Modelling Complex Phenomena in Gas Dispersion.

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Abstract: Gas dispersion over open flat terrain has been extensively studied over the last two decades. More recently research has focused on modelling more realistic conditions, including such features as obstacles to flow (eg buildings, plant) and the effects of non-level terrain, as well as assessing the importance of the presence of liquid drops in the cloud.

In a recent EC programme of work such effects have been studied in a joint project involving collaborators from seventeen institutions and companies across Europe. The methods applied have involved field trials, wind-tunnel experiments, computational fluid dynamic approaches and development of simple hazard analysis models. AEA Technology's contribution to this has focused on the last area with a strong emphasis on comparison with experiment and with other methods. This has resulted in some remarkably simple ideas for improving hazard estimates in a number of more realistic conditions.

Keywords: Dense Gas, Dispersion, Obstacles

1. INTRODUCTION

Mathematical models of gas dispersion play an essential part in assessing the hazards associated with the accidental release of a wide range of commonly stored materials. A variety of integral (or "box") models, which embody a good broad understanding of the physics of heavy gas dispersion, have been very successfully compared with a range of experimental data taken in fairly idealised conditions. Such models are now used routinely for risk analysis.

One frequent criticism of such models is that they apply typically to open flat terrain and do not model "real" situations. On the other hand, the turbulence associated with moving regions of strong stratification in 3-dimensional heavy gas dispersion problems continues to render these difficult for Computational Fluid Dynamic techniques.

Ideally for risk analysis one would like a quick, reasonably accurate assessment of the effect of obstacles on the dilution of clouds. We have therefore investigated ways of extending integral models to cope with a variety of different obstacles in different positions and orientations relative to the release point of the cloud. The physical assumptions made in the interaction model are simple and transparent.

The results comprise a set of algorithms which an be incorporated into almost any model of dispersion to give estimates of the effects of the obstacles. The performance of the model, of course, depends both on the obstacle algorithm and on the accuracy of the model when used in open terrain. We have incorporated these algorithms into the code DRIFT, written for the UK Health and Safety Executive, and applied it to a range of data with and without obstacles. The comparisons are all satisfactory and some are much better than satisfactory. We believe that these comparisons, combined with the intuitively reasonable physical assumptions of the model, form an excellent basis for incorporating the effects of obstacles into risk analyses.

2. A FENCE DOWNSTREAM OF A HEAVY GAS RELEASE

For the sake of simplicity let us first consider an infinitely long fence or wall downstream of a heavy gas source and transverse to the wind direction. In reality this may lead directly an adequate model of the effects of the boundary wall of a hazardous site.

2.1 The Wind Tunnel Experiments of Britter (1989)

As part of his report on the effects of obstacles on dense-gas dispersion, Britter (1989) describes the behaviour of 2D and 3D steady plumes as they interact with a fence. Experiments were carried out where the cloud to fence height ratio was varied systematically for releases of different Richardson number. A line source, filling the width of the wind tunnel, was used for a 2D source. Of more interest here were the 3D experiments, which used an area source.

From his observations, Britter argues that the effect of a fence is to broaden a plume upstream of the fence and dilute it in the lee. He also argues that the two quantities of prime importance are the cloud Richardson number (Ri) in the absence of the fence and the ratio (H/h) of the fence height H and the plume height h (also in the absence of the fence). To these we would add the cloud height to width ratio (aspect ratio) in the absence of the fence.

Britter observed a significant broadening and dilution of dense low plumes as they cross the fence but very little effect on plumes much higher than the fence. We follow his approach and model the fence as causing a discontinuous transition in a steady plume characterised by the four quantities: concentration, height, width, velocity (denoted C, h, W, U). This is clearly not valid in the region very close to the fence but may be adequate a few fence heights or more up- or downstream of the fence.

We shall assume that upstream of the fence, the plume is unaffected and that the state of the plume is given by C_{nf} , h_{nf} , W_{nf} , U_{nf} , where subscript "nf" indicates values when *no fence* is present. These change to C_f , h_f , W_f , U_f immediately downstream of the fence - see Figure 1. The objective is to model these latter quantities in terms of the former, in order to provide an effective source downstream of the fence. We need four relations to connect these four quantities.

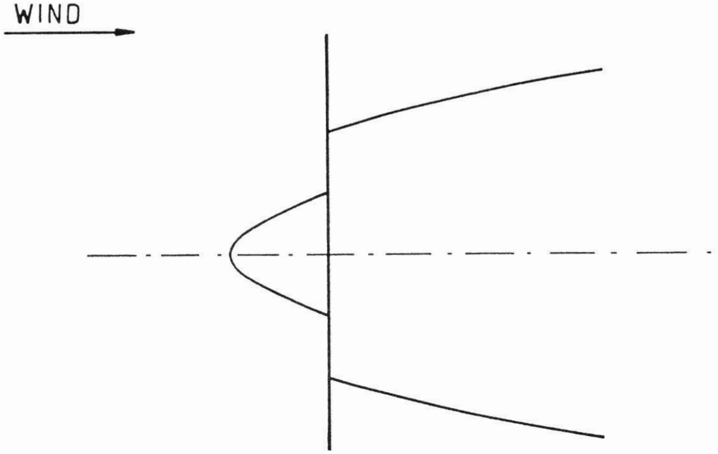


Figure 1. Idealised plan view of a plume encountering a fence showing a step change in the cloud width.

For a steady plume conservation of contaminant flux provides the first:

$$C_f W_f h_f U_f = C_{nf} W_{nf} h_{nf} U_{nf} \tag{1}$$

The second relation is provided by the assumption that the plume advection velocity is at most only weakly affected by the fence and only very close to it. We therefore set $U_f = U_{nf}$ and reduce equation (1) to

$$C_f W_f h_f = C_{nf} W_{nf} h_{nf} \tag{2}$$

The third of our four relations is a very simple geometric consideration. If the cloud is sufficiently high before it reaches the fence, we assume that its height is completely unaffected by the fence; if it is initially lower than the fence then it mixes in the lee to a height controlled by the height of the fence. Thus we assume

$$h_f = Max(\lambda H,\ h_{nf}) \tag{3}$$

where H is the fence height and λ is a free parameter of order 1.

