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Building downwash algorithm for the OML atmospheric dispersion model

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Abstract:	The report describes the results of studies aimed at improving the building downwash algorithm, which is currently used in the Danish OML atmospheric dispersion model. These studies will have to be followed by additional work before a revised model can be brought into general operation. The report contains a brief review of methods for treatment of building effects as they are found in the scientific literature. It also describes and examines the current procedure for treatment of building downwash in the OML model. Finally, the principles of a new, proposed algorithm is outlined. The studies reported were carried out as part of a project supported by the Danish Environmental Protection Agency; they constitute the first phase in the development of a new building downwash procedure for the OML model.
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1 Introduction

The present report describes the results of studies aimed at improving the building downwash algorithm, which is currently used in the Danish OML atmospheric dispersion model.

The model was developed in the 1980's, and in view of developments since then - both theoretically and experimentally - it seems now appropriate to reconsider the model's treatment of the effect of buildings. Building effects are a matter of great practical concern because of their large influence on ambient air concentrations. At the same time, building effects are difficult to parametrise correctly.

The studies reported here will have to be followed by additional work before a revised model can be brought into general operation.

The present report contains first a brief review of methods for treatment of building effects as found in the scientific literature (Chapter 2).

The current procedure in the OML model for treatment of building downwash is described in Chapter 3. This description is followed by a closer examination of some of the consequences of the use of the current algorithm, where various problems with the existing algorithm are identified (Chapter 4).

In Chapter 5 the principles of a new, proposed algorithm is outlined, while Chapter 6 contains conclusions.

The studies reported here were carried out as part of a project supported by the Danish Environmental Protection Agency ("OML opdatering"), ending November 1999. A follow-up project is planned.

2 Modelling air pollution in the presence of buildings - a review

Scope of the review

If a building or another large obstacle is situated close to a stack, plume dispersion can be disturbed. While atmospheric flows are relatively simple in the case of the flat terrain, they can become very complex when considering the influence of bluff bodies like buildings and structures. The present chapter contains a brief review of methods for treatment of building effects as found in the scientific literature.

It is known in hydrodynamics that the effects of separation, recirculation and reattachment can be observed, and that various types of eddies can be generated. These effects can be reproduced in the framework of computational fluid dynamics (CFD). Corresponding computer models, however, are too bulky to be used presently in regulatory applications. Therefore, CFD models are not included in the short review presented here.

2.1 Basics

The main part of the existing information about the structure of the wind flow near obstacles comes from model experiments in laboratory conditions (wind tunnels, towing tanks etc.). This kind of information is extremely valuable, but special precautions should be taken when transferring the results obtained from laboratory conditions to field conditions - not all aspects of atmospheric flow can be reproduced in the laboratory.

Concept of recirculation cavity

The very early experiments with visualisation of the flow around two-dimensional buildings indicated that at the corners of the building an outer flow was separating from the hard boundaries forming a ”cavity” with recirculating flow downwind of the building. A similar effect could be predicted mathematically with use of simple models of the potential flows. For this reason the idea of a cavity attached to the bluff body as a bubble was used for many years in development of building-downwash algorithms. It was recognised later, however, that three-dimensional flows can give a much more complex structure, with the streamlines just sliding around the obstacle and not necessarily going over it. The paper by Hunt et al. (1978) can be mentioned as being very instructive in this connection.

Three approaches

Historically, there have been three main approaches to account for building-downwash effects in regulatory dispersion models.

2.2 Gaussian model approach

Gaussian approach: σ_y and σ_z are modified

The first approach is based on a modification of the Gaussian formula, so it takes into account the initial dilution of the emitted material in the vicinity of buildings (see Gifford, 1968; actually this approach was formulated in 1960 and attributed to Fuquay; for further development see, for example, Wilson and Netterville, 1978, and Ramsdell and Fosmire, 1998a, b). Actually, the idea of the Gaussian approach is to replace the dispersion parameters σ_y and σ_z in the denominator of the Gaussian formula with their modified values Σ_y and Σ_z. For the axial concentrations in a plume emitted from a ground-level point source, for example, this will result in the following expression:

$$C = \frac{Q}{\pi \Sigma_y \Sigma_z U}, \qquad (2.1)$$

where C is the pollutant concentration, Q is the emission rate and U is the wind speed. The following approximations have been suggested:

$$\Sigma_y^2 = \sigma_y^2 + cA/\pi; \qquad \Sigma_z^2 = \sigma_z^2 + cA/\pi, \qquad (2.2)$$

where A is the building cross-section area and c is a constant with a typical value of 0.5.

Valid only far away from building

Expression (2.1) is assumed to be valid for distances far away from the building.

2.3 Box model approach

Box model: concentrations are considered uniform within the cavity

For concentrations within the cavity another approach - based on the box model - can be applied. Here it is assumed that C is uniform inside the cavity. From a simple balance consideration one can derive the following expression for concentrations inside the cavity, if we consider the case of a block-shaped building with the source located inside the cavity:

$$C = \frac{cQ}{U_H H W}. \qquad (2.3)$$

Here, H is the building height, W is the building width, U_H is the wind speed at the reference (building) height, and c is an empirical constant usually varying between 0.5 and 5.0 (see, for example, Meroney, 1982, where, however, this interval was indicated as limited by the values of 0.2 and 2.0). Eq. (2.3) is assumed to be valid for the case where the wind direction is perpendicular to the building face; however, also in the case of a non-perpendicular wind direction, C can be determined from Eq. (2.3), if W is taken to be the projected building width perpendicular to the wind direction.

2.4 Virtual source and splitting

Splitting: contributions come from both the original source and a virtual source

The third approach to building downwash modelling is based on the idea of a virtual source intended to simulate the extra dispersion, which is introduced by the buildings. Initially, this was achieved by shifting upwind the location of the source (Turner, 1969; Barker, 1982; Meroney, 1982; Huber and Snyder, 1982). Wilson and Netterville (1976) introduced a concept of a virtual source which has a height different from that of the original source, and which functions simultaneously with it. In this review the method will be referred as "splitting"; Wilson and Netterville assumed that the virtual source should be at ground level.

2.5 Subsequent developments

Puttock and Hunt's approach to determine concentrations within the cavity

In the 1970's and 80's a number of publications appeared dealing with the experimental and theoretical description of building-downwash effects which were based on the aforementioned ideas. A new approach to development of the box-type models was presented in the paper by Puttock and Hunt (1979). Starting with approximation of the wind velocity distribution near the cavity, based on the potential flow around the ellipse and using the analytical solution of the advection-diffusion equation in the potential co-ordinates (Boussinesq variables), they showed that, in the case of rapid mixing inside the two-dimensional cavity, the mean concentration C in the cavity is approximately equal to the average value of concentrations along the outer boundary of this cavity, calculated under the assumption that this boundary cannot be penetrated by the pollutant. Puttock (1979) published experimental data supporting this conclusion.

