUCTION

1.1 Background

Accidental releases of hazardous materials may affect surrounding areas if toxic or flammable vapours disperse in the atmosphere. Calculation of such dispersion, for inclusion within risk assessments, is straightforward for uniform unobstructed flat terrain. However, practical releases may be affected by the presence of adjacent buildings, generally resulting in enhanced dispersion.

The effects of buildings on dispersion have been reviewed in Phase 1 of this study (Lines et al$^{(1994)}$). Phase 2 has included a substantial effort in the application and validation of CFD modelling to the problem (Hall$^{(1996)}$), but has also investigated the extent to which simple models could be used to calculate the dispersion of releases in building wakes. This investigation, reported herein, supplements the CFD work being undertaken, in that the simple modelling often provides a clearer understanding of the parameters which are of most interest when assessing the results of CFD modelling. Conversely, the CFD modelling also provides additional insights into the areas where simple models are weak and could be improved, and may be used to enable constants to be evaluated.

The Phase 1 study gave a detailed review of simple models for predicting mean concentrations in the near-wake region. It focused upon the limitations of current modelling, and identified the following particular areas as being suitable for further research:

i) Non-normal wind incidence
ii) Dense gas releases in building wakes
iii) Jet releases in building wakes

Jet releases with significant momentum are less likely than others to be affected by a building wake, since the initial momentum may be sufficient to take most of the released materials out of the wake region. Alternatively, if the momentum is directed towards the ground or towards the building, there will be very rapid mixing due to impingement, and a fully-mixed wake model will be appropriate. Attention has therefore been focussed on the first two of these issues, which are discussed in more detail in the remainder of this report.

Although data is becoming available on the fluctuation of the concentrations in building wakes (Higson et al$^{(1994)}$), such information is not currently in regular use in risk assessments. This report therefore deals only with mean concentration predictions, and is primarily focussed upon the near wake effects, where the relatively strong mixing within the building wake is the dominant feature.

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1.2 Types of Model Reviewed

Large buildings may have a significant effect on the dispersion from elevated plumes. In this case, the enhanced mixing may bring the plume down to ground level more rapidly, thus increasing ground level concentrations. This feature has been incorporated within the standard pollution dispersion model ADMS (Hunt et al(1990)), using the methods developed by Apsley(1988). Whilst this work takes full account of the wake structure, it is only applicable to the modification of passive Gaussian plume models. Since the main concern in this study is for ground level dense gas releases, this work was not considered further.

The building wake in a turbulent shear flow is extremely complex, and a brief review of its structure has already been given in the Phase 1 study (Lines et al(1994)). Hunt(1981) studied a range of wakes, and included quantitative results of velocity and turbulence profiles in the wakes of cubes and of cylinders. Further discussion of wake structure, including vortex downwash for non-normal incidence, was given by Hunt & Robins(1982). Schofield and Logan(1990) also provided some schematic visualisation of the streamlines within 3D wakes.

The result of all these studies has been to demonstrate the complexity of typical building wake structures. In order to make some progress with simple 'zone' type models, as distinct from the complex CFD models used in the companion study (Hall(1996)), it is necessary to make some assumptions about the mixing within the wake. The most common assumption which is made is that, because of the strong mixing, the concentration is uniform within some specified wake region. This is the basis for the models discussed in Section 2, and is generally sufficiently accurate for input to a model for the downwind dispersion. However, the accuracy of such models is difficult to determine, since the actual variation of concentration within the wake makes comparison with measurements difficult, unless the concentration field is so extensively mapped that a realistic average can be calculated.

Alternative assumptions can be made, depending upon the conditions being considered. For example, dense gases are known to form stratified layers, and this characteristic can be used to define zones, as in the Brighton(1986) model described in Section 3. In this case, the single well-mixed wake zone is replaced by two layers, each of which covers the full horizontal area of the wake, but only part of the wake depth. Mass flux is then allowed into, out of and between these layers, but each layer is assumed to be at uniform concentration.

2.0 EFFECTS OF WIND ANGLE ON WAKE DISPERSION

This section considers the influence of the angle of wind incidence on the concentrations within the wake of a building. The discussion concentrates on releases which occur at low level, as this is the situation most commonly encountered for major accident hazards. It should be noted, however, that many of the experimental studies have considered high level releases, such as stack discharges; much of the available information is therefore appropriate to releases which originate away from the building (e.g. Thompson(1993)).

2.1 Existing Simple Models for Normal Wind Incidence

Simple models of building wake dispersion have generally been developed for rectangular buildings where the wind direction is normal to one of the building faces. One of the most well known of these models is the near wake recirculation model of Vincent (1977, 1978), which assumes that the release is uniformly mixed throughout the recirculating building wake. This model, which was recommended by the UK Atmospheric Dispersion Model Working Group (Jones(1983)), gives the concentration within the recirculating wake as:

$$\chi_w = CUA/Q = \beta \frac{\tau_r}{\lambda_w} \qquad (2.1)$$

where χ_w = non-dimensional wake concentration
C = actual concentration within wake (assumed uniform)
U = wind speed
A = cross-sectional area of the building
Q = release rate
β = wake shape factor (typically 0.5)
λ_w = normalised wake length = L_r/h
τ_r = normalised residence time = UT_r/h
h = building height
T_r = actual residence time
L_r = actual wake length

Fackrell and Pearce(1981) and Fackrell(1984) indicated that β should be constant ('of order 1') over a wide range of building shapes. However, little guidance is available on how β should be determined; some discussion of its derivation and meaning is given in Appendix 1. The Fackrell work did present the following formulae for λ_w and τ_r:

$$\lambda_w = \frac{1.8\ (b/h)}{(l/h)^{0.3}\ [1 + 0.24\ (b/h)]} \qquad (2.2)$$

$$\tau_r = \frac{11\ (b/h)^{1.5}}{1 + 0.6\ (b/h)^{1.5}} \qquad (2.3)$$

where b = building width
l = building length in wind direction

For $l/h < 0.3$, the result for $l/h = 0.3$ should be used, and similarly, for $l/h > 3$, the result for $l/h = 3$ should be used.

In order to predict concentrations at greater downwind distances, a transition is made at the end of the wake region described above. The effective source is simply defined as an area b_r x h at a distance L_r downwind of the building, with a total volume flux of diluted material of Q, at a concentration C. The width of the recirculating wake, b_r, for buildings where $b/h > 0.2$ is given by:

$$b_r = 1.1\ b + 0.6\ h \tag{2.4}$$

The effective source may then be used as an input to an area source Gaussian plume model or even a dense gas dispersion model. The parameters b_r and h may also be used to define a virtual source location, so that, if appropriate (ie. no density effects) a point source Gaussian plume model may be employed. Jones(1983) suggests that the effective release height for the virtual source should be h/3 and that the virtual source location for the point source Gaussian plume model should be defined by:

$$\sigma'_z\ (x{=}0) = h/3 \tag{2.5}$$

$$\sigma'_y\ (x{=}0) = b/3 \tag{2.6}$$

where x is measured from the downwind edge of the building, so that the dispersion parameters at a distance x from the edge of the building are then obtained from $\sigma'_y(x) = \sigma_y(x + x_{vy})$ and $\sigma'_z(x) = \sigma_z(x + x_{vz})$, where σ_y and σ_z are the dispersion parameters for a point source. In general, the virtual source locations for the horizontal and vertical spread are not identical, ie. $x_{vy} \neq x_{vz}$.

2.2 Models for Non-Normal Wind Incidence

If a rectangular building is oriented at an oblique angle to the wind, then the flow field around the building is substantially altered, with enhanced vortices being produced. This is most significant for high level releases (from an elevation greater than the building height) as the vortices can lead to material being rapidly brought down to ground level. The remainder of this section, however, concentrates on releases at a lower level, within the wake, as most major hazard releases tend to occur at ground level.

Jones(1983) notes that less is known about the behaviour of λ_w and τ_r for non-normal wind incidence. However, he states that the above relationships (Equations 2.2 and 2.3) may still be used, provided that the effective building dimensions are used, and L_r is measured from the nearest building face mid-point, as illustrated in Figure 2.1. The width of the recirculating wake is given by Equation 2.4, but, once again, effective building dimensions should be used for non-normal wind incidence.

Fackrell (1984) states that Equations 2.2 and 2.3 for the wake residence time and wake length give agreement with experiments for various building shapes to within ~ ± 20% in most cases, even for those cases with the buildings at 45° to the flow, provided that the total width normal to the flow is used for b/h. This conclusion is surprising, as it is well known that non-normal wind incidence generally sets up strong spiralling vortex motions in the near wake, which would be expected to lead to greater advection out of the wake and hence lower residence times and concentrations. One possible explanation may be that the concentration in a non-normal wake varies from one part of the wake to another, due to the strong vortex motions. Fackrell's conclusion may therefore not be generally true throughout the whole wake, but may have been based upon measurements in a particular region.

2.3 Assessment of Accuracy for Non-Normal Incidence

In view of the accuracy implied by Jones(1983) and Fackrell(1984), it is worth examining the predictions of the above model a little more closely. Figure 2.2 shows the variation in residence time, wake length and concentration against θ (the angle between the wind direction and a line normal to the long building face) for a building shape with $b/h = 3$ and $l/h = 1$. Figure 2.3 shows just the variation of normalised concentration with wind angle for a wider range of building shapes.

These figures illustrate the effect of building orientation over a 180° range, and include some plan views showing the building orientations. It is noted that the figures give the non-dimensional wake concentration both as $\chi_w = CUA/Q$ (as given by the simple wake model described above) and as CUh^2/Q, which is the parameter usually of most interest (and which is generally quoted in experimental studies). These two non-dimensional concentrations are obviously simply related, for any particular building, but it is important to remember that there may be a significant difference between their values, particularly for buildings of high aspect ratio (b/h).

The performance of the simple model described above can be assessed against experimental data, such as that of Hall (in Robins(1985)) who describes a series of wind tunnel experiments using simple block shape buildings of dimensions h x b x h, for aspect ratios (b/h) in the range from 1 to 25. The passive source was located in the centre of the rear face, and concentration measurements were made at ground level along a line parallel to the rear face and h/2 from it. Experiments were undertaken for angles of incidence in the range $\theta = 0°$ to $45°$ (with 0° being normal to the long face). The results of these experiments have been reproduced in Figure 2.4.