Before we look at the final assumption let us note that Britter's data allow us to test the model thus far. To do this we note that the above implies

In Figure 2 we plot H/h_{nf} against $(C_f W_f H) / (C_{nf} W_{nf} h_{nf})$ showing points extracted from

$$\frac{C_f W_f H}{C_{nf} W_{nf} h_{nf}} = Min\left(\frac{1}{\lambda}, \frac{H}{h_{nf}}\right) \tag{4}$$

Britter's data and a line representing the prediction if we take $\lambda=1$. The agreement supports the simple idea that clouds initially higher than the fence are unaffected by it, whereas clouds lower than the fence are mixed in the lee to the height of the fence.

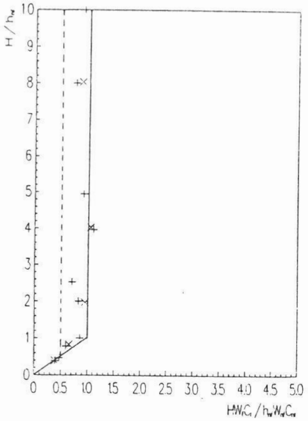


Figure 2. The ratio of plume [concentration x width x height] either side of the fence (horizontally) against the ratio of fence to plume height. The data of Britter (1989) are shown for different Richardson numbers as well as predictions of the simple model with $\lambda=1$ (solid line) and $\lambda=2$ (dashed line).

2.2 Dilution at the Fence

To complete the model we need one more equation relating the cloud state after the fence to that before. It is intuitively simplest to couch this in terms of the cloud's width or aspect ratio.

In fact we shall simply make the hypothesis that the entrainment at the fence, which is sufficient to get the cloud over the fence and mix it in the lee, alters the aspect ratio (for any given initial aspect h_{nf} / W_{nf} and any given Richardson number Ri) in exactly the same way as the aspect ratio alters in open terrain while the height increases to H.

This assumption is intuitively appealing; it embodies the idea that denser clouds spread more than lighter ones during air entrainment, irrespectively of whether the entrainment is occurring as the cloud surmounts a fence or advects down wind. It clearly requires testing against data.

In fact it is also an easy assumption to use in generalising almost any heavy plume model to make predictions for the extra dilution incurred as the plume passes a fence. It can be very simply implemented by adopting the following procedure.

i Progress the model from the source to the fence exactly as if the fence were not there, and use these predictions for the region upwind of the fence.

ii If the cloud is now lower than the fence height, progress the model, ignoring all predictions, until the height of the cloud reaches the fence height.

iii Adopt the state of the cloud at this point as the state immediately in the lee of the fence, and progress the model downstream from this source state at the fence.

This simple "virtual source" model is illustrated in Figure 3. In the next Section we shall explore the consequence of applying this procedure to the code DRIFT which embodies a model of an initially dense steady plume - see Webber, Jones, Tickle, and Wren (1992).

However it is also important to be able to compare our ideas with instantaneous release data. In the case of an instantaneously released gas cloud we shall adopt the nearest equivalent model. In this case the total mass of contaminant is conserved as the cloud passes the fence. In addition we assume that the cloud must increase in height to the fence height, that its velocity is unaffected, and that as it passes the fence, its aspect ratio again changes exactly as it would have done when undergoing the same dilution during advection.

The same procedure can now be applied as in the steady plume. In this case one allows the model to run beyond the fence until height H is achieved and then starts the cloud from the fence in this new state as shown in Figure 4.

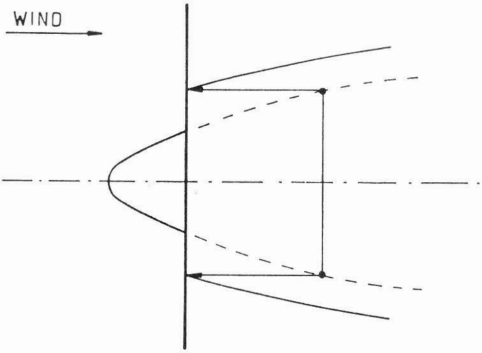


Figure 3. The model described in the text assumes the cloud is unperturbed upstream of the fence, and takes the starting conditions in the lee of the fence to be those which would have been attained anyway when the cloud reached the fence height. The results downstream of the fence thus consist of the unperturbed results with a constant backward displacement.

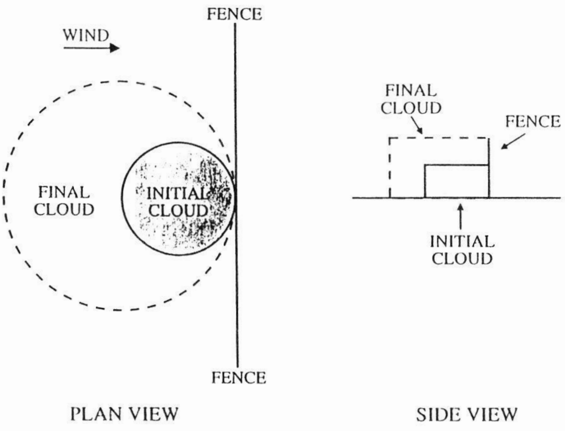


Figure 4. Plan view of the model for an instantaneous cloud.

2.3 Comparison of the Model DRIFT with Continuous Release Data

In developing the fence interaction model within DRIFT we used the wind tunnel data of Britter (1989). In order to do a proper validation of the model we shall compare its predictions with other data sets. All the DRIFT results quoted in this chapter were obtained using version 2.15 of the code.