3-D case

In the three-dimensional case for an arbitrary cavity shape this formalism was generalised by Berlyand et al. (1987a) who developed a regulatory dispersion model, which accounts, in particular, for building-downwash effects (Berlyand et al., 1987b).

Weighting scheme for a splitting approach

When the source is considered as being split into a real and a virtual part, each producing its own concentration field, it is relevant to know the weights to be used to combine these two fields into one. Several formulations have been used for this purpose. The original formulation, probably suggested by Wilson and Netterville (1976), can be found, for example, in the paper written by Schulman and Scire (1993). It assumes that the fraction of the emission rate attributed to the virtual source (which is the fraction of the plume captured by the cavity) is calculated as the portion of the plume below the cavity height. A more sophisticated approach was exploited by Robins et al. (1997) in the UK ADMS model. Using the idea of Puttock and Hunt (1979), they calculated first the mean concentration inside the cavity, C_R, and then determined what value of emission rate should be substituted into the box model (a generalisation of Eq. (2.3) is used in ADMS) to generate this concentration. The corresponding emission is called Q_R. Finally, the weight for the virtual source can be determined as the ratio between Q_R and the initial emission rate of the source, Q.

Recirculating flows are intermittent

In the model introduced by Berlyand et al. (1987b; see also Genikhovich et al., 1987), the weights are derived from the idea that recirculation flows in the cavities are intermittent due to variability of the instantaneous wind direction in the atmosphere. The concept of a critical angle (defining a range of angles around the normal to the building wall) was introduced in this model. It is assumed that the flow has a recirculating pattern when the instantaneous wind direction is within the range of the critical angle; such a critical angle depends on the geometry of the building. With such an approach, the weight for the virtual source is just the probability that the wind direction is found inside the critical angle. This concept is used in the new building downwash procedure for the OML model that is under development (described in Chapter 5).

Cavity dimensions

An algorithm for calculation of cavity dimension which was implemented in the MDNB model (Genikhovich and Snyder, 1994) is outlined in Chapter 5; this algorithm is the one which it is planned to use in a revised building downwash algorithm in the OML model.

2.6 Laboratory experiments

Classic laboratory experiments

The majority of the building-downwash algorithms rely on empirical descriptions of the dimensions of the cavities gained mainly from experiments in wind tunnels. The number of corresponding publications is very high, but, probably, the most frequently referred works are those published by Wilson (1979) and Fackrell (1982, 1984). Two comprehensive reviews of the state of the art in this area were provided by Hosker (1984) and by Hosker and Pendergrass (1986). The results of laboratory measurements, which are collected and systematised in these publications, can be used to estimate the size of the cavities around a simple block-shape building. The corresponding formulae are usually corrected by the developers of dispersion models, in accordance with their understanding of the connection between laboratory and field flows.

2.7 Multiple buildings

Current models do not account fully for multiple buildings

The case of multiple buildings, simultaneously interacting with the flow, seems to represent an extreme challenge for existing dispersion models. The level of the knowledge on this issue as it existed in the mid-eighties was well characterised by Hosker and Pendergrass (1986). At present, a multiple-building option is implemented only in two of the variety of operational building-downwash algorithms in use, namely, OND-86 (Berlyand et al, 1987b) and ADMS (Robins et al., 1997). None of these models, however, accounts properly for changes in the mean and turbulent characteristics of the upcoming wind flow due to the influence of the surrounding buildings.

Recent work on multiple buildings

The most recent development in this field was initiated by publications by Petersen (1997) and Bottema (1997). Petersen, in particular, used wind-tunnel data to test several theoretical formulae for the roughness length as a function of the geometry of the obstacles. Bottema (*op. cit.*), and later Macdonald et al., (1998a) and Duijm (1999) noticed that clusters of buildings influence not only the roughness length but also the displacement height. To describe these effects, Bottema and Duijm used a formalism, which was previously developed for description of the turbulent wind flows and dispersion inside a vegetation canopy. These results seem to be of practical importance if they are included into regulatory dispersion models.

3 The current OML building algorithm

The current versions of the OML model (OML-Point 2.x and OML-Multi 4.2) use a procedure for building effects which was developed in the 1980's, and which is based on work by Schulman and Scire (1980). The procedure will be described in the present chapter, while the subsequent chapter discusses some limitations of the current procedure.

OML: Dilution is enhanced and plume rise decreased in the presence of a building

According to the OML building downwash algorithm, building influence has two main effects: it increases the initial dilution of the plume, and it decreases the plume rise. Most often, both effects contribute towards an increase of ground level concentrations. The total effect can be considerable.

The basis for the current OML model is an empirical procedure developed by Schulman and Scire (1980). The effects of a building on a dispersing plume are modelled by assuming that the plume has an initial dilution radius, R_0. The radius R_0 is used to calculate the initial enhanced diffusion parameters (σ_y and σ_z), and to reduce the plume rise.

In the next subsections we will go into more details. First, it will be shown how the initial dilution of a plume lowers plume rise. Next, the empirical formula used in the model for calculation of the initial dilution radius R_0 will be presented in general terms. Finally, the practical implementation of the R_0-algoritm will be discussed.

3.1 Decrease of plume rise due to initial dilution

Conservation of momentum and plume rise

The rise of buoyant plumes can be derived using the momentum conservation equations (Briggs, 1984):

$$wr^2 u = F_B\, t \qquad (3.1)$$

$$w = \frac{dz}{dt} \qquad (3.2)$$

$$r = \beta z \qquad (3.3)$$

Here, w is the vertical velocity of the plume, r is the radius of the plume, u the horizontal wind velocity, F_B the buoyancy flux, and t the travel time. The height of the plume centerline above the stack top is denoted z. Eq. (3.3) is the closure assumption, which relates the plume radius to plume rise. The proportionality coefficient β (the entrainment rate) is assumed to be 0.6.

Solving Eqs. (3.1) to (3.3) with the initial condition z=0 at t=0, we obtain:

$$z = \left(\frac{3}{2\beta^2}\right)^{1/3} \left(\frac{F_B}{u}\right)^{1/3} t^{2/3} \qquad (3.4)$$

Classic equation for initial plume rise

When we substitute the expressions β = 0.6 and $t = x/u$, we obtain

$$z = 1.6\,\frac{F_B^{1/3}}{u}\,x^{2/3} \qquad (3.5)$$

Eq. (3.5) is the well-known formula for the initial plume rise (Briggs, 1984).