Hall's results relate to measurements at specific locations in the wake, rather than the average assumed in the simple model. The results are seen to be seen to be markedly different from those obtained using the simple model described above, particularly at high aspect ratios, thus indicating the inhomogeneity of the wake concentration field. The simple model predicts a monotonic decrease in normalised concentration (CUh^2/Q) with increasing building width (see Figure 2.5), for all values of θ, whereas Hall found significant increases in concentration as b/h was increased above about 4, especially for the $\theta = 0°$ case. In fact, for $b/h = 10$ and $\theta = 0°$, the simple model predicts a concentration which is about a factor of 30 less than that measured by Hall. This difference is much greater than the probable error suggested by Jones (1983) and Fackrell (1984), based on the simple parameterisation of τ_r and λ_w, and suggests that the range of validity for the model needs to be specified more closely.

For example, it is considered that the model should only be used for $b/h < 4$, as Hall showed that wake concentrations may increase significantly for higher aspect ratios (for any value of θ in the range 0° to 45°, but especially for $\theta = 0°$). For higher values of b/h, the peak concentration in the wake generally increases significantly above that predicted by the model. Although Fackrell [(1984)] identified some of the changing characteristics of the wake as b/h increased, it was not indicated that the model significantly under-predicted concentrations for high b/h.

The main reason for the monotonic decrease in concentration with increasing b/h (as shown in Figure 2.5) is that the concentration in the simple model is inversely proportional to the cross-sectional area of the building. Thompson[(1993)] presented wind-tunnel results for a wide range of source conditions near buildings ranging from a cube (h x h x h) to a wide building (h x 4h x h). He also collated data from other wind tunnel experiments, and demonstrated that the cross-sectional area, A, was less appropriate for non-dimensionalising the concentration (see Equation 2.1) than h^2, if the width b exceeds h. This study, together with the data of Hall and others, demonstrated that the plume does not expand uniformly to fill the wake cavity for these wide buildings with high values of b/h.

2.4 Improvements to Model

Thompson [(1993)] suggested that the simple model described above should only be used for $b/h < 1$, and that, for larger building widths, the cross-sectional area (A) should be replaced by an 'effective area' h^2. The effect of implementing this recommendation into the simple model is shown in Figure 2.6. (Note that the vertical scale in this figure is linear, compared with the logarithmic scale on Figure 2.5.) Comparison of these predictions with the data of Hall indicates that this modified simple model is much more appropriate for high values of b/h, but that it significantly over-predicts the concentration for $30° < \theta < 45°$ and $5 < b/h < 20$. This apparent over-prediction may be ascribed partly to the changing vortex structure of the wake with increasing wind angle. The low values obtained by Hall may also be a function of the measurement location, and may therefore not be truly representative of the average through the well-mixed wake region.

It is considered that the best approach for refining this type of model to match the data for a range of building aspect ratios and angles of wind incidence would be to continue to use the $\chi_w = CUA/Q = \beta\tau_r/\lambda_w$ model, with τ_r and λ_w as defined above, but to find an improved formulation for an effective area 'A' as a function of b/h and θ. The parameter 'A' would then represent the effective cross-sectional area of the plume within the wake It should be noted that the overall building 'width' normal to the incident wind flow is $b \cos\theta + l \sin\theta$, as shown in Figure 2.7. It should be noted that this differs from the definition of effective width 'b' given by Jones[(1983)], as illustrated in Figure 2.1, and is not the same as the wake width given by Equation 2.4.

In summary, there are the following three possibilities:

i) Simple model, no allowance for θ

$$A = bh \tag{2.7}$$

ii) Simple model, including effect of θ (see Figure 2.5)

$$A = (b \cos \theta + l \sin \theta)h \tag{2.8}$$

iii) Modified simple model (see Figure 2.6)

$$\begin{aligned} A &= (b \cos \theta + l \sin \theta)h && \text{for } b \cos \theta + l \sin \theta \leq h \\ A &= h^2 && \text{for } b \cos \theta + l \sin \theta > h \end{aligned} \tag{2.9}$$

The data shows that none of the above formulations is adequate for all possible values of b and θ, and it is considered that a better parameterisation could be developed. It is possible that the results of parametric studies using CFD modelling could provide useful data required for an improved model of this type.

It appears that the most important effect of varying the angle of wind incidence is in the case of wide buildings, where the wake structure changes from being two to three dimensional as the angle θ increases (causing a marked decrease in wake concentration due to additional air entrainment). For low aspect ratio buildings ($b/h < 3$), wind direction has relatively little effect on wake concentration, as the wake is three dimensional for all angles.

It is emphasised that the above conclusion is only appropriate for releases which are fully entrained in the recirculating building wake. For high level sources, the angle of wind incidence has a major effect on ground level concentrations close to the building, as the extent of mixing is determined largely by the vortex motions in the building wake. For upwind releases, Higson et al(1994) have shown that the non-dimensional wake concentration is strongly dependent upon the width of the incident plume relative to the width of the building; a narrow plume gives a wide range of concentrations over the rear face while a broad plume gives a more uniform (and generally lower) normalised wake concentration.

3.0 DENSE GAS RELEASES IN BUILDING WAKES

3.1 Background to Brighton's Model

The only simple model that has been proposed to deal with dense gas releases in building wakes is that of Brighton (1986). This is a two layer model, and is shown schematically in Figure 3.1. Concentration and volume flux conservation equations are solved in order to derive analytical solutions for the concentrations in the upper and lower layers, and the basic equations are reproduced in Appendix 2. The principal parameters which determine the wake concentrations are:

- The non-dimensional volume release rate ($\bar{Q} = Q/UA$)
- The non-dimensional buoyancy parameter ($B = g'_o Q / U^3 b$)
- The non-dimensional building length and breadth (l/h and b/h)

It should be noted that the gas density will only affect the wake concentrations if the buoyancy parameter is sufficiently large. Britter & McQuaid(1988) discuss this in some detail, with particular reference to experimental results for wakes behind a flat square plate (b=h). The following broad dispersion regimes are noted but discussed in more detail in Section 3.3:

$B > 1$	Dispersion unaffected by obstacle
$B > 0.2$	Dilution enhanced in immediate lee, but affected little in far field
$B < 0.04$	Wake concentration can be estimated from passive models.

Hence it appears that there is a relatively narrow range of values of B for which Brighton's model would be used, assuming that the above results can be generalised firstly to buildings with some depth, and secondly to a non-square cross-section for the incident face. It is therefore assumed in this study that the range $10^{-2} < B < 1$ is of greatest interest for the application of the model.

This model has not been developed subsequent to Brighton's original study, nor does it appear to have been used in any detailed dispersion calculations. WS Atkins have encoded a simplified version of the method into a software tool which uses the model to determine the dilution due to a single block-like building, given the dimensions and concentration of an incident dense gas cloud. The existence of the two layers of Brighton's model has not been specifically investigated in the parallel CFD study, although the predictions for the industrial site do indicate strong stratification of a dense cloud, even within the wake of large buildings; the results of the parallel CFD study are discussed in greater detail in Section 4.2.

In spite of its potentially limited application, it is worth identifying some of the principal assumptions used in this model, most of which were recognised by Brighton, who noted that the model could be elaborated as more experimental evidence becomes available. Some of the main assumptions and points worth noting in the model are:

i) The dimensions of the wake are based on the correlations of Fackrell(1984), which were derived from wind tunnel measurements.

ii) Volume fluxes of gas and air are preserved on mixing (i.e. the gas and air are at the same temperature or have equal molar specific heats).

iii) The volume flux of air into the lower layer is taken to be zero ($F_{AL} = 0$).

iv) The volume fluxes between the two layers are taken to be identical. ($F_{LU} = F_{UL}$).

v) Brighton gives the flux of air into the upper layer in a simplified form.

vi) The model uses various constants which need to be determined empirically.

vii) Brighton only considers the case where roof flow reattachment occurs.

viii) Brighton's example (his Figure 4), whilst correct, could be slightly misleading if not carefully interpreted.

Items v) to viii) are considered in more detail in the remainder of this section. Section 3.2 considers items v)-vii), since these all affect the model constants in some way. Section 3.3 considers the influence of the buoyancy parameter, with particular reference to the interpretation of Brighton's Figure 4, while some comments on the further development and application of the model are given in Section 3.4.

3.2 Review of Model Constants

The following sub sections consider in more detail points, v, vi and vii identified in Section 3.1, ie.

a) Flux of air into upper layer
b) Roof flow reattachment
c) Empirical constants used

Flux of Air into Upper Layer

Brighton gives the flux of air into the upper layer as:

$$\begin{aligned} F_{AU} &= c_1\,(h_U/l)^{0.3}\,\bar{h}_U \quad \text{with } c_1 = 0.5, \text{ for } l/h_U \geq 0.3 \\ F_{AU} &= c_2\,\bar{h}_U \qquad\qquad\quad \text{with } c_2 = 0.7, \text{ for } l/h_U < 0.3 \end{aligned} \tag{3.1}$$

The constants c_1 and c_2, as given by Brighton, were determined for a 'mean' building width. The exact solution, based on Fackrell's correlations, is as follows:

$$c_1 = \frac{1.8\;[1 + 0.6(b/h_U)^{1.5}]}{11\;\beta\;[1 + 0.24(b/h_U)](b/h_U)^{0.5}} \qquad \textit{for}\;\; 0.3 \leq l/h_U \leq 3 \tag{3.2}$$

$$c_2 = 0.3^{-0.3}\, c_1 \qquad \text{for } l/h_U < 0.3$$
$$c_2 = 3^{-0.3}\, c_1 \qquad \text{for } l/h_U > 3 \tag{3.3}$$

The table below gives the values of c_1 and c_2 for various possible values of b/h_U, based on a range of wake shape parameter (β) values see (Equation 2.1). It should be noted that little guidance is given on the value of β, which is expected to remain of order 1 (Fackrell and Pearce[(1981)]). Further discussion on the appropriate value of β is given in Appendix 1, but the values used in the following comparison are expected to cover the range which may be applicable in practice. (Note that, in each case, c_1 and c_2 are inversely proportional to β).

b/h_U	c_1 ($0.3 \leq l/h_U \leq 3$)			c_2 ($l/h_U < 0.3$)			c_2 ($l/h_U > 3$)		
	$\beta = 0.5$	$\beta = 1$	$\beta = 1.5$	$\beta = 0.5$	$\beta = 1$	$\beta = 1.5$	$\beta = 0.5$	$\beta = 1$	$\beta = 1.5$
0.1	1.03	0.52	0.34	1.48	0.74	0.49	0.74	0.37	0.25
0.3	0.61	0.31	0.20	0.88	0.44	0.29	0.44	0.22	0.15
0.5	0.50	0.25	0.17	0.72	0.36	0.24	0.36	0.18	0.12
1	0.42	0.21	0.14	0.61	0.30	0.20	0.30	0.15	0.10
2	0.42	0.21	0.14	0.61	0.30	0.20	0.30	0.15	0.10
3	0.45	0.23	0.15	0.65	0.33	0.22	0.33	0.16	0.11
10	0.61	0.30	0.2	0.87	0.44	0.29	0.44	0.22	0.15

Table 3.1 Constants Used to Determine Air Flux into Upper Layer

From this table, it can be seen that Brighton's choice of $c_1 = 0.5$ is quite a reasonable approximation, but it should be noted that it is not appropriate for high or low values of b/h_U or for values of (β) other than 0.5. Similarly, $c_2 = 0.7$ is a reasonable choice for $l/h_U < 0.3$, with the same provisos. It is noted that Brighton did not consider the case of $l/h_U > 3$, for which a value of $c_2 = 0.35$ is recommended for typical building shapes.