First we shall look at the continuous propane release trials of Heinrich and Scherwinski (1991) where data were taken with and without a fence downstream of the release. In these experiments the fence was initially present, and then after a time removed, effectively instantaneously. Figure 5, taken from one of the trials, shows some of the concentration measurements at different points in the flow. From the data from many of the sensors (those which show two distinct steady concentration regions) it is possible to get a good estimate of the concentration with and without the fence being present. (The data need careful interpretation; some sensors clearly show the cloud going around the edge of the fence.)

In two of the trials fences were used which did not present a 100% blockage. Our model does not consider porous fences, but nevertheless we shall use these data sets, considering them as solid obstacles. The validity of this assumption is questionable but may be judged from the results.

The propane was released from a large, fixed, storage tank connected to the release point via a 200m pipeline. A number of exit nozzles were available to give horizontal or vertical jet-like sources with varying momentum. A "cyclone" device was also available, to provide a momentum free source for some trials. For full details of the test facility, measuring equipment, and experimental results see Heinrich and Scherwinski (1991), and Nielsen and Jensen (1991).

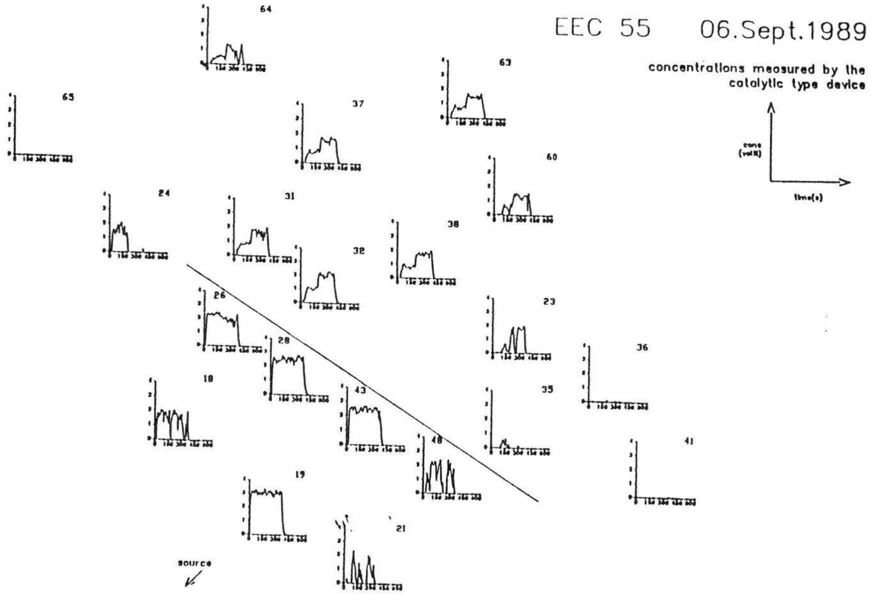


Figure 5. Field trial data for EEC55 after Heinrich and Scherwinski (1991)

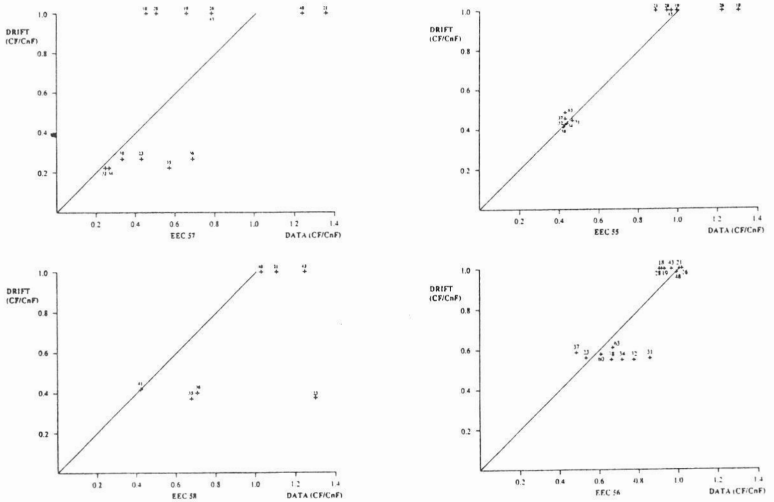
A preliminary analysis of this data was reported by Jones and Webber (1992) using models of dense gas dispersion over uniform flat terrain. It was shown that concentrations could increase in places where cloud broadening affects were important. Centre-line concentrations in the lee of the fence were reduced due to the additional entrainment required to surmount the obstacle. This analysis concentrated on five experiments, designated EEC54-EEC58 inclusive. Of these three used a jet-like source with a spill rate of 3kg/s and two used a momentum free source. We shall consider these separately.

For the jet releases, the code DRIFT does not itself address the high momentum depressurisation phase. Some additional processing is therefore required first. We therefore applied the jet code TRAUMA (Wheatley 1987a,b) for the high momentum jet phase and DRIFT there after. Jones and Webber (1994) give details of how this was done.

On the other hand momentum free releases can be modelled in their entirety using DRIFT. The problem here is that the source conditions are less well defined. Not all of the propane vaporises in the "cyclone"; some is seen to form a liquid pool, the volume of which was estimated after the discharge had terminated. From this an average vapour discharge rate can be assumed (approximately 2/3 of the liquid discharge rate in these experiments). The initial cloud size, close to the "cyclone" is not specified and the analyst must make some assumptions. Since the aspect ratio of the plume as it encounters the fence is important in our model the choice of initial aspect ratio may be critical. All other input parameters are well defined in the experimental data set.

If we adopt the ground roughness length (roughly 15cm) quoted by Heinrich and Scherwinski (1991) we find that DRIFT predicts the cloud to be higher than the fence when the obstacle is encountered, for all release configurations. In this case little or no additional entrainment should take place at the fence. Although no cloud height data are available from the field trials the concentration records clearly contradict this. But in order for DRIFT to predict concentrations accurately in the absence of the fence (see Jones *et al* 1992), the ground roughness length had to be reduced by about one order of magnitude below that quoted by Heinrich and Scherwinski (1991). Here we adopt the same, reduced, value used previously, (especially as the roughness length of 10mm used by us is in close agreement with the - even smaller - average value of 6mm found by Nielsen (1993) from further studies of the meterological data for trials EEC56 and EEC57.)