The initial dilution of the plume is taken into account by modifying Eq. (3.3)

$$r = \beta z + R_0 \qquad (3.6)$$

where R_0 is the initial plume radius.

Solving Eqs. (3.1), (3.2) and (3.3), we obtain

$$z = \left[\left(\frac{3}{2\beta^2}\right)\frac{F_B t^2}{u} + \left(\frac{R_0}{\beta}\right)^{1/3}\right]^{1/3} - \frac{R_0}{\beta} \qquad (3.7)$$

Plume rise for diluted plume

If we compare Eqs. (3.7) and (3.4), we can conclude that the effect of initial dilution on plume rise can be expressed as follows

$$\Delta h = \left[\Delta h_0^3 + \left(\frac{R_0}{\beta}\right)^3\right]^{1/3} - \frac{R_0}{\beta} \qquad (3.8)$$

Here, Δh is the rise when taking initial dilution into account, while Δh_0 is the rise of a source free of initial dilution.

In the OML model, Eq. (3.8) expressing the modification due to building effects is used for both the initial and the final plume rise.

In order to apply (3.8), R_0 must be known. The next section deals with this problem.

3.2 Determination of initial plume dilution radius, R_0

The initial plume dilution radius is determined by an empirical method suggested by Schulman and Scire (1980). The procedure is as follows:

Step 1: Evaluate plume height at specified position

i) The effective plume height due to momentum and thermal rise is computed at a position two building heights downstream of the source. As a first approximation, neglecting building effects, we have:

$$h_{ef} = h_s + \Delta h_0 \qquad (3.9)$$

where h_s is the stack height and

$$\Delta h_0 = \left[3F_M \frac{x_B}{((0.4 + 1.2\frac{u}{v_s})u)^2} + 4.17\, F_B \frac{x_B^2}{u^3} \right]^{1/3} \quad (3.10)$$

Here, F_M is the momentum flux and F_B the buoyancy flux. The distance x_B is the distance from the stack to the point P, where the plume height is evaluated. Presently, we assume x_B to be equal to 2 H_B , where H_B is the building height; some modifications follow later. The remaining parameters in (3.10) are wind velocity u and stack exit velocity v_s. With h_{ef} computed from (3.9), the ratio h_{ef}/H_B can be calculated; this ratio is used next.

Step 2: Determine dilution radii R_{0y} and R_{0z}

ii) The initial dilution radii, R_{0y} and R_{0z}, are determined as a function of the ratio h_{ef}/H_B. If the ratio is greater than 3, no enhancement of dispersion is assumed, i.e. R_{0y} =R_{0z}=0. If h_{ef}/H_B<1, then R_{0z}=H_B and R_{0y}=0.5H_B. The enhancement of the horizontal radius R_{0y} is furthermore assumed to be zero if h_{ef}/H_B>1.2. When the ratio h_{ef}/H_B is between these extreme values, a linear interpolation is performed (*Fig. 3.1*).

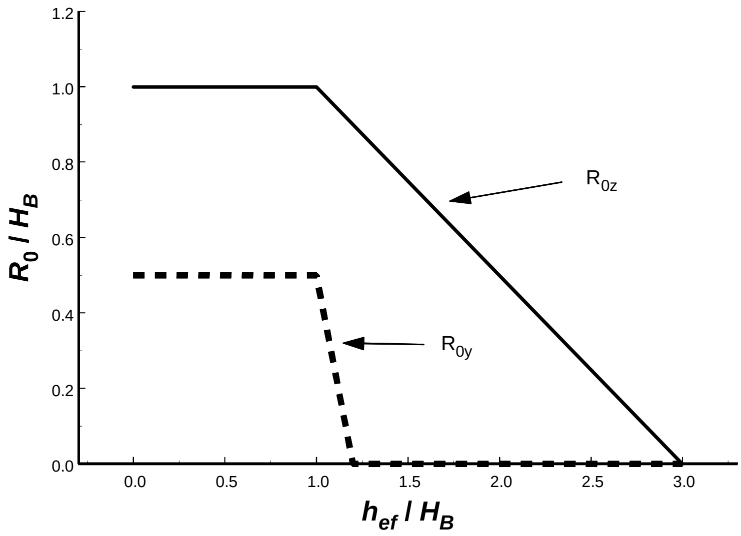

Fig. 3.1 Initial dilution radii in, respectively, vertical and horizontal direction. The radii are functions of h_{ef}/H_B.

Only the vertical R_0 (i.e. R_{0z}) is used for plume rise calculations. Thus, the plume rise after modification due to building effects is determined from (3.8), where it is assumed that R_0=R_{0z}.

Both R_{0z} and R_{0y} are used for calculation of the enhancement of the dispersion parameters. These contributions to the dispersion parameters, $\sigma_{y\_building}$ and $\sigma_{z\_building}$, are computed assuming a 'top-hat' distribution of the concentrations in the plume:

$$\sigma_{y\_building} = \sqrt{2/\pi}\ R_{0y} \qquad (3.11)$$

$$\sigma_{z\_building} = \sqrt{2/\pi}\ R_{0z}$$

3.3 Implementation of the R_0-algorithm in the operational model

"Computational building height"

First, let us explain the notion of a so-called "computational building height", H_B, which is used in the OML model. For "wide" buildings (i.e. buildings with a width larger than their height), H_B is identical to the physical height h_{phys}. For narrower buildings, the following formula applies:

$$H_B = \frac{h_{phys} + 2W_{pr}}{3} \qquad (3.12)$$

W_{pr} is the width of a building, or more precisely, the width of the projection of the building along the wind direction (*Fig. 3.2*) .

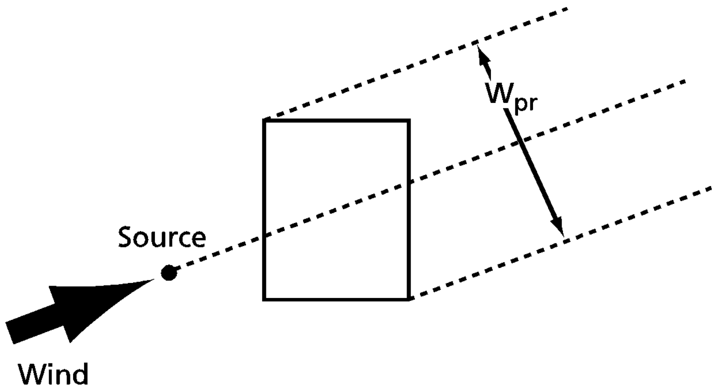

Fig. 3.2

Domain of influence

When the effect of buildings is to be evaluated in the OML model, the underlying assumption is that a building of (computational) height H_B creates a domain of influence, which extends $2H_B$ downstream of the building. If a stack is placed within this domain, dispersion from the stack may be affected by the building. If, on the other hand, the stack is placed outside of the influence domain, the plume remains unaffected.