Roof Flow Reattachment

Fackrell's formula for λ_w, as used by Brighton, generally relates to the case where the flow reattaches on the roof of the building. This may not be the case for some buildings, and it is typically assumed not to occur if the building length (l) is both less than about one building height (h) and less than about half the building width (b). i.e.

Re-attachment typically does not occur when both $l < h$ and $l < b/2$

Fackrell[(1984)] and Robins[(1994)] give a more complete description of the nature of the roof flow regime, including the effect of ambient turbulence levels (Robins[1994]).

Fackrell suggests that it may sometimes be more appropriate to use Hosker's[(1979)] original formulation for λ_w for some cases where separation occurs (e.g. when $b/h > 5$).

It is also noted that Fackrell (1984) misquotes Hosker's equation for λ_w for when the flow does not reattach, but the correct result is presented below.

$$\lambda_w = \frac{[3.7\ (l/h)^{-1/3} - 2.0]\ (b/h)}{1 + [0.305\ (l/h)^{-1/3} - 0.15]\ (b/h)} \tag{3.4}$$

Brighton validates the two layer model using wind tunnel data for square plates mounted normal to the flow in a wind tunnel, where roof reattachment is clearly impossible. However, the use of Fackrell's formula may still be adequate in this case, since $b/h < 5$.

In cases where there is re-attachment, Equation (3.4) gives values of λ_w which may differ significantly from the value of 2.08 which Brighton uses. For example, for $l/h = 1$, Equation (3.4) reduces to

$$\lambda_w = \frac{1.7 b/h}{1 + 0.155 (b/h)} \tag{3.5}$$

which varies from 1.5 at $b/h = 1$ to values ranging from 4.8 - 6.7 for $b/h = 5\text{-}10$. Similarly, fixing $b/h = 5$, Equation (3.4) gives $\lambda_w = 6.2\text{-}4.8$ for $l/h = \tfrac{1}{2}\text{-}1$.

It should also be noted that the wake correlations which have been developed by a number of authors and discussed here all relate to cuboid buildings. One of the main differences when seeking to apply such methods to pitched roof buildings will be the nature of the roof separation. It is suggested that the cuboid building wake correlation can still be applied to pitched roof structures, but with the appropriate re-attachment conditions, as for example discussed by Cook(1985).

In summary, when using Brighton's model, consideration should be given to whether the roof flow is separated or reattached, and to which formulation for λ_w is most appropriate. It may also be possible to incorporate the variation of λ_w with b/h and l/h, rather than just retaining a constant value.

Empirical Constants Used in Model

Brighton's model employs a number of empirical constants in order to determine the concentration and height of the two layers in the wake. Any practical application of the model therefore requires guidance on appropriate values. The four main empirical constants that are used by Brighton are:

- α_I A mixing coefficient (Brighton uses a value ~ 0.017)
- α_M A mixing coefficient (Brighton uses a value ~ 1)
- γ_1 A constant
- γ_2 A constant

Appendix 2 shows how these constants are used in the specification of volume fluxes. It is worth noting that one of the main attractions of the model is that the solution for the concentration in the lower layer (i.e. $C_L = 1 - \alpha_I \lambda_w / B$), where there is suppression of mixing due to density stratification, only requires knowledge of one of these parameters (i.e. α_I). However, in general, all four constants are required to allow a specification of the layer heights and concentrations.

The constants γ_1 and γ_2 are used to define the volume flux out of the lower layer F_L by the equation:

$$F_L = (\gamma_1 + \gamma_2 D^{1/3})\overline{h_L} \tag{3.6}$$

Brighton gives no guidance on the choice of suitable values for γ_1 and γ_2, although the results he presents in his Figure 4 can be replicated by using $\gamma_1 = \gamma_2 = 1$.

3.3 Influence of Buoyancy Parameter

Brighton presents, in his Figure 4, a comparison of the results of his model against some of the small-scale results produced by Britter in the early 1980's. They are presented as a plot of C_L against B, and two theoretical curves (for $\dot{Q} = 0.01$ and 0.1) are included. This figure is reproduced here in Appendix 2, and shows that, above a value of B of around 0.03-0.04 (corresponding to a Richardson number, as defined in Appendix 2, of $Ri_T = 0.017$), C_L is dependent only on B, whereas, below this value, C_L tends to a constant value which is roughly proportional to $\dot{Q}$. This has been confirmed for the following practical sets of parameters; h=b=5m, and the values of Q, u and $\dot{Q}$ shown in Table 3.2.

$Q(m^3/s)$	1	1	10	10
u(m/s)	2	5	2	5
$\dot{Q}$	0.02	0.008	0.2	0.08

Table 3.2 Parameters used for results of Figure 3.2

The results are shown in Figure 3.2, which confirms those presented by Brighton, in his Figure 4, for $\dot{Q}=0.01$ and 0.1. The upper layer concentration (C_u) is not shown, but, for small B, is around $0.75C_L$, decreasing as 1/B for B > 0.03 - 0.04.

It should be pointed out that, in this figure, the variation of C_L with B is obtained by keeping $\dot{Q}$ fixed. Thus, this would apply for fixed release rate and wind conditions, but varying gas density, and hence g_o'. In practice, it would be of more interest for a particular set of release scenarios to fix g_o', and vary B by varying Q, and hence $\dot{Q}$. In this case, with the parameters as noted above, but fixing u = 2m/s and varying Q from around 0.001 to $300m^3/s$, the results appear as in Figure 3.3.

The independence of the results on $\dot{Q}$ for large B is clearly evident, although the constant value of C_L for small B is now replaced by a linear dependence on B (and hence on $\dot{Q}$). Figure 3.3 also includes the variation of χ (= $C/\dot{Q}$), which is constant for small B, but then decays as 1/B for large B.

It is also worth reviewing how this compares with current information on the influence of the buoyancy parameter. The Britter McQuaid Workbook(1988) suggests various buoyancy regimes, as outlined in Section 3.1 and described in more detail below:

$B < 0.004$	Release density has negligible effect on dispersion.
$0.004 < B < 0.04$	Density stratification is limited to the immediate lee of the building ($CUh^2/Q \sim 20$ at $x/h=1$).
$B > 0.2$	Obstacle has little effect, although plume dilution in the immediate lee is enhanced.
$B > 1$	Obstacle has no effect on plume growth and dispersion.

Brighton $^{(1986)}$ describes experiments for which Britter$^{(1989)}$ provides an excellent summary of the visual observations and the concentration measurements in the near field and at the end of the recirculating wake. It should be noted that the above regimes were based, at least in part, on these observations, and also that Brighton used them in the development of his model. The experiments showed that:

$B \sim 0.0014$	Plume is passive in wake and remains passive further downwind.
$B \sim 0.05$	Mixing throughout wake, but reverts to low-lying spreading heavy-gas plume further downwind.
$B \sim 0.34$	Plume confined to a fraction of obstacle height. Obstacle has little effect.

The results shown in Figures 3.2 and 3.3 are in good agreement with the above experimental data. For example, at low values of B (<0.01) in Figures 3.2 and 3.3, the plume is well mixed throughout the wake, so that the concentrations in the upper and lower layers are very similar. At values of B above 0.1, density effects are dominant and the lower layer concentration is much greater than that in the upper layer. These results indicate that Brighton's model is well suited to modelling these phenomena. However, his Figure 4 (see Appendix 2) does raise the following points, which may be worthy of further consideration in any subsequent model development:

- In the data included on that figure, there is a clear distinction between concentrations at $x = h$ and those at $x=2h$, suggesting that mixing is far from uniform within the defined 'layers' of the wake region.

- Whilst there is clearly a transition in the variation of C_L at around $B = 0.03$, the change in the experimental data is rather less abrupt than the model would suggest.

- Although the value of C_L increases rapidly towards 1 with increasing B, the thickness of this lower layer can become very small. For example, at $B=.035$, $h_L \sim 0.75\bar{Q}$. For $Q=1$ and $u=2$, $\bar{Q}=.02$, giving $\bar{h}_L=.015$, which, for $h=5m$, suggests that $h_L = .075m = 75mm$. In practice, therefore, this layer may not be established, and rather more mixing may be apparent, as noted above.

Further consideration of the solution for large B ($Ri > Ri_T$) suggests that, since $\bar{h}_L$ can be very thin, it may be useful to consider the average concentration ($C_m = C_L\bar{h}_L + C_u\bar{h}_u$) as input to a dispersion model. Manipulation of Equations 3.21 and 3.22 from Appendix 2, using $\alpha_1 \lambda_w = 0.036$, gives:

$$\chi_m = \frac{C_m}{\bar{Q}} = \frac{1 - 0.036/B}{1 + B^{1/3}} + \frac{0.051}{B} \tag{3.7}$$

which decreases from 1.42 at B = .036 to 0.53 at B=1.