Figures 6 illustrate the ratio of ground level centre line concentration with the fence present to that without the fence. The plots are of predicted versus experimental values; the line of exact agreement is the 45 degree diagonal, which is also shown. Individual data points are numbered according to the sensor type and position in the notation adopted by Heinrich and Scherwinski (1991).



Figures 6. Comparison with field trial data for EEC55 to EEC58. The solid line ($y=x$) represents an exact agreement.

It can clearly be seen that the model is extremely successful in predicting the ratio of concentrations with and without the fence in the jet releases EEC55 and EEC56. In fact the results for EEC55 are far better than one should expect from such a simple model. The EEC56 results are a better indication of what we should regard as a good fit. (It is tempting to conclude that the greater success of EEC55 over EEC56 may be due to the fact that the latter used a 50% porous fence instead of a solid obstacle, but that would be taking the closeness of the fit for EEC55 far too seriously and, in any case, without further data it is difficult to draw firm conclusions.)

The results of Trials EEC57 and EEC58 are not fitted quite so well, but we still predict concentration reductions to within a factor of two or so. This we still regard as an excellent fit, particularly in view of the greater uncertainty in the initial conditions from the "cyclone" source. Had the cloud aspect ratio close to the source been better defined, then perhaps we would have been able to attain the same degree of success we did for the high momentum releases. The distinction between solid and porous fence data is less discernable here. Perhaps this too is due to the greater uncertainty in the source conditions.

2.4 Comparison of the Model DRIFT with Instantaneous Release Data

Our cloud-fence interaction model for instantaneously released clouds can be compared with the data of Hall *et al* (1992). This data was taken using the Warren Spring Laboratory wind tunnel to investigate the natural variability which occurs when dense gas clouds are released suddenly into an ambient flow.

The release was designed to be a 1/100 scale model of the Thorney Island trials. That is a source of uniform density in the form of an erect cylinder of height 13cm and radius 7cm. Fences, both solid and crenellated (50% porosity), ranging from 1.6cm to 15.3cm high were used, but in these experiments there is enough solid fence data to make a meaningful comparison without having to consider the crenellated fence data, and so we exclude it for the purposes of this paper.

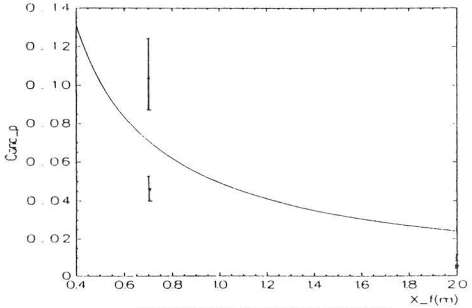
Concentration measurements were made at a point upstream and a point downstream of the fence. Hall *et al* quote both a maximum measured concentration at each point and a concentration averaged over the time during which the sensor was in the cloud. The many repeat runs allow an estimate of the variability of the measurements. This data is therefore uniquely useful in giving a good idea of the significance of any discrepancy between the data and the model predictions.

The data covered a range of densities. The bulk Richardson number Ri defined as

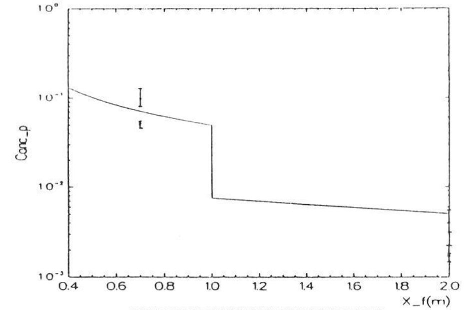
$$Ri = g\frac{\rho_{(gas)} - \rho_{(air)}}{\rho_{(air)}}\frac{L}{U^2} \qquad (5)$$

(where g is the gravitational acceleration, L is a characteristic length scale, in this case the initial cloud height (13cm), and U is the wind speed at height L) was arranged to take values 0,1,2,5, and 10.

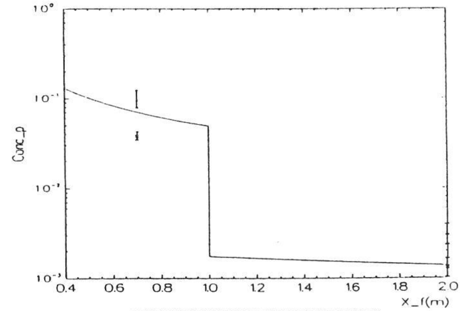
The predictions of DRIFT are compared with the data in Figures 7. (We show only a selection of the results here. A comparison with the complete data set may be found in Webber *et al* (1994)) .



COMPARISON WITH WARREN SPRING FENCE DATA.
RICHARDSON NUMBER 10, FENCE HEIGHT 1.6M

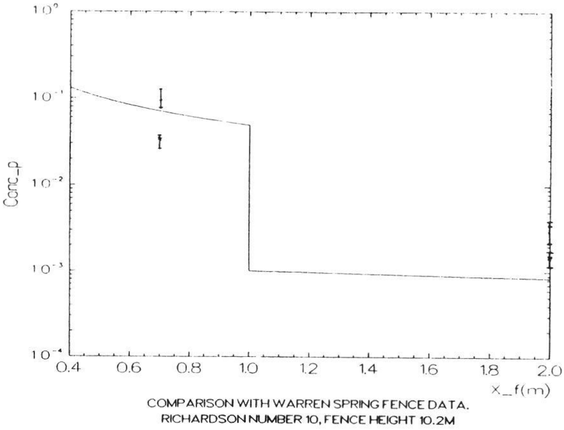


COMPARISON WITH WARREN SPRING FENCE DATA.
RICHARDSON NUMBER 10, FENCE HEIGHT 3.8M



COMPARISON WITH WARREN SPRING FENCE DATA.
RICHARDSON NUMBER 10, FENCE HEIGHT 7.6M

Figures 7. See caption below.