Definition of point P where plume height is evaluated

For the following discussion, please refer to *Fig. 3.3*. In the model, the height of the plume centerline above a certain point *P* is evaluated. There is such a point *P* for each wind direction; once the geometry of the buildings surrounding the stack has been defined, the positions of all points *P* can be determined. As a main rule *P* is the point at the downwind edge of the influence domain (i.e. at a distance of 2 H_B from the building as shown in *Fig. 3.3*); if, however, the stack is downstream of the building, *P* is defined as being 2 H_B *from the stack.*

Plume height above the point *P* is evaluated in order to determine the amount of building influence. If the plume height at that point is greater than 3 H_B, building effects will be ignored. If, on the other hand, it is smaller, modifications are imposed upon the plume rise and the dispersion coefficients through the parameter R_0 discussed in the previous section.

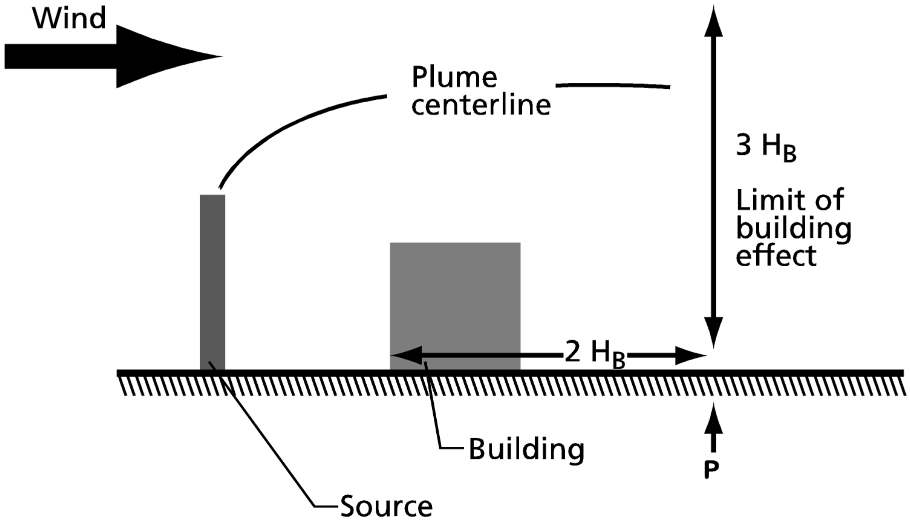

Fig. 3.3 Illustrates the criteria to determine whether the plume is affected by a building. Plume height is evaluated at the point P. If the plume height is less than 3 H_B, the plume is affected by the building.

Evaluation of dilution radii

As accounted for earlier, R_0 is determined from the ratio h_{ef} / H_B. Here, h_{ef} is evaluated at the point P (implying that x_B in Eq. (3.10) is equal to 2 H_B except for a configuration, where the stack is upstream of a building).

Thus, for each meteorological scenario, the parameters R_{0z} and R_{0y} are determined. These parameters are used to modify the dispersion parameters, σ_y and σ_z. Furthermore, based upon the value of R_{0z}, a modified plume height according to Eq. (3.8) is calculated for each receptor along the path of the plume.

Handling of multiple buildings

When several buildings are present at the same time, the flow can be very complex. As a simplification, it is assumed that one of the buildings has the dominating influence, and only this building is considered. The OML model handles the situation by considering - for each meteorological scenario - separately the effect of each building; the building causing the greatest initial dilution radius R_0 is chosen and used for the subsequent computations.

OML procedure is meant to be applied far downwind

The building downwash procedure in the current OML model is based on simple semi-empirical methods, whereas in reality, aerodynamics in the wake of a building is an extremely complex matter. The primary intention of this building effect algorithm has been to provide concentration estimates applicable for distances beyond, say, ten building heights downwind. With this procedure, concentration estimates close to buildings should not be considered reliable.

4 Limitations of current OML algorithm

The current OML building downwash algorithm represents a simplification of the reality, which is in some respects quite crude. In the present chapter, some shortcomings of the present algorithm will be identified.

Problems with current OML algorithm

The following problems will be discussed in this chapter:

- OML assumes that buildings do not affect concentrations if the stack is further than 2 H_B upwind or downwind of the building. This assumption seems to represent a severe problem.
- OML does not distinguish between a very "wide" building (across-wind width) and a moderately wide building (but OML does give "narrow buildings" - i.e., buildings with height greater than width - special treatment). This problem seems to be of moderate importance.
- OML does not account for the "depth" of a building (the along-wind length of the building). This problem is of less importance than the problems mentioned above.

An inherent limitation in the current OML algorithm is that it is not designed to predict concentrations close to a building. As noted in the previous chapter, the model is intended only to predict concentrations at receptors located several building heights downwind.

Thompson's wind tunnel experiments

A series of wind tunnel experiments performed by Thompson (1993) are well suited to provide insight in important characteristics of building downwash, and provide a basis for comparison of these characteristics with model behaviour.

The next section will describe some of Thompson's investigations and roughly compare them to features of the current OML model. Then follows a section, which contains more detail on the results of comparisons of the current OML model with Thompson's results.

4.1 Thompson's wind tunnel studies

Building Amplification Factor (BAF)

Thompson (1993) determined the so-called Building Amplification Factor, BAF. The BAF is formed by comparing two situations: a situation where a building is located near a stack, and a reference situation without any building. For both situations, the maximum ground-level concentration is determined. The ratio between these two concentrations (irrespective of where they are found) is the BAF. The value of the BAF depends on the height and position of the stack relative to the building.

Graphical presentation of Thompson's results

Fig. 4.1 is a reproduction of a very instructive figure by Thompson. The figure was constructed by repeating wind tunnel experiments with the stack in various positions. Four different building shapes were considered. The figure shows contours for the BAF value for these four buildings. The axes in each panel of the figure indicate the position of the stack in question. W is building width and H building height (otherwise called H_B in the present text).

Building 1 is a cube, while buildings 2 and 3 are wider. Building 4 is "deep", as it has an alongwind length of $2H_B$. In the set of building-and-stack configurations studied by Thompson, the largest observed BAF value was around 8.

Extent of building influence

Several features can be noted. If one defines the regions with BAF's larger that 1.4 as being severely influenced by the building, it appears that this regime of severe influence extends 12-14 building heights upwind of the building and 8-14 H_B's downwind; this is substantially more than predicted by the current OML algorithm.