3.4 Applications of Brighton's Model

At this stage, it is probably useful to clarify the calculation steps required in order to apply Brighton's model to a particular situation, involving, for example, a release of 1 m^3/s (approximately 3 kg/s) of chlorine in the wake of a building which is 5 m high and 5 m wide in a 2 m/s wind speed.

1. Calculate non-dimensional release rate $\bar{Q} = Q/UA = 1/(2 \times 5 \times 5) = 0.02$
2. Calculate $g'_o = (\rho/\rho_o - 1)g = (2.5-1)9.81 \approx 15$ (taking chlorine density as 2.5 times that of air.)
3. Calculate buoyancy parameter $B = g'_oQ/U^3b = 15 \times 1 / (2^3 \times 5) = 0.375$
4. Calculate $\gamma = \gamma_1 + \gamma_2B^{1/3} = 1.72$, (arbitrarily taking $\gamma_1 = \gamma_2 = 1$)
5. Calculate non-dimensional lower layer height $\bar{h}_L = \bar{Q}/\gamma = 0.02 / 1.72 = 0.012$
6. Calculate non-dimensional upper layer height $\bar{h}_U = 1 - \bar{h}_L = 0.988$
7. Calculate non-dimensional wake length using Fackrell's equation, $\lambda_w = 2.08$
8. Calculate transitional Richardson number $Ri_T = \alpha_1/\alpha_M = 0.017 / 1 = 0.017$

The next step is complicated by the fact that the choice of the equations required to calculate the layer concentrations C_L and C_U, depends on whether the Richardson number $Ri = (C_L - C_U)g'_oh/U^2$ is greater or less than Ri_T. However, the value of Ri is not known at this stage of the calculation as it depends on the values of C_L and C_U.

Thus, a trial and error iterative approach may be necessary, as described below.

9. Assume $Ri < Ri_T$ and calculate upper and lower layer concentrations using Equations 3.19a, b

   $C_L = 0.037$ $C_U = 0.028$ $Ri = 0.17$

   It can be seen that this is in fact incorrect, as $Ri > Ri_T$

Therefore, calculate upper and lower layer concentrations using Equations 3.21 and 3.22 for when $Ri > Ri_T$

$$C_L = 0.91 \qquad C_U = 0.0027 \qquad Ri = 16.9$$

Since Ri has been shown to be greater than Ri_T, this is now consistent.

10. Calculate χ_L and χ_U using $\chi = C/\dot{Q}$, $\chi_L = 45$ and $\chi_U = 0.14$

In its present form, the model clearly has to be applied carefully. In particular, the following points should be noted.

- The concentration within the wake is unlikely to be horizontally homogenous.
- The depth of the lower layer (h_L) may be very small. If so, it may be more appropriate to use the depth-averaged concentration, C_m, as calculated in Equation (3.7).
- For a given geometry and material, use of Brighton's Figure 4 may be misleading when considering which releases are affected by buoyancy. The plot presented in Figure 3.3 would be more useful in that respect.

In summary, this model may be used to provide an assessment of dense gas releases in the vicinity of buildings, using the methodology summarised above. However, use of the model is not straightforward and it may be more appropriate to codify it within a simple expert system. This would facilitate further validation of the approach with the results of wind tunnel and CFD modelling.

4.0 CONCLUSIONS

4.1 Errors in the Application of Simple Modelling

The use of building wake models in dispersion studies is not extensive at present. The errors which should be considered will therefore originate from two sources:

a) Errors caused by ignoring building wake effects
b) Errors caused through uncertainties in the use of the models

In the first case, it is clear that the magnitude of any errors will depend upon the relative size of the release compared with the building dimensions. The greatest errors will therefore occur when the cloud or plume cross-section is comparable to or less than that of the buildings.

The discussion in this report has more specifically addressed the second type of error, and shown how the effective wake width in particular should be chosen with care, and building orientation effects should also be treated carefully. The magnitude of such errors can be seen readily by comparing Figures 2.5 and 2.6.

Further errors could be introduced by using a passive dispersion wake model in place of a dense gas model. This is discussed in Section 3, where the extent of wake stratification is noted. Likely errors in the use of such models can be assessed by referring to Figure 3.2, which shows the variation of lower layer concentration with buoyancy parameter.

4.2 Results from CFD study

The parallel CFD study (Hall(1996)) considered a range of test cases for dispersion in wake regions. Since these were primarily designed to provide validation, they were generally limited to situations for which physical data, usually from wind tunnel modelling, was available. However, one test case was undertaken which related to a real site, and considered dense gas dispersion in building wakes with non-normal wind incidence.

The main building under consideration was of non-standard shape, and was also embedded in a group of other (generally smaller) buildings. Thus, although non-normal wind incidence was considered, it is difficult to draw any direct parallels with the simple modelling presented here. However, the CFD results did demonstrate a number of features which relate directly to the application of Brighton's model, as discussed in Section 3, and generally confirm the main assumptions underlying the model i.e. that the high release density results in wake stratification. In particular, the following points are noted:

a) The dense gas cloud does not mix fully over the height or width of the leeward building face.

b) The stratification persists to a distance of 100m or more from the rear building face.

c) Groups of buildings result in channelling effects which may be significant in determining the exact 'footprint' of a dense gas cloud.

4.3 Potential Applications of Simple Modelling

Simple models for building wake dispersion are worthy of further consideration, as they enable rapid assessments to be made of the likely concentrations resulting from accidental releases. Although the models have generally been validated for simple cuboid buildings oriented normal to the flow, the models can be applied to more complex shapes and to non-normal wind incidence, as described in this document. However, it must be recognised that the models should be used with caution for cases involving buildings with aspect ratios b/h or *l*/h which differ significantly from unity, particularly for cases where the angle of wind incidence is not normal to one of the building faces. This document gives some guidance on the nature of the errors which may occur when using such simple models, as noted in Section 4.1.

As noted in Section 1.2, the UK ADMS pollution dispersion model has been developed to include the building wake effects model of Apsley$^{(1988)}$. Since this is geared to the modification of standard Gaussian plume models, it is not appropriate to the problems considered in this study. However, a similar development for dense gases released into building wakes, based upon the models considered in this report, and not restricted to the framework of a Gaussian plume model, would be appropriate and would fill a gap in current methodologies.

It is therefore suggested that it would be worthwhile to develop a better formulation for the effective crosswind area occupied by the plume within the building wake. This area would be a function of the building dimensions and the angle of wind incidence, and could be based on existing wind tunnel data, and on results of appropriate future CFD runs.

The only simple model for building wake dispersion involving heavier-than-air releases is that of Brighton, which has been reviewed in some detail. It appears that this model can be used successfully to predict wake concentrations, and comparison of the results with those of CFD modelling would be of interest. Several features of Brighton's model are addressed in some detail in this document, and some brief suggestions for areas where the model could be modified have been discussed. It is particularly interesting to note that the kind of accidental releases which would be most significantly affected by dense gas building wake effects are those which typically dominate the risks around major hazard plant, such as failures of road tanker connections. The dispersion of larger dense gas releases is initially dominated by effects such as gravity driven slumping, rather than building wake effects, whilst smaller dense gas releases essentially behave in a manner similar to passive releases. The dispersion of moderate dense gas leaks, which tend to dominate the risk, will, however, be affected by building wakes.

It has been demonstrated that practical application of a two layer model is not entirely straightforward, and it would be useful to automate the methodology. This would enable it to be used more readily to provide the inputs required for standard dense gas dispersion models. It has also been noted, however, that it needs to be applied with some care, in order that appropriate conclusions are drawn.

One approach which could be adopted is to develop an expert system type model, based on the type of information presented in this report, which would determine the most appropriate methodology to characterise the wake, and provide an output describing the various wake parameters, together with the data required to link into a medium to far field dispersion model.

The key inputs would be:

- building dimensions
- building orientation relative to wind
- wind speed
- release location
- release density
- release rate

and the main outputs would include wake characteristics:

- wake dimensions
- residence time
- wake concentration

and input parameters for gas dispersion models:

- aspect ratio of cloud
- cloud density and concentration
- virtual source location

The system would also need to provide an indication of the range of the uncertainty in the various output parameters.

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Contents

APPENDIX 1

The Wake Shape Parameter, β

The simple model for the wake concentration includes the wake shape parameter, β, which is the ratio of the volume of the wake to that of the enclosing cuboid. This is derived by assuming that the volume of the wake behind a building of cross-section b x h is

$$V_w = b_r\, h_r\, L_r \qquad (A1.1)$$

where L_r = wake length
b_r = wake width
h_r = wake height

It is generally assumed that $h_r = h$, although this may be an underestimate for cases where the separated flow on the roof does not re-attach. (See Section 3.2 for a discussion of the conditions for this to occur). If the flow remains separated, $h_r = 1.5h$ seems more appropriate (Robins(1995)). For the purposes of the discussion in this Appendix, it is assumed that $h_r = h$.

Relating b_r to b by the wake shape parameter, β, then gives

$$V_w = bhL_r/\beta \qquad (A1.2)$$

If a cuboid wake region is assumed, with the wake width, b_r, as defined by Equation 2.4, then it can be shown that:

$$\beta = \frac{1}{1.1 + 0.6(h/b)} \qquad (A2.2)$$

Typical values of β for a range of b/h values are presented in Table A1.1.

b/h	0.2	0.5	1	2	5	10
β	0.24	0.43	0.59	0.71	0.82	0.86

Table A1.1 Variation of wake shape parameter, β

If, however, b_r, h and L_r represent the extremities of the wake, which does not completely fill this cuboid region, then β would exceed these values. For example, if the wake was of semi-ellipsoid form, the volume of the ellipsoidal region is V_e compared with V_c for the enclosing cuboid:

$$V_e = \frac{\pi}{6}\; b\; h\; L_r \qquad (A1.4)$$

$$V_c = b\; h\; L_r \qquad (A1.5)$$

$$\text{Hence}\quad \frac{V_c}{V_e} = \frac{6}{\pi} = 1.9 \qquad (A1.6)$$

This suggests that the β values in Table A1.1 could be factored by 1.9 to give the range:

$$0.46 < \beta < 1.63 \qquad \text{(A1.7)}$$

It should be noted, that the parameter β will effectively also include the ratio h/h_r. Whilst this will be unity for some buildings, it will be around 2/3 for others. This would tend to reduce values of β, so that

$$0.31 < \beta < 1.09 \qquad \text{(A1.8)}$$

In order to cover most realistic eventualities, the values 0.5, 1.0 and 1.5 have therefore been used as representative in Table 3.1

The discussion above would seem to suggest that β is a function of building width, although this is not implied in any of the relevant references. It therefore appears that, in addition to the normalisation by h^2 instead of bh, as suggested in Section 2.4, there may be scope for further tuning of the simple model by adjustment of the parameter β.