Figures 7. A comparison with the Warren Spring fence data for the largest fence height and all Richardson numbers. The higher data point represents the average value of the peak concentration observed in all repeats of the same scenario (typically 50 or 100 runs). The lower data point represents the average value (again averaged over all repeats) of the mean concentration (the average concentration seen at a single sensor during a single run) observed in the same experiments. Error bars are used to represent the 10 and 90 percentile values of the data.

The graphs show concentration (C/C_0) as a function of cloud front position for each scenario. Of the two data points at each sensor location, the larger value represents the maximum concentration (averaged over 50 repeat runs), whilst the lower value is the mean concentration (also averaged over the 50 repeat runs). The error bars are used to represent the 10 percentile and 90 percentile values in each case. Ideally the model predictions should lie within the error bounds of the maximum concentration data (80% of the time!).

In a number of cases, particularly those runs with low fences and low Richardson numbers, the model predicts the cloud to be higher than the fence when the obstacle is encountered. In this case the model assumes that the cloud should pass the obstruction with no additional dilution. The data show this not to be the case. Some extra dilution does take place and the model therefore over-predicts concentrations beyond the fence.

For all other release configurations the model predicts that the cloud does indeed interact with the obstacle. Here model predictions and data are in excellent agreement. Beyond the obstruction, model and data are showing concentration reductions of about an order of magnitude over similar releases on flat terrain. Potentially this is of enormous importance in plant design and for risk assessment work.

Some comments are in order on the passive dispersion (ie ambient density) limit. In the passive limit DRIFT predictions differ from experimental data in that there appears to be considerable entrainment near to the source which is not modelled correctly. Britter and McQuaid (1988) found a similar behaviour when comparing the wind tunnel data of Meroney and Lohmeyer (1982) with an analysis based on Lagrangian similarity theory from Yang and Meroney (1972). A simple comparison shows that the data of Hall *et al* (1992) agrees favourably with that of Meroney and Lohmeyer (1982), whilst DRIFT compares well with Yang and Meroney (1972). The mechanism used by models predict acceleration to the wind speed seems to be flawed in the passive limit. Momentum transfer from the ambient flow to the cloud appears to take place much slower than models predict, hence model clouds appear to accelerate too quickly. This results in a lower dilution at any given distance from the source than is actually observed.

3. ISOLATED BUILDINGS DOWNSTREAM OF THE SOURCE

The empirical success of these very simple ideas in modelling the net effects of the interaction with infinite transverse fences prompts us to extend the model to cover obstacles of finite width downstream of the source. The complication in this case is that the cloud may go around one or both sides of the obstacle or over the top or completely engulf the obstacle. In principle this variety of possibilities will require more data against which to test any ideas.

3.1 Definition of the Model

In considering a single, isolated obstacle downstream of the source we adopt the same approach as for the fence interaction model. For steady dispersion we again adopt the (constant velocity) flux conservation equation (2) and make the same assumption about the effect of the turbulence around the obstacle on the aspect ratio of the cloud.

However equation (3), the condition that the cloud must go over the fence is replaced by a more general *dilution condition* which is described below. The procedure is then the same as before, but in order to find the effective source in the lee of the obstacle, the cloud is now advanced until the dilution condition is achieved.

The dilution condition allows the cloud either to pass over the obstacle or to go round it or both. We therefore write it in logical form as

$$DD = HH \;\; or \;\; WW \qquad \textbf{(6)}$$

where DD represents the *dilution condition* and HH is a *height condition* (the condition that the cloud is high enough to pass over the obstacle) and WW is a *width condition* (the condition that the cloud is wide enough on one or both sides to pass around one or both sides of the building).

The height condition is taken to be essentially as before (equation 3). (In fact we modify it by demanding also that if the cloud is narrower than the fence height it becomes at least as wide as the fence is high as it passes. This modification is inspired by the following arguments about eddy sizes and in fact has no effect on any of the cases we have examined with fences.) We shall see in the case of an infinitely wide obstacle that the *width condition* is unachievable and that the model therefore reduces appropriately to the above fence model.

Again as before we note that a sufficiently large cloud approaching a small building may fulfil either or both conditions HH and WW on approach and will be unaffected by the obstacle in our model.

The new feature in the building interaction model is therefore the *width condition*.

3.2 The Width Condition

In deriving a condition under which the cloud may go around the building our objective has been to find one which is a s simple and successful as the *height condition* of the fence model. This was conceived on simple geometrical considerations (the cloud must achieve the height of the fence) and from very simple turbulence properties in the wake (the characteristic eddy size is determined by the height of the fence and this will tend to mix the cloud on this scale).

A three dimensional obstacle is more complicated but nevertheless we shall try to apply some reasonable physical arguments at this simple level. First let us assume a characteristic eddy scale determined by the minimum of the breadth b_E and height H presented by the building to the wind. We write

$$L_e = \text{Min}(\alpha\, b_E, \quad \beta\, H_b) \qquad (7)$$

where α and β are dimensionless parameters of order 1. (In fact our first guess was to take $\alpha = 0.9$ and $\beta = 1.0$ and we have not yet had any compelling reason to change them.) It is assumed that turbulence near the edge of the building and affects most strongly a region of length **$L_e/2$** either side of the building's ends, as shown in Figure 8. (It is important here that α should be less than or equal to one.)

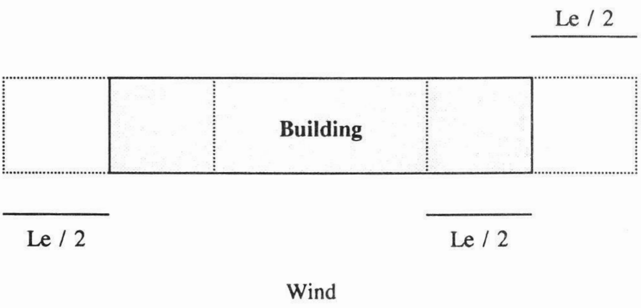


Figure 8. The assumed region of turbulence near the edge of the building.