The OML model assumes that the dispersion is not affected by the presence of the building when the stack is further away from the building than 2 H_B. Thus, OML will predict BAF of 1.0 when x/H_B is

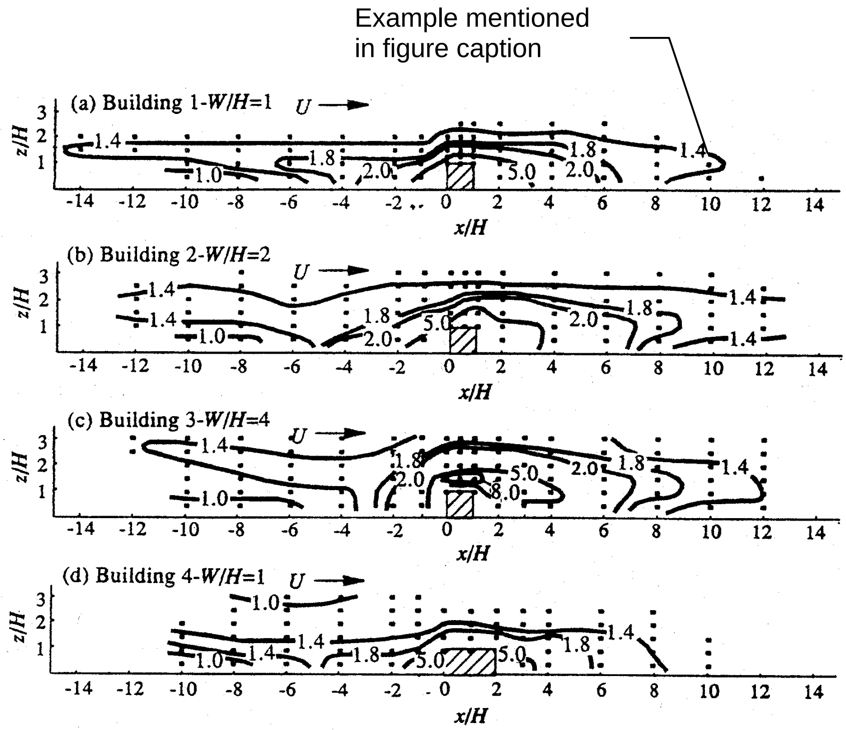

Fig. 4.1 Results from Thompson's wind tunnel investigations, where a stack was placed in various positions relative to a building. Four different building shapes were considered. Contours for BAF value for these four buildings are shown. The axes in each panel of the figure indicate the position of the stack in question.
For instance, a stack which has the same height as the building and which is placed 10 building heights downwind of the building, has a Building Amplification Factor (BAF) of 1.4.
[Reprinted from Thompson (1993) with permission from Elsevier Science.]

outside of the interval [-2,3] (this statement holds true for *Fig. 4.1* (a)-(c); in *Fig. 4.1*(d) the corresponding interval is [-2,4]). It must therefore be concluded that the 2-H_B-limit of the OML model is in need for a change.

Effect of building width

Another problem is that the OML algorithm does not account for the width of a building (unless the building is "narrow"). This means that OML will give the same result for buildings 1-3 (*Fig. 4.1* a-c). This is seen to be a rather crude approach. The very wide building (3) will lead to BAF values larger than buildings 1 and 2. The BAF for building 3 is above 8 when the stack is placed in the most critical position, slightly above the roof of the building.

In the vertical direction, OML will predict a BAF of 1.0 when z/H_B is larger than 3. This prediction is in reasonable agreement with the observations. However, the agreement is better for Buildings 1,2 and 4 than for the very wide Building 3 (*Fig. 4.1*c). For this wide building the zone affected by the building extends higher than for the other buildings.

Effect of building depth

Another potential problem is that OML does not let the "depth" (alongwind length) of a building influence results (except for a displacement of the concentrations). Building 4 is deeper than the others. A comparison of *Fig. 4.1*d and the other panels of the figure indicates that the depth of a building does have some, but not an overly dramatic, effect in the cases studied.

4.2 Results from the OML algorithm

Normalisation of OML results

We have made studies of concentrations computed by the OML model and compared them to data from the wind tunnel measurements of R.S. Thompson. *Fig. 4.2* shows one example of such a comparison. We consider situations with a short stack (h_s/H_B=0.5), and a building which is cubic. The concentrations have been non-dimensionalised according to the equation

$$C = u_H (H_B)^2 \frac{c}{Q} \qquad (4.1)$$

where c is concentration, C the non-dimensional concentration, u_H the wind speed in the height of the top of the building, Q emission rate, and H_B building height. For the OML computations H_B was 60 meters, and it has been attempted to set meteorological parameters to match wind tunnel conditions as closely as possible.

Results for a short stack

Two things can be noted from the figure:

- First, the level of the OML concentrations is generally somewhat lower that the level of the wind tunnel experiments. The reasons for this discrepancy are not yet resolved.
- In respect to building effects, it is obvious that the influence of a building according to wind tunnel results is larger and extends to greater distances than modelled by the OML model. This is another way to view the problem identified in the previous section: that the $2H_B$-limit of OML is not realistic.

Results for higher stacks

Fig. 4.3 shows additional comparisons of OML results and wind tunnel data. These comparisons include data for higher stacks (h_s / H_B=1, 1.5 and 2) where the building effect is less pronounced.

A main result from this study is that the building downwash effect should extend to greater distances that the current OML algorithm predicts. Also, there are discontinuities in the present OML algorithm (the discontinuities occur when the stack is moved relative to the building), which seem unphysical.

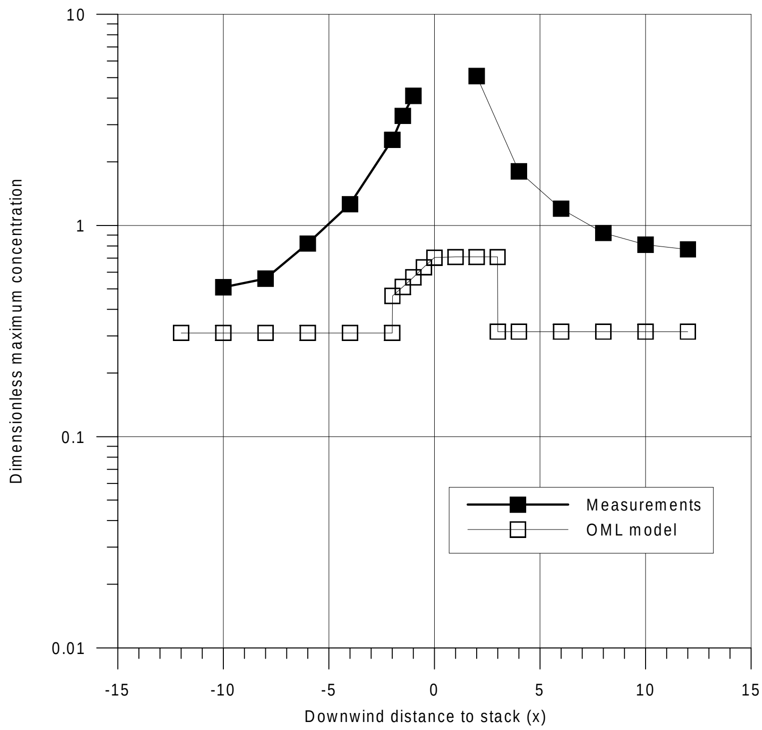

Fig. 4.2 Maximum ground-level concentration for a low stack (h_s / H_B = 0.5), which is placed at various positions relative to the building. OML results are compared to wind tunnel measurements. The x axis indicate distance to the stack in units of building height. A cubic building is situated at the interval [0,1] along the x axis.