APPENDIX 2

Brighton's Two Layer Model (from Brighton, 1986)

See Figure 3.1 for schematic diagram.

Flux Conservation Equations **Eqn. No.**

$$\bar{Q} + F_{AL} + F_{UL} = F_{LU} + F_L, \qquad \bar{Q} + C_U F_{UL} = C_L(F_{LU} + F_L) \tag{3.7a, b}$$

$$F_{AU} + F_{LU} = F_{UL} + F_U, \qquad C_L F_{LU} = C_U(F_{UL} + F_U) \tag{3.8a, b}$$

Specification of Fluxes

$$F_{AL} = 0 \tag{3.12}$$

$$F_{LU} = F_{UL} = \alpha_I \lambda_w / Ri \qquad \text{if } Ri \geq Ri_T \tag{3.13a}$$

$$F_{LU} = F_{UL} = \alpha_M \lambda_w \qquad \text{if } Ri \leq Ri_T \tag{3.13b}$$

$$Ri = (C_L - C_U) g'_o h / U^2 \tag{3.14}$$

$$Ri_T = \alpha_I / \alpha_M$$

$$F_L = \gamma\, \bar{h}_L \qquad \text{with } \gamma = \gamma_1 + \gamma_2 B^{1/3} \tag{3.15}$$

$$F_{AU} = 0.5 (h_U / l)^{0.3}\, \bar{h}_U \quad \text{for } l/h_U \geq 0.3\,, \quad = 0.7 \bar{h}_U \text{ otherwise} \tag{3.16}$$

$$\bar{h}_L = \bar{Q} / \gamma \tag{3.18}$$

Note $\bar{h}_u$ and $\bar{h}_L$ are normalised (h_u/h etc), so that $\bar{h}_u = 1 - \bar{h}_L$

Solution for $Ri \leq Ri_T$

$$C_L = \frac{(\alpha_M \lambda_w + 0.7\, \bar{h}_U)\, \bar{Q}}{0.7\, \bar{h}_U\, \alpha_M \lambda_w + \bar{Q}(\alpha_M \lambda_w + 0.7\, \bar{h}_U)}\,, \qquad C_U = \frac{\alpha_M \lambda_w C_L}{\alpha_M \lambda_w + 0.7\, \bar{h}_U} \tag{3.19a, b}$$

Solution for $Ri \geq Ri_T$

$$C_L = 1 - \alpha_I \lambda_w / B \tag{3.21}$$

$$C_U = \alpha_I \lambda_w / (0.7\, \bar{h}_U\, Ri_o) \qquad \text{where } Ri_o = g'_o h / U^2 \tag{3.22}$$

Some of Brighton's results (his Figure 4) are reproduced here, in order to facilitate comparison with the results obtained in this study, and presented in Figure 3.2.

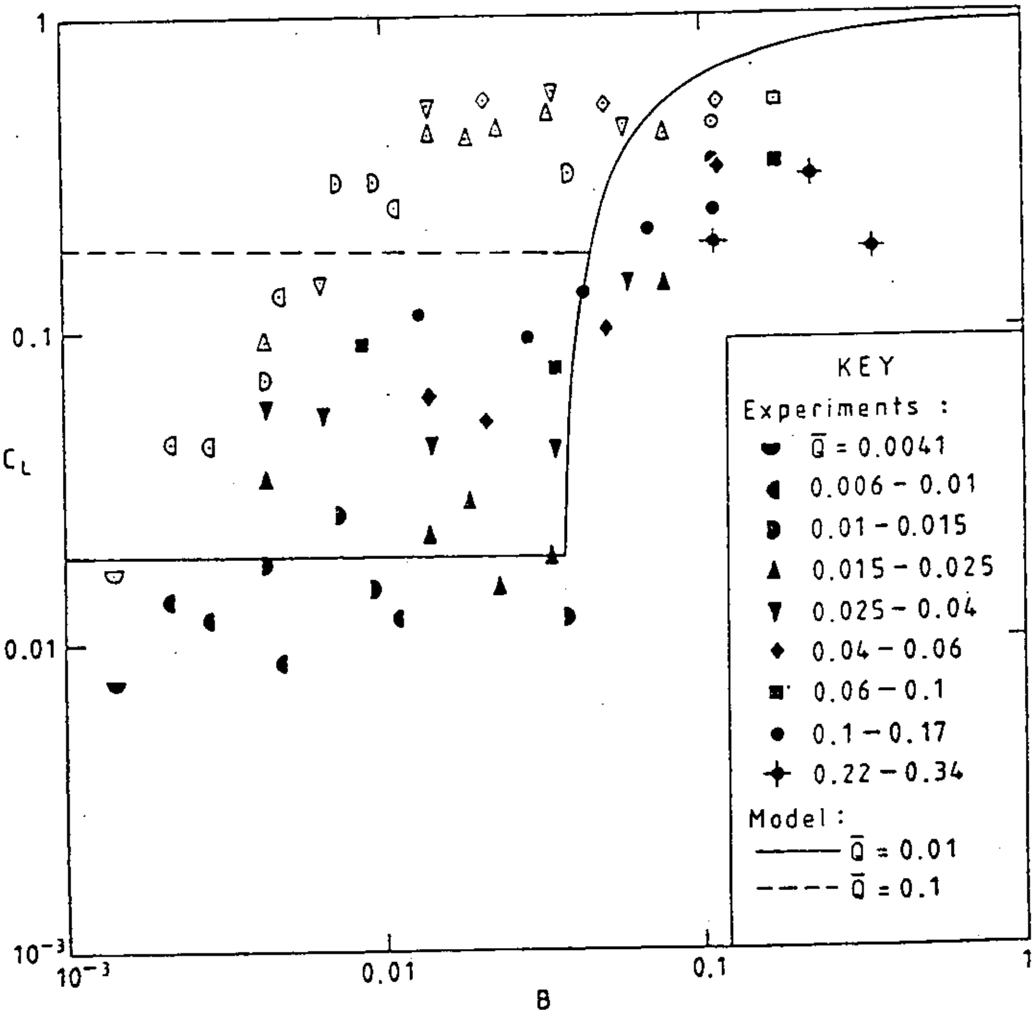

Figure.4 Measurements of Ground-Level Concentrations for Heavy-Gas Release in the Wake of A 3D Obstacle. Open Symbols at x=h Closed at x = 2h

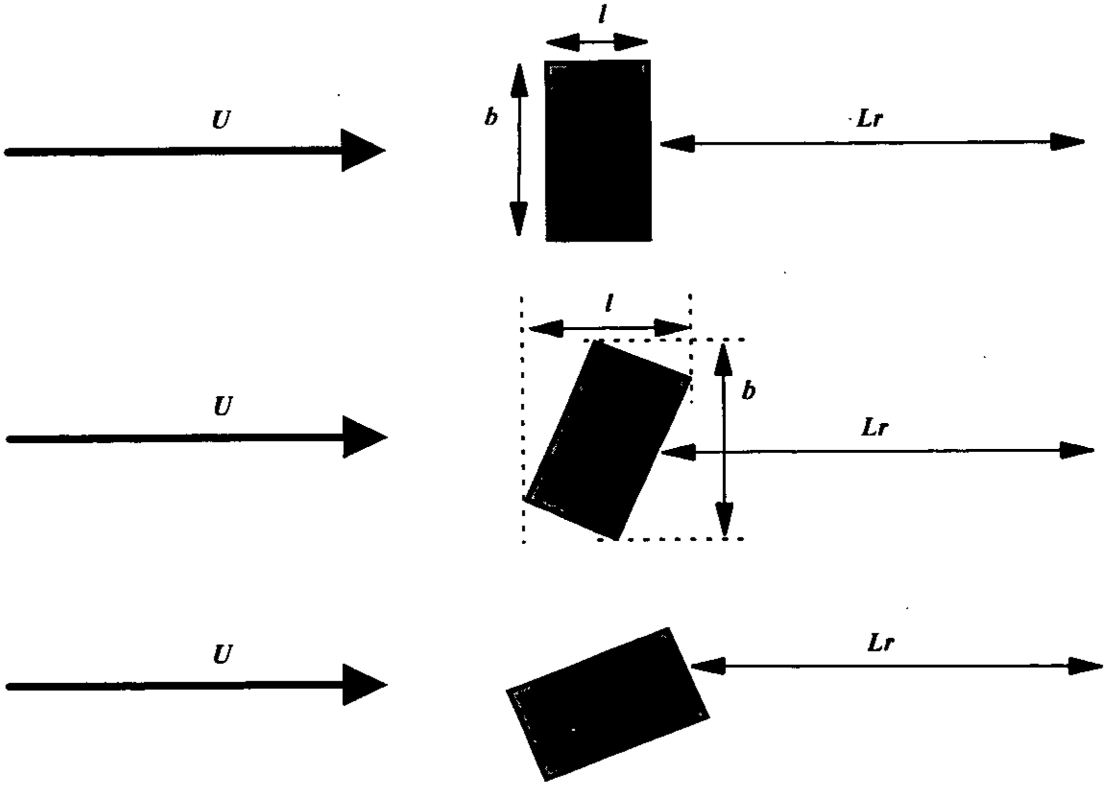

Figure 2.1 Definition of Effective Building Dimensions (From Jones, 1983)