In order to propose a *width condition* let us first establish some notation. Let y be the coordinate in the horizontal plane orthogonal to the wind direction. Let the building be centred at y_b and extend laterally between

$$\begin{aligned} y_{b+} &= y_b + \frac{b_E}{2} \\ y_{b-} &= y_b - \frac{b_E}{2} \end{aligned} \tag{8}$$

Similarly, if the centre of the cloud is at y_c then the ends of the gas cloud are at

$$\begin{aligned} y_{c+} &= y_c + \frac{W_c}{2} \\ y_{c-} &= y_c - \frac{W_c}{2} \end{aligned} \tag{9}$$

where W_c is the width of the gas cloud just upstream of (and in the absence of) the obstacle. We shall define the width condition in terms of these variables. Here we shall consider the case where the cloud centre is to the right of the building centre ($y_c \geq y_b$); the other case is defined symmetrically.

For the width condition to be achieved, we demand that the outermost edge of the cloud (y_{c+} in this case) moves out to $L_e/2$ outside the edge of the building if it is not at least that far out already. That is

$$y_{c+}^{new} = \max\left(y_{c+} \,,\; y_{b+} + \frac{L_e}{2} \right) \tag{10}$$

In the first instance it is assumed that the cloud centre is not displaced. That is

$$y_c^{new} = y_c \tag{11}$$

This gives for the other cloud edge

$$y_{c-}^{new} = 2\,y_c - y_{c+}^{new} \tag{12}$$

If this edge is then found to be sufficiently close to the other end of the building, (within $L_e/2$), then it is assumed to be broadened beyond that end of the building also by $L_e/2$. This implies that the cloud's centre moves laterally. In other words if

$$\left(y_{b-} + \frac{L_e}{2} \right) \geq y_{c-}^{new} \geq \left(y_{b-} - \frac{L_e}{2} \right) \tag{13}$$

then we set

$$y_{c-}^{new} = y_{b-} - \frac{L_e}{2} \tag{14}$$

In either event, the new width of the cloud is

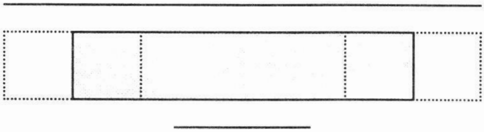
$$W_c^{new} = y_{c+}^{new} - y_{c-}^{new} \tag{15}$$

and the position of cloud centre line becomes

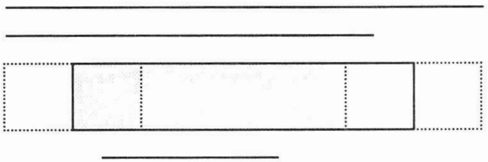
$$y_c^{new} = \frac{(y_{c+}^{new} + y_{c-}^{new})}{2} \tag{16}$$

The following diagrams illustrate the broadening of the cloud implied by this width condition. In the diagrams the cloud is thought of as moving from bottom to top with its width and lateral position before interaction shown below the building, and the configuration after the interaction shown above it. The building is the shaded area with distances of ***L$_e$/2*** from the ends shown as dotted lines. We assume for the moment that the height condition is not achieved for these cases.

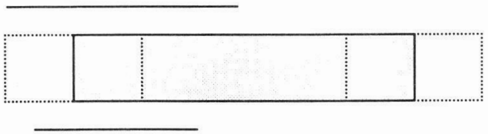
In the case where the cloud approaches the building on it's centre line, it is broadened to ***L$_e$/2*** beyond each end of the building:



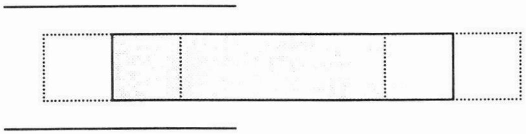
If the cloud is not on the building centre line but still completely overlapped by the building then it will be broadened to $L_e/2$ beyond the end of the building it is closest to. The other end of the cloud is also broadened so as not to alter the position of the cloud's centre in the cross wind direction. This is indicated by the lower of the two lines above the building. In this case the second stage of the algorithm defined above ensures that the right hand side of the cloud also moves outside the building, as the edge is within $L_e/2$ of the end of the building. This increase is indicated by the higher, and longer, of the two lines above the building. This has the effect of moving the cloud's centre.



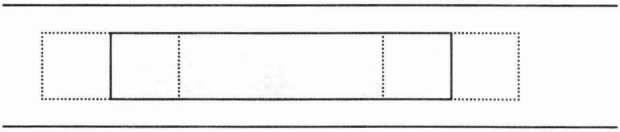
For a cloud with one edge just outside the building the cloud is broadened to $L_e/2$ beyond the end of the building. In this case there is no additional broadening as the other edge of the cloud is not within $L_e/2$ of the end of the building, and the position of the cloud's centre will not be affected.



When one edge of the cloud is well outside the building, ie greater than $L_e/2$, then there is no change in the size of the cloud.



Similarly when both edges of the cloud are well outside the building, ie greater than $L_e/2$, then again there is no change in the size of the cloud. This means that the cloud is not diluted by its interaction with the building.



Again we emphasise that this model is used to compute an effective source in the lee of the building. The results of using that source are not considered to be valid close to the building. In fact in reality the maximum concentration just downstream of the building is likely to be close to the edge of the building, and a cloud which goes around both edges may have a double peak in its lateral concentration profile for some distance downstream.

Whilst the above ideas may be regarded at best as a first attempt at a simple model, (and are not on as firm a footing as the fence model) it is interesting to compare them with data.

3.3 Comparison with Thorney Island Trial 26

The Thorney Island experiments, (McQuaid and Roebuck(1985)) consisted of large scale instantaneous releases of a dense gas. These releases were on to level ground and for some experiments obstacles were positioned in the path of the cloud. One experiment, trial number 26, consisted of a release of dense gas with a cuboid building in its path.