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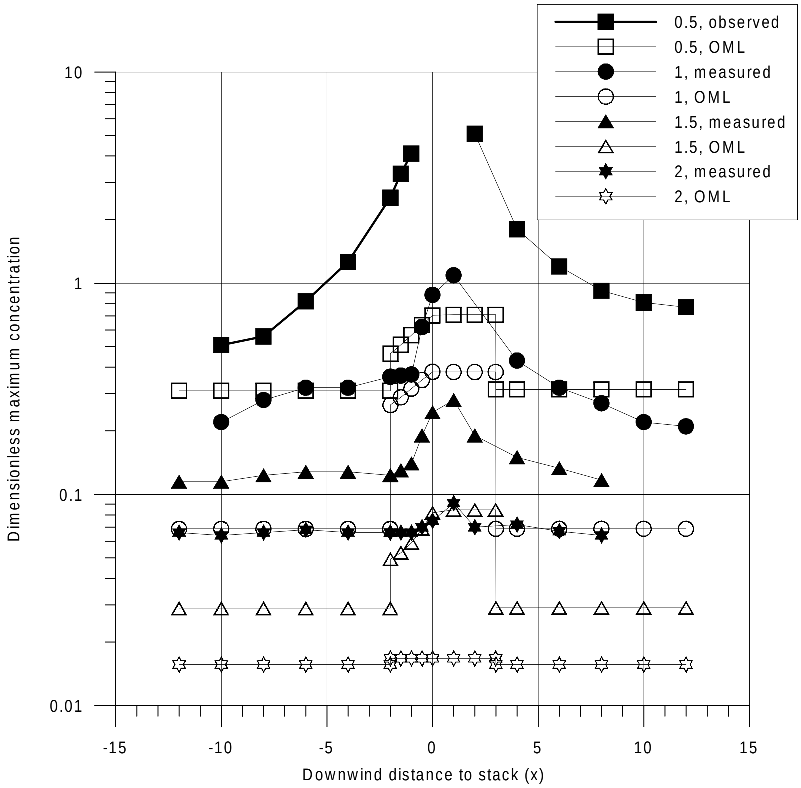

Fig. 4.3 The curves show the maximum ground-level concentration for various stack heights (stack height in units of building height) and for various positions of the stack relative to the building. The legend indicates the value of h_s/H_B (relative stack height). A cubic building is situated at the interval [0,1] along the x axis.

5 New building downwash procedure

5.1 Introduction

In the present chapter we will describe a new procedure for the determination of the effect of building downwash. When the procedure has been fully developed, it is intended to replace the current, very simple procedure in the OML model.

New procedure uses splitting approach

The new procedure is based on the same principles as the MDNB model by Genikhovich and Snyder (1994), which was briefly discussed in chapter 2. An important feature of this procedure is that the concentration is computed as a sum of two parts, one resulting from recirculating flow and the other from non-recirculating flow. The new procedure will remove the unrealistic 2-H_B-limit of the current OML algorithm.

At present, the procedure has not been fully implemented in the form of computer code for OML, but a number of the necessary subroutines have been produced. The details of the procedure and the parameters to be used have not yet been settled during the current project. As it will be apparent from the subsequent text, there are still many issues that require investigation before an operational code can be released.

In the next section the basic principles underlying the procedure will be exposed. Then follows a section explaining in more detail the steps to be taken in a computer program, which implements the principles.

Finally, the status and outlook for the work is summarised.

5.2 Principles of the Genikhovich-Snyder approach

In the following, we will consider a single, rectangular building.

Definition of cavity zones

According to the Genikhovich-Snyder approach, for a given wind direction, the flow around a building can be divided into several zones as depicted in *Fig. 5.1.*

Upwind, rooftop and downwind cavities

Close to the building there are three cavities: an upwind, a rooftop and a downwind cavity. Depending on geometry, the rooftop and the downwind cavities may exist as separate zones or as one joint zone. These cavities are surrounded by a zone of intensified turbulent mixing (ITM) which comprises a much larger volume than the cavities.

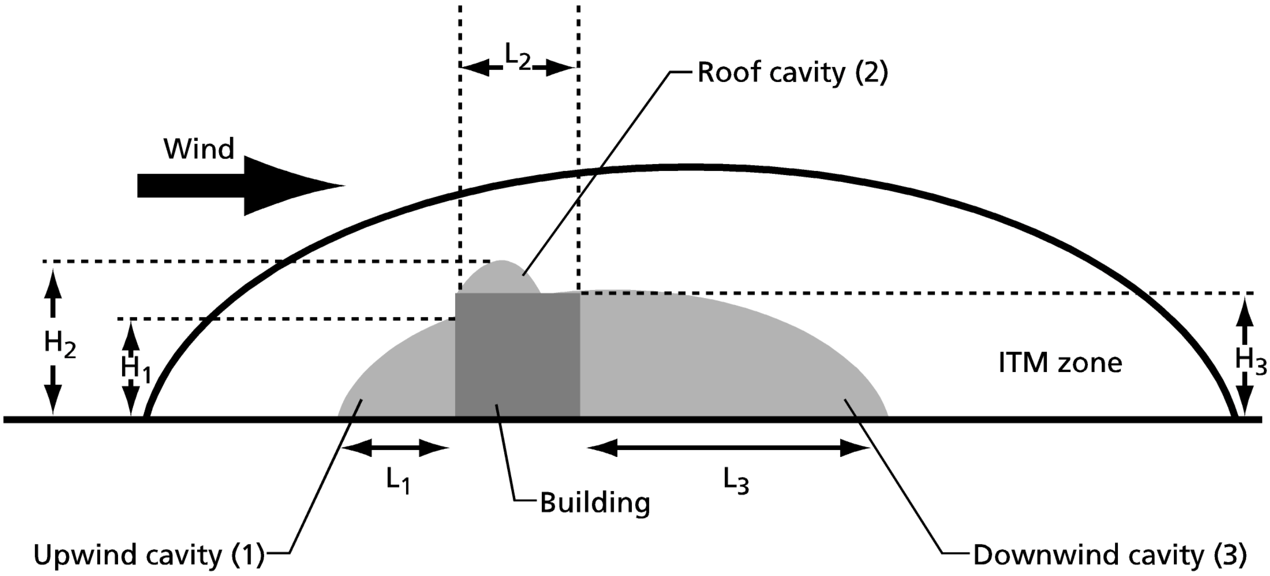

Fig. 5.1 Schematic diagram illustrating the concepts of the Genikhovich-Snyder approach: there are three cavity zones embedded in a zone of intensified turbulent mixing.