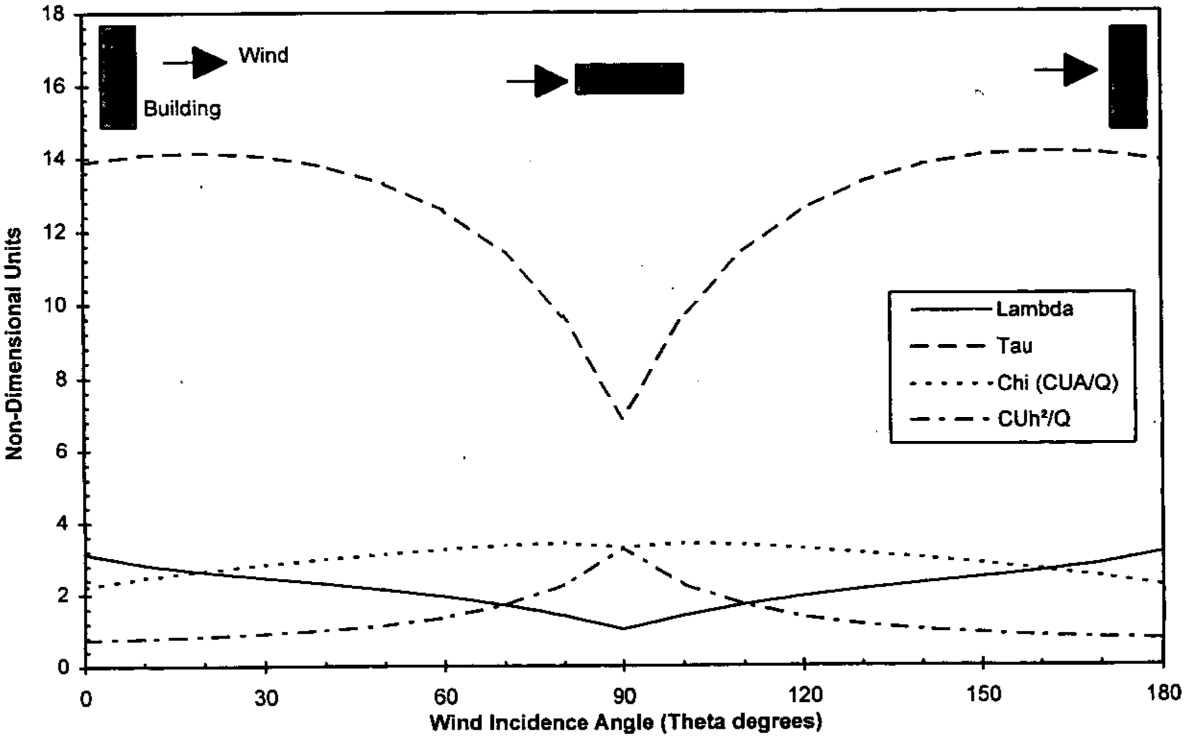

Figure 2.2 Variation of Concentration and Wake Parameters With Angle of Wind Incidence

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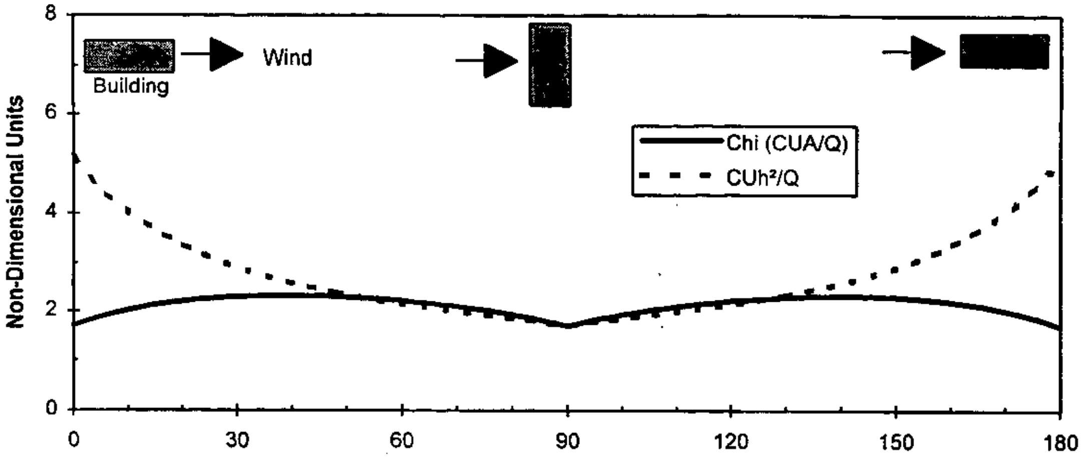
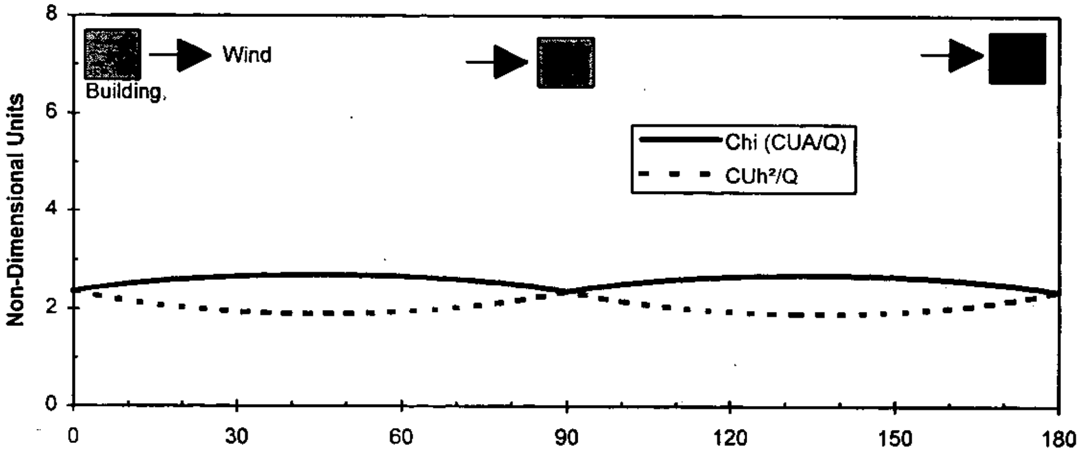
Case a)

b/h = 1/3
l/h = 1



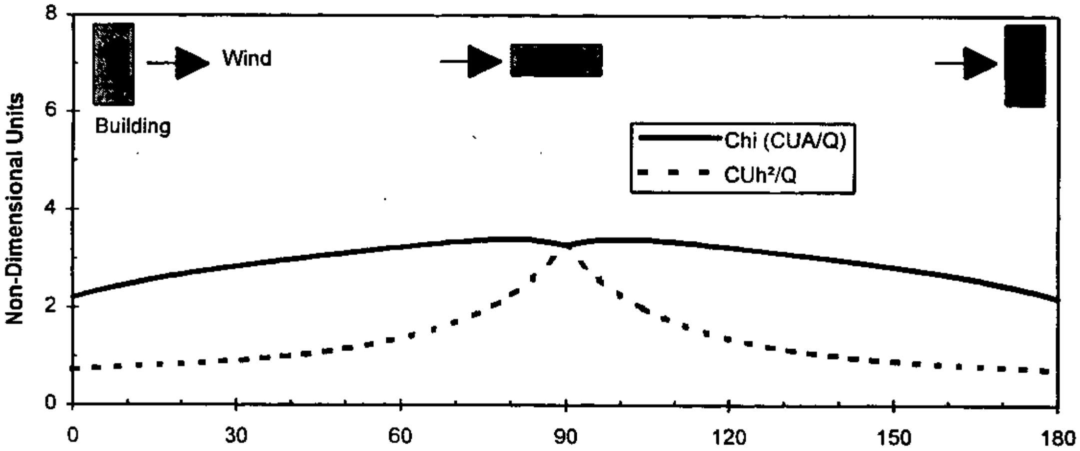
Case b)

b/h = 1
l/h = 1



Case c)

b/h = 3
l/h = 1



Case d)