In the DRIFT calculation, when the cloud reached the building its height was much less than the building's height, 1.34 m compared to 9.2 m, but it was very much broader than the building, 75.48 m compared to 9.6 m. According to our model the building will have had a negligible effect on the dilution.

McQuaid and Roebuck (1985) give maximum concentration measurements for the contaminant at various positions and heights within the region of the path of the gas cloud. From these results the centre line maximum concentrations along the wind direction, at a height of 0.4 m were extracted. Figure 9 compares the experimental results with those obtained from DRIFT. The graph gives the concentration in parts per million (ppm) as it varies with distance. The crosses are the results from the Thorney Island measurements. The first two crosses are measurements taken before the building, the rest after the building. The three lines are from the DRIFT calculation. The middle line is the concentration in pm. The two outer lines represent 95% confidence levels based on wind tunnel data. The results show that the Thorney Island experimental data fall within the 95% confidence limits, and that DRIFT's prediction of minimal effect of the building is therefore essentially consistent with the data.

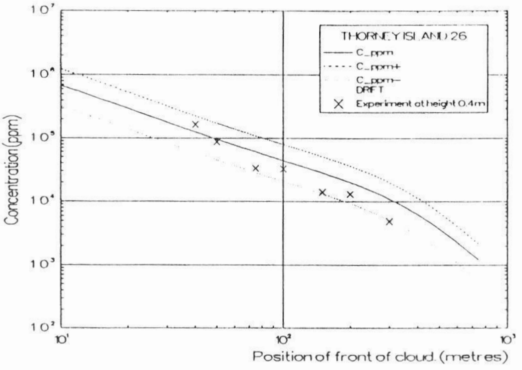


Figure 9. Comparison with Thorney Island Trial 026. The lines C_ppm+ and C_ppm- are the upper and lower expectation values based on evidence from repeat wind tunnel experiments.

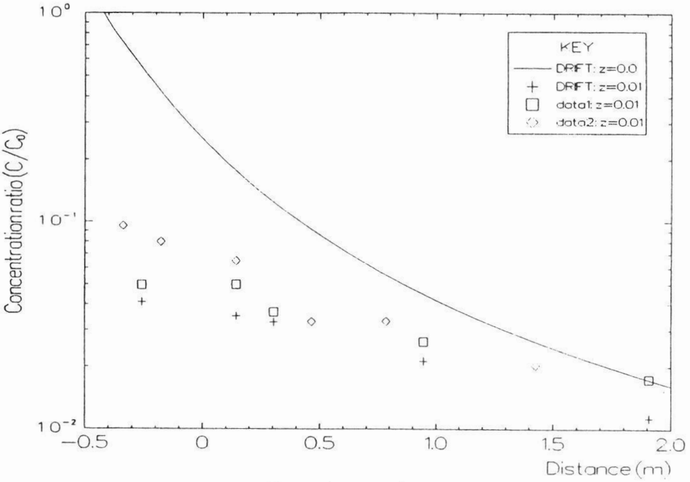
3.4 Comparison with TNO Wind-Tunnel Data

Dispersion experiments with dense gas and building effects were carried out in one of TNO-ME's atmospheric boundary layer wind tunnels. Experiments were performed for flat terrain and three building configurations. The height H_b and depth L_b were always 0.161m. The building widths W_b were H_b, $3H_b$, or $5H_b$. The gas is emitted from a circular source flush with the ground and a diameter of 0.107 m. The centre of the source was located 0.241m upwind of the upwind building face in the experiments which concern us here. (Releases were also done into the wake of the obstacle.) Passive and dense releases were performed. The dense gas was SF_6, with a relative density $(\rho_o - \rho_a)/\rho_a$ of 4.12. The gas flow rates q_o have been 0.000178 m^3/s for all experiments. For more details see Duijm *et al* (1994). The concentration measurements discussed here were done mainly to calibrate more detailed laser sheet measurements which are not yet available at time of writing.

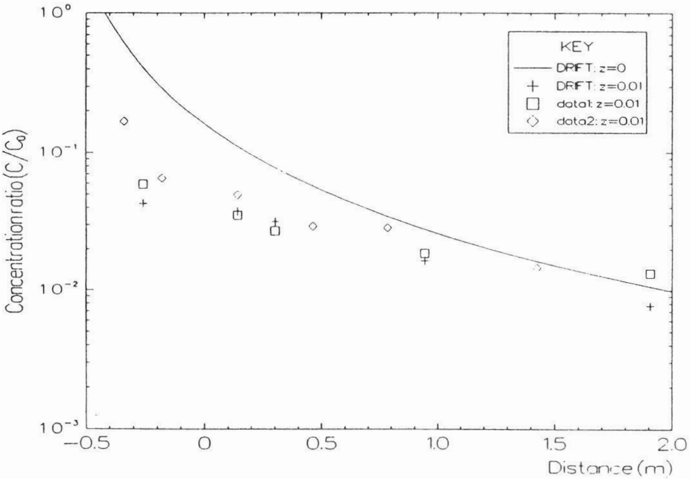
It is important to note that the measurements were taken sufficiently close to the building that we have to throw away all the caveats of our model if we are to perform a comparison. Nevertheless, and particularly as the model is only a fairly rough Ansatz anyway, it is interesting to see the results if we proceed in this cavalier fashion. We shall compare our model maximum (ie centre line concentration) with the maximum measured concentration, despite the facts (a) that the maximum measured concentration is clearly not on the centre line (as discussed above) and (b) there are not enough measurements to be sure that the maximum concentration was in fact measurements. (The laser sheet data should of course rectify this when it becomes available.)

Some of the comparisons we have made are presented in Figures 10 and 11. The flat ground comparisons (Figure 10) are very good and lend further confidence to the basic model in DRIFT. The building effects in Figure 11. Note in the case of the dense releases that the cloud was sufficiently low that DRIFT's predictions at the measurement height of 1cm are significantly closer to the experimental data than the ground level predictions.