ITM zone

Conceptually, the wind flow inside the ITM - but outside the cavities - can be regarded as being similar to the flow over a hill. The "hill" is formed by the outer boundaries of the cavities, and by the building itself. The "hill" deflects streamlines. Inside the cavities, mean velocities are assumed to be small and turbulence intensities very large.

The cavities are intermittent

A further feature of the Genikhovich-Snyder approach is that due to the low-frequency fluctuations of the wind direction, the cavities as described above are intermittent and exist only during a fraction of the time. In order to describe the time-averaged concentrations at a given point in space, it is therefore pertinent to consider the concentration as a the sum of two parts, one caused by the "recirculating flow" (when cavities exist) and the other by "non-recirculating flow" where the presence of the building is ignored.

A key parameter in this splitting procedure is the probability p that the flow is recirculating. If we consider the angle between the wind direction and the downwind face of the building, it is assumed that a critical angle φ_k exists, so that when the instantaneous wind direction is within the range of the critical angle we have recirculating flow. Therefore, p is the probability that the instantaneous wind direction is found within the range of the critical angle. p is calculated as follows:

$$p = \int_{\gamma-\varphi_k}^{\gamma+\varphi_k} f_\theta(\varphi - \overline{\varphi})\,d\varphi \tag{5.1}$$

where f_θ is the probability density of fluctuations of the plume axis azimuth φ relative to its mean value $\overline{\varphi}$, and γ is the azimuth of the vector perpendicular to the downwind wall of the building. In the calculations, f_θ is approximated with the Gaussian distribution. Eq.

(5.1) indicates that p is a function of the source position relative to the building, building geometry and wind direction.

p is used as a weighting factor when concentrations are computed:

$$C = p\,C_{recirc} + (1-p)\,C_{nonrecirc} \qquad (5.1)$$

The concepts outlined here are the basis for the algorithm to be described in the following section.

5.3 Step-by-step approach in building algorithm

In the following, we will step by step outline the actions that are performed in a computer implementation of the procedure. We will consider the case of a simple, rectangular building. Through a series of steps a number of scaling parameters are derived which are used in the further computations.

Specification of building co-ordinates

The source position is assumed to be known. In the horizontal plane, the building co-ordinates may be uniquely specified by five numbers. A practical choice* of such numbers are the co-ordinates of the mid-points of two opposing sides plus the distance between the other pair of opposing sides as illustrated in *Fig. 5.2*

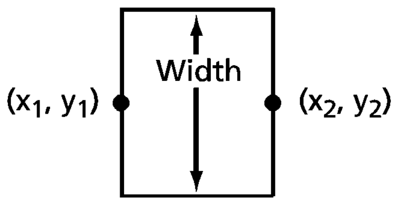

Fig. 5.2 The co-ordinates of a rectangular building can be uniquely specified in terms of the 5 numbers indicated (x_1, y_1, x_2, y_2, width).

Computation of building geometry

When building co-ordinates and a wind direction are given, the width and length of the building, W_u and L_u, can be determined (*Fig. 5.3*). The angle between the building diagonal and the wind direction determines which of the two building dimensions is designated "width".

The projected width W_{pr}

The projected width (W_{pr}) is found by projecting the building on a line perpendicular to the wind direction as shown in *Fig. 5.3*.

Length scales L_* and L_{min}

For later use, determine L_* as min(H_b , W_u) where H_B is the building height. Also determine L_{min}=min(H_b , W_{pr}) and L_{max}=max(H_b , W_{pr}).

* Many of the other conceivable ways to specify building co-ordinates will lead to redundant information. Redundant information makes it necessary to perform a consistency check and to take an appropriate action if the information is not consistent. This would add complexity to the procedure.

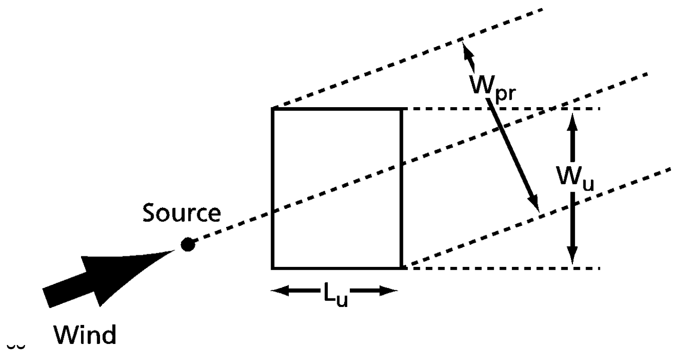

Fig. 5.3 Definition of building length, width and projected width.

Wilson's scale length L_w

Next, determine "Wilson's scale length" L_w. L_w depends on H_b and W_{pr}. If H_b and W_{pr} are identical, L_w is equal to them. In general, L_w is a kind of average value between these two, given by:

$$L_W = L_{min} (L_{max} / L_{min})^{1/3} \quad for\ L_{max} < 8L_{min}; \qquad (5.2)$$
$$L_W = 2L_{min} \quad for\ L_{max} \geq 8L_{min}.$$

Incidence angle δ and "traverse-building distance" L_δ

Two further parameters which are needed for the subsequent computations are the incidence angle δ and "traverse-building distance" L_δ which are depicted in *Fig. 5.4*. δ is the acute angle between the wind direction and the normal to the face of the building.

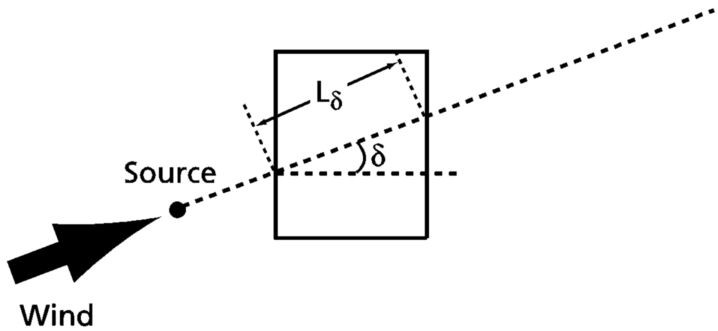

Fig. 5.4 Definition of incidence angle δ and "traverse-building distance" L_δ.