b/h = 10
l/h = 1

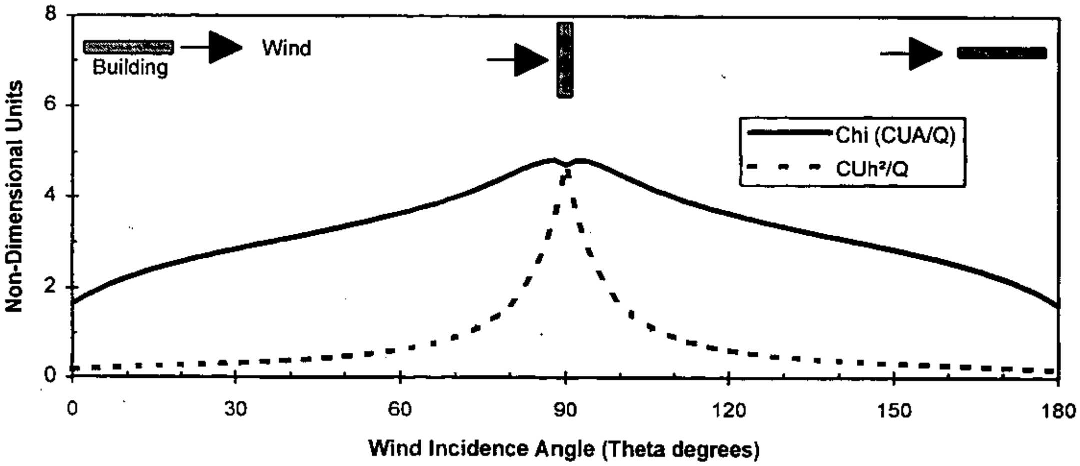


Figure 2.3 Variation of Normalised Wake Concentration V

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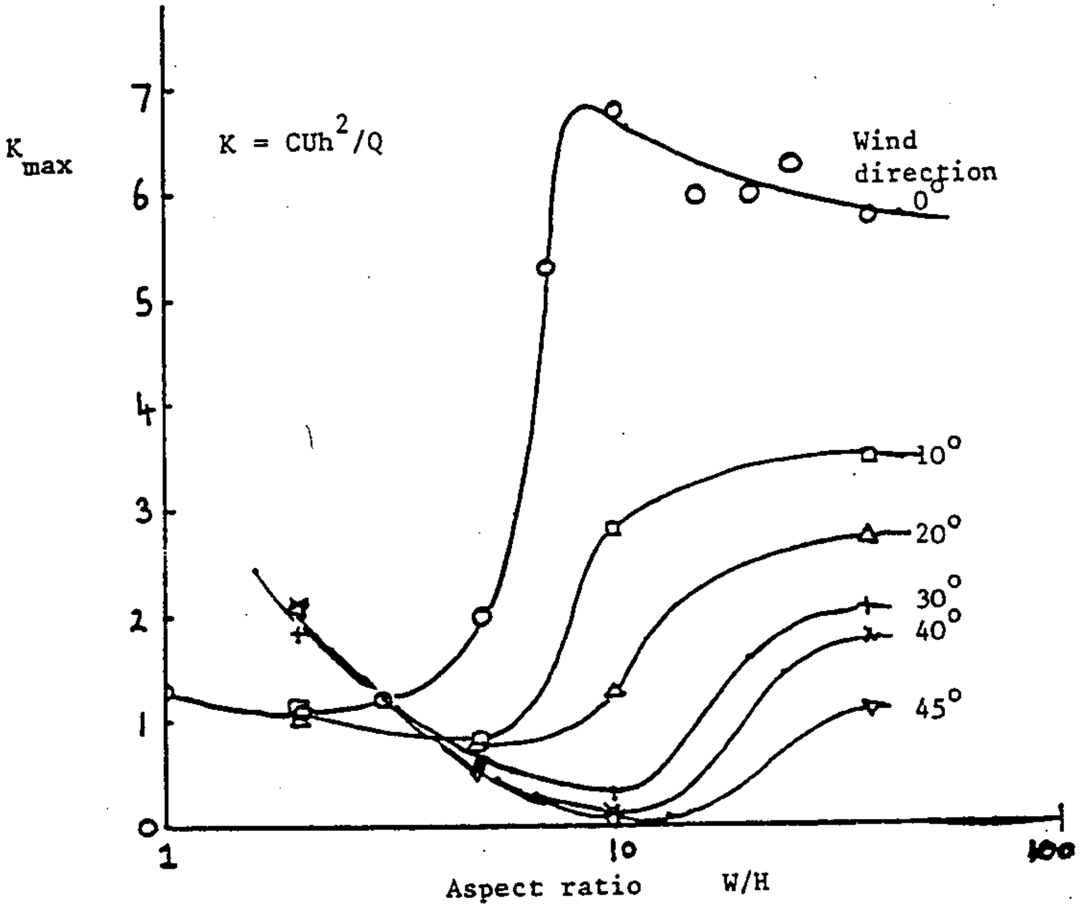

Figure 2.4 Peak Normalised Concentration as a Function of Building Aspect Ratio and Wind Direction (From Hall, in Robins, 1985)

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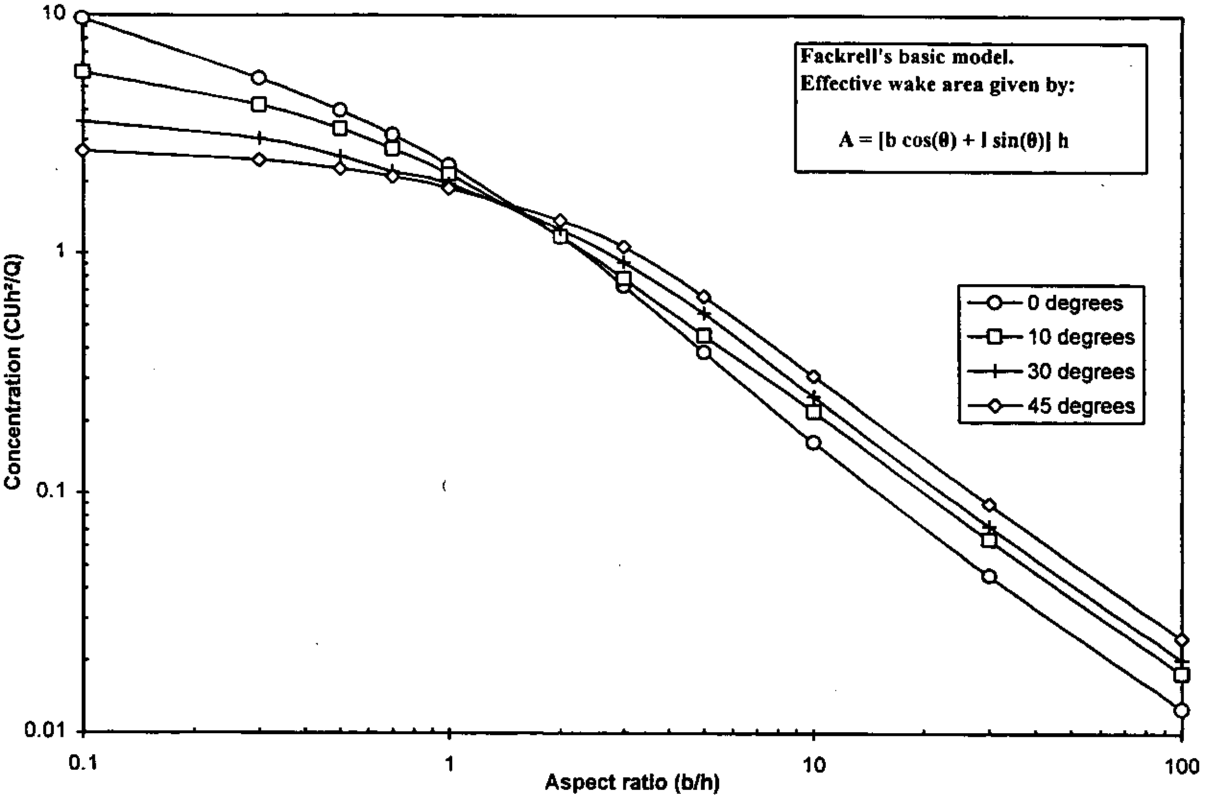

Figure 2.5 Wake Concentration Using Simple Model

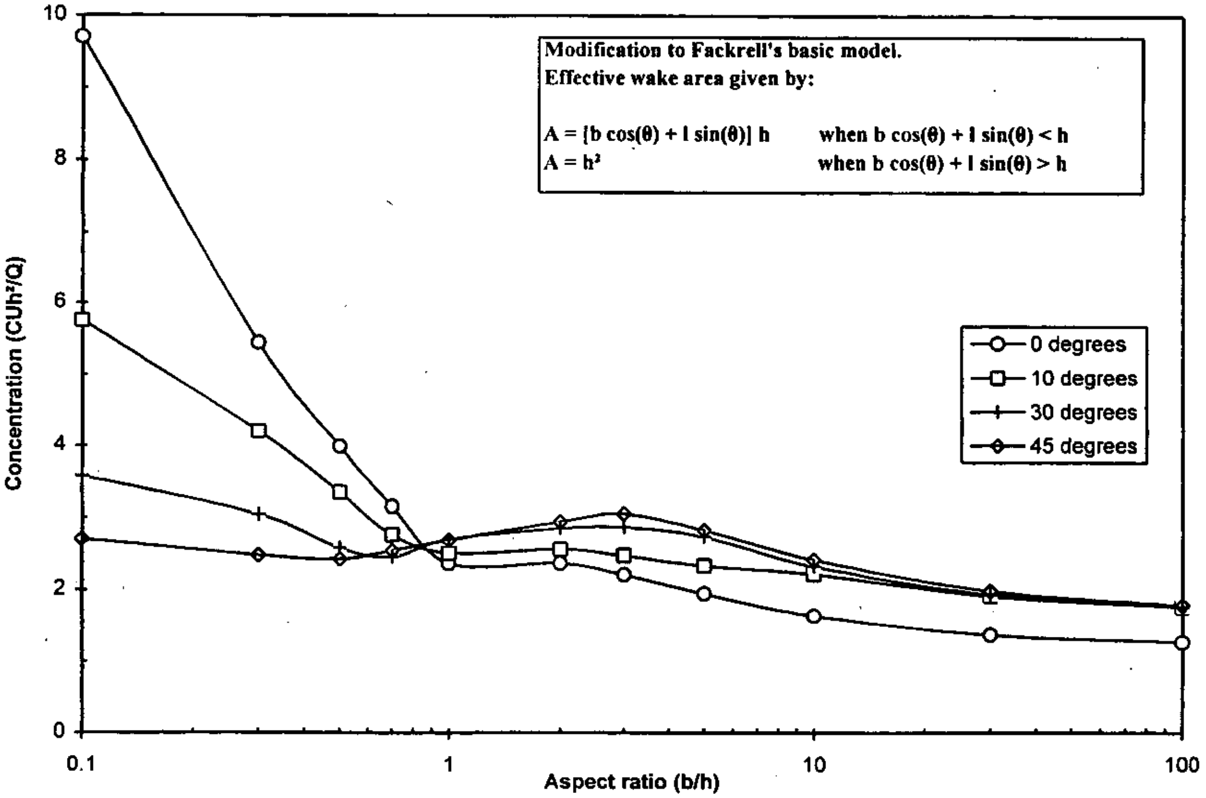

Figure 2.6 Wake Concentration Using Modified Model

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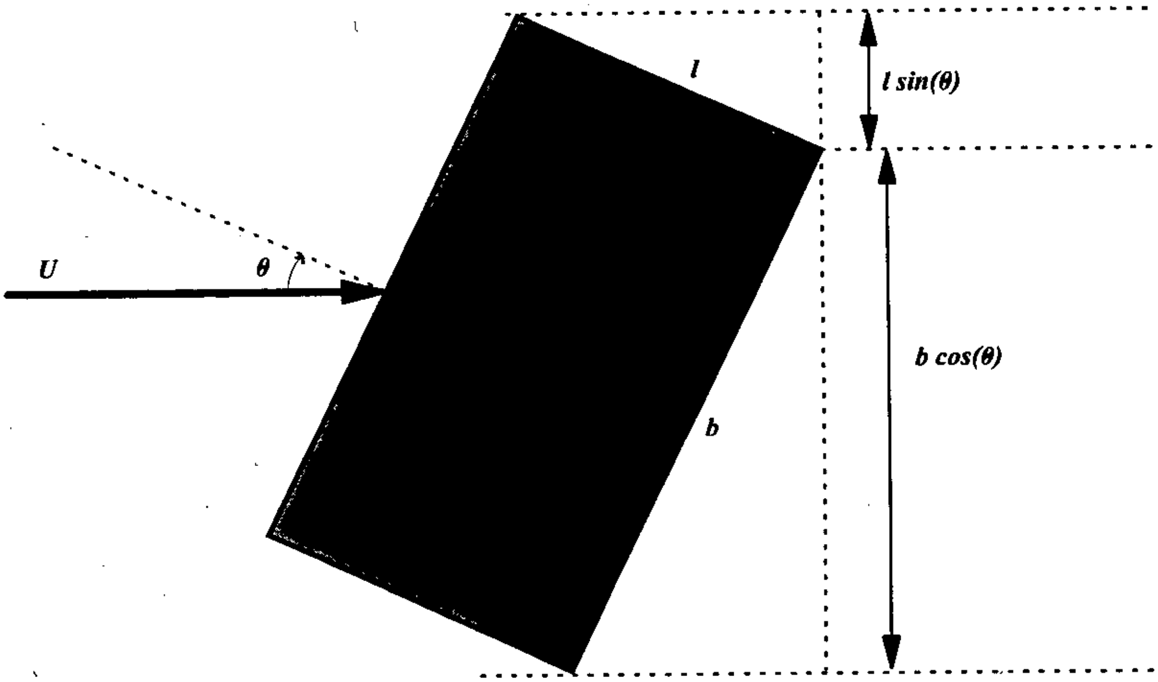