Given the multiple uncertainties, we regard the predictions as a satisfactory first attempt, and would welcome the opportunity to test the model against more complete data and possibly refine it if required. A fuller set of comparisons is given by Duijm *et al* (1994) (where space was less of a consideration!).

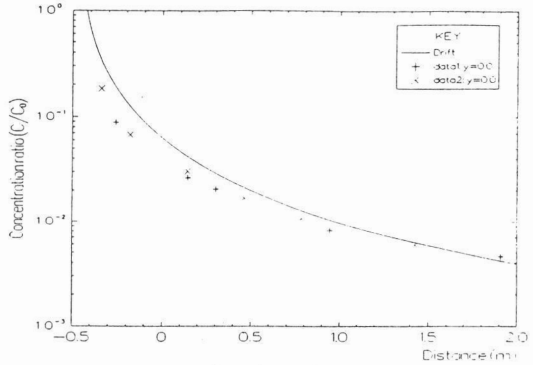


Dispersion over flat ground
SF_6 source in 0.7m/s wind at 0.160m

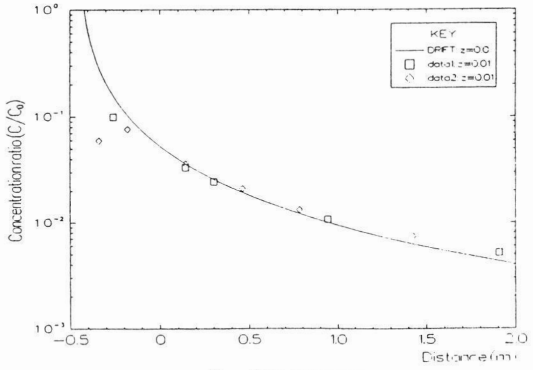


Dispersion over flat ground
SF_6 source in 1.1m/s wind at 0.160m

Figures 10. See caption below

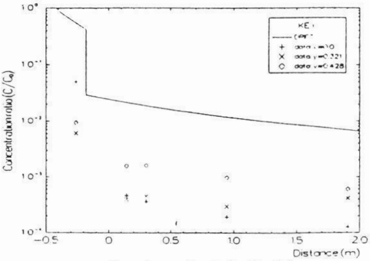


Dispersion over flat ground
SF_6 source in 2.2m/s wind at 0.160m

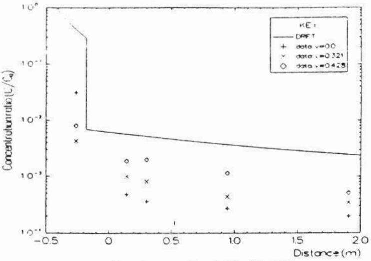


Dispersion over flat ground
Passive source in 2.2m/s wind at 0.160m

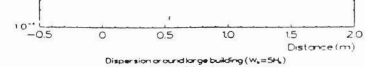
Figures 10. A comparison with the flat ground data from the TNO wind tunnel. DRIFT's predictions at the sensor height are in remarkable agreement with observations.



Dispersion around large building ($W_b = 5H_b$)
SF_6 source in 0.7m/s wind at 0.160m



Dispersion around large building ($W_b = 5H_b$)
SF_6 source in 1.1m/s wind at 0.160m



Dispersion around large building ($W_b = 5H_b$)
Passive source in 2.2m/s wind at 0.160m

Figures 11. A comparison with the TNO obstacle data for all Richardson numbers and the largest obstacle. (A comparison with the full data set may be found in Webber *et al* (1994)).

4. CONCLUSIONS

We have developed a simple approach to modelling the effects of an infinite transverse fence on a passing heavy gas cloud and generalised it to the case of a single isolated obstacle. The result is a model algorithm which can be incorporated into almost any model of gas dispersion.

We have incorporated the algorithm into the computer code **DRIFT** (**D**ense **R**eleases **I**nvolving **F**lammables and **T**oxics) which has already been well validated against data on unobstructed dispersion (see Jones *et al* 1993) and compared it with a range of data with different obstacles.

The comparisons with field trial data (Heinrich and Scherwinski 1991) for a steady, heavy plume encountering a transverse fence show an excellent fit. Given the simplicity of the approach, and the ease with which it may be implemented in any dispersion model, the accuracy attained is remarkable. There are no free parameters which need be "tuned" to experimental data.

The model for instantaneous releases also compares well with the wind tunnel data of Hall *et al* (1992).

Let us note that the greatest scope for error in the model appears to be the situation where it predicts a cloud just higher than the fence at the fence location, when the data indicate that it should be just lower (and possibly *vice versa*). A heavy cloud can require significant dilution to overcome the fence in this case, whereas the model predicts that it requires none. This is in effect a strong sensitivity in the model to the height of the cloud when it encounters the fence, which in turn means sensitivity to the source term and to the accuracy of the dispersion model in the upwind region. This is not a strong drawback if the model is used for risk analysis, as long as the analyst is careful to include possible sources which cover both cases: cloud higher than the fence and cloud lower. It is recommended, in any event, that any application of the model to a problem involving a fence warrants a careful check on the relative height of cloud and fence, and that a sensitivity study is performed if these are near equal.

The model also tends to over-estimate the time taken for clouds to surmount the obstacle, and hence the arrival time at downwind locations. This is purely an artefact of the assumptions made about the behaviour of the cloud centre as the obstacle is overcome, and the relative effect will decrease the further one goes down stream.

The generalisation of the model, on fairly intuitive grounds, to estimate the effects of buildings in the flow is more speculative but, we believe, is a valuable first step. Given the uncertainties in the comparison, DRIFT's agreement with the highest measured concentrations at different points is remarkably good.

We therefore believe that this approach involving simple models backed up by thorough comparison with experimental data can lead to valid and useful estimates of concentration in obstructed flows.

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