Equations for cavity dimensions

On the basis of the information derived above, the shape and dimensions of the cavities and of the ITM zone can be determined. The basic dimensions (length and maximum height) of the respective cavities are given by the following equations:

Upwind cavity:

$$L_1 = 2.5L^*; \; H_1 = 0.7L^*; \qquad (5.3)$$

Roof cavity:

$$L_2 = 1.1L_W; \; H_2 = H_b + 0.81L_W \exp(-1.3L_\delta / L^*); \qquad (5.4)$$

Downwind cavity:

For $L_\delta < 2H_b$:

$$L_3 = \frac{[11.9 - 10.15(0.5 \cdot L_\delta / H_b)^{1/3}](W_u \cos\delta / H_b)}{(0.5 \cdot L_\delta / H_b)^{1/3} + [1.4 - 1.15(0.5 \cdot L_\delta / H_b)^{1/3}](W_u \cos\delta / H_b)} L^*$$

For $L_\delta \geq 2H_b$: (5.5)

$$L_3 = \frac{1.75 W_u \cos\delta / H_b}{1 + 0.25 W_u \cos\delta / H_b} L^*$$

For $L_2 < L_\delta$:

$$H_3 = H_b$$

For $L_2 \geq L_\delta$:

$$H_3 = H_b + (H_2 - H_b)(1 - \frac{L_2 - L_\delta}{L_2})^{1/2}$$

Equations for the entire cavity boundaries

Equations, which describe the outer boundaries of the respective cavities and the boundary of the ITM as a function of downwind distance *x* are complex and will not be reproduced here.

Weighting factor p

The next step in the implementation of the procedure is to compute the weighting factor, *p*, expressing the probability of recirculating flow for the given combination of source, building and wind speed.

Principles for computation of concentrations

As stated before (Eq. 5.1), the total concentration at a receptor is determined as the sum of two contributions. When evaluating Eq. 5.1 it is necessary to distinguish between various cases. Each case is characterised by the position of the source relative to the cavities. We will not here consider all cases, but as an example look at a case with a source is inside the ITM, downwind of the building. The situation is depicted in *Fig. 5.5*. Let us consider the concentration in point A (inside the ITM, downwind of the source and above the downwind cavity).

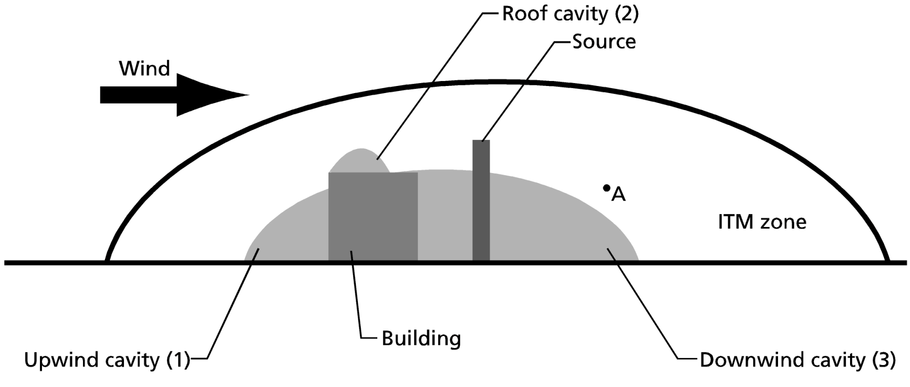

Fig. 5.5 Location of source and receptor (A) for the case discussed in the text.

C_{recirc} is determined by the usual (OML) procedure for computation of concentrations, *but* under the assumption that the stack height is not the physical stack height, but the height of a “virtual stack”. This is a way to account for the fact that the streamlines are deflected in the vertical direction in a similar manner as streamlines over a hill.

The virtual stack is at the same position as the real stack, but its height is lower.

When evaluating C_{recirc} for point A, it is not the height of A above the ground which enters the computations, but the height of A above the “virtual hill”, which is formed by the cavities.

5.4 Status and outlook

Status

The work undertaken until the end of the current project (November 1999) has constituted an initial phase of the development of a new building downwash procedure for the OML model. A number of the necessary parts of the procedure have been developed. The OML model has been transformed into subroutine form, which is a necessary prerequisite for the procedure to be built. Subroutines for computation of parameters related to building geometry etc. are now available.

The Genikhovich-Snyder approach has previously been tested with success (Genikhovich and Snyder 1984), but a substantial amount of work remains to be undertaken before a complete working procedure for all of the cases has been composed and compared to experimental results.

Outstanding problems

During a second phase of the work with the building algorithm, a number of issues deserve continued attention. The parametrisations involved have to be fully resolved; so far some of the parametrisations have been of a tentative nature.

Outstanding problems are:

- All of the various cases with source position relative to the building have to be considered.
- The parametrisation of virtual source height has to become settled.
- The parametrisation of the effect of enhanced turbulence in the cavities and the ITM have to become settled.
- The treatment of plume rise in the various cases considered has be become settled.
- As extensive validation as possible should be undertaken with available databases. An inherent difficulty is that most experimental data come from wind tunnels. Such data do not include all effects that take place in the atmosphere.

Multiple buildings

After the end of the work, it is envisaged that even a revised OML model will have a simplified method for handling of *multiple buildings*. A correct treatment of multiple buildings would be extremely complex and is not a normal part of operational dispersion models at present.

The realistic, pragmatic approach to the multiple-building problem is to adhere to the same philosophy as in the current OML building algorithm: For a given wind direction *only one building* will be regarded as the "active", flow-disturbing building. The current algorithm makes a choice between up to three buildings (one upstream, one at the source, and one downstream) and appoints one of these as the one responsible for the disturbance of the flow. A similar solution is envisaged for the revised model.

6 Conclusions

Some important experiences from the studies conducted so far can be summarised as follows:

- The present OML model only accounts for the effect of buildings, if the buildings are very close to the source - within a distance of two building heights. In reality, also buildings at greater distances are of importance for the dispersion; actually, the distance where buildings can safely be ignored is larger than ten building heights.
- The amount of work required to develop an improved algorithm for building downwash is very large. During the present project a framework has been defined within which an improved algorithm can be constructed. Also, several necessary subroutines (Fortran computer code) for the improved model have been constructed. However, much work remains to be done in order to settle a large number of details and verify parametrisations in the new algorithm.

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