Figure 2.7 Calculation of Effective Building Width for Non-Normal Wind Directions

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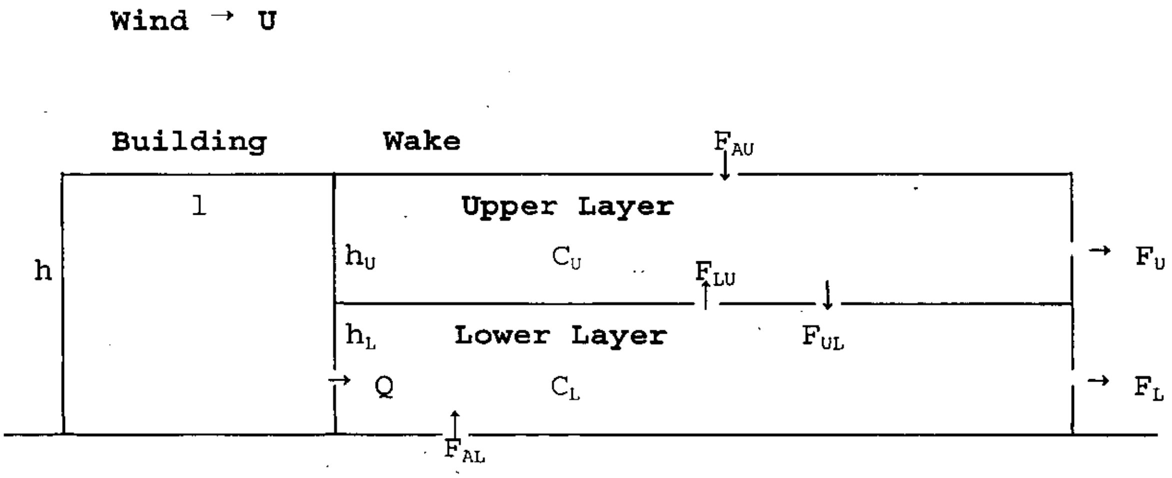

Figure 3.1 Schematic Diagram Illustrating Two Layer Model

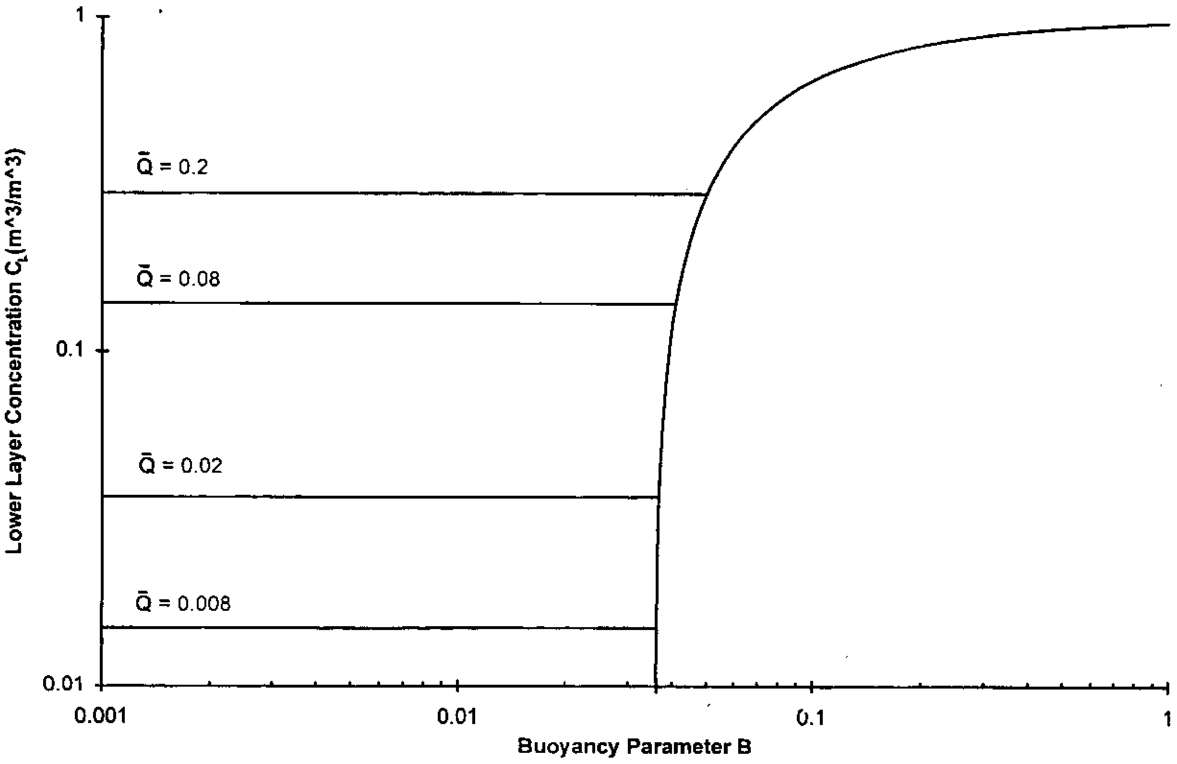

Figure 3.2 Variation of Lower Layer Concentration (C_L) With Buoyancy Parameter (B) for Fixed Values of $\tilde{Q}$

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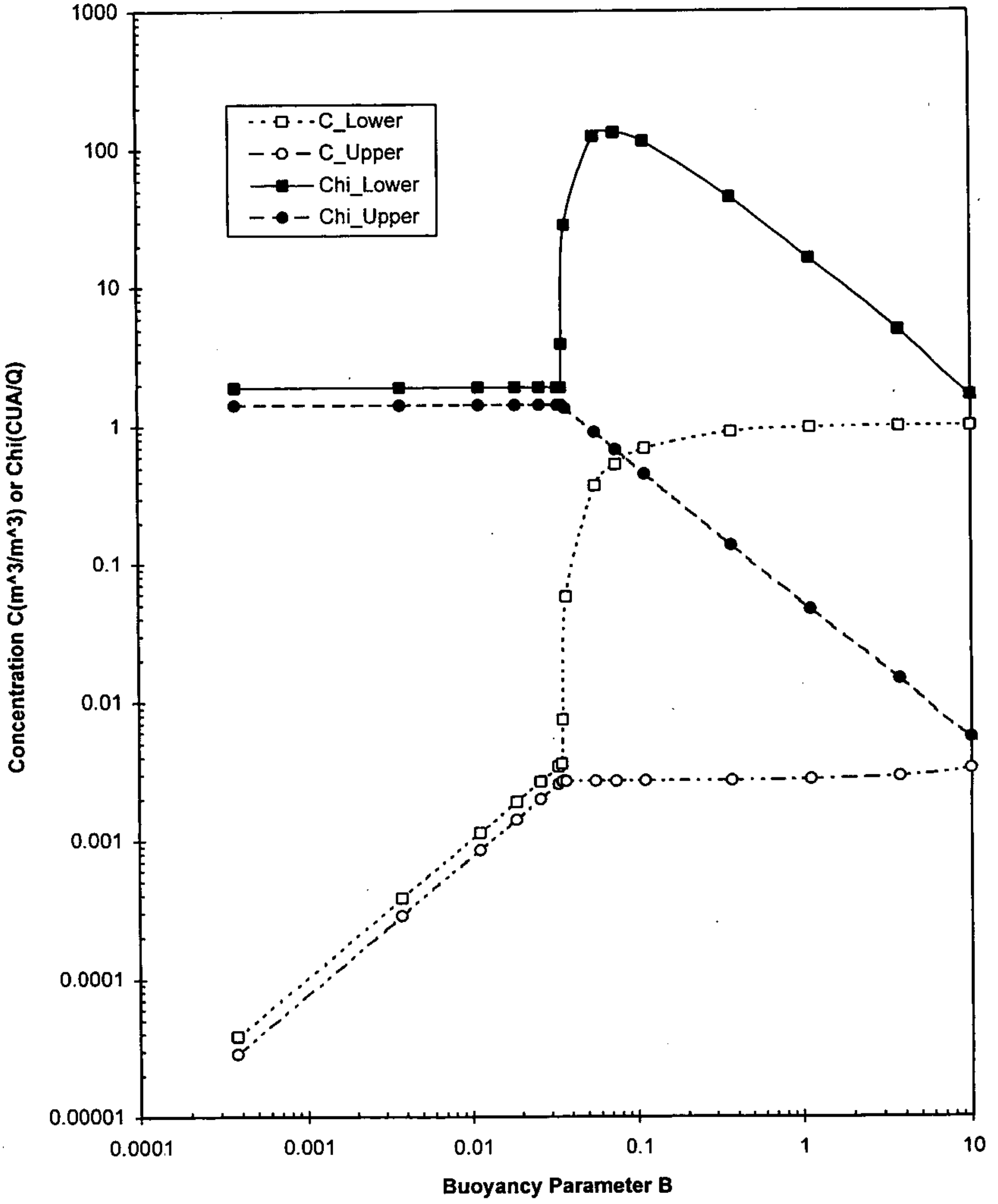

Figure 3.3 Variation of Upper and Lower Layer Concentrations With Buoyancy Parameter, Based on Brighton's Two Layer Model

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