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THE CALIBRATION OF A SIMPLE MODEL FOR DENSE GAS DISPERSION USING THE THORNEY ISLAND PHASE I TRIALS DATA

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Summary

Data from the Phase I Thorney Island trials are compared with observations of other effectively instantaneous releases of denser-than-air clouds. They are then used to calibrate a simple mathematical model to predict the dispersion of this type of release. The model was developed jointly by British Gas and Cremer and Warner and it incorporates a momentum relationship to detemine the cloud advection speed. It is found that the edge mixing and momentum parameters take well-defined values but that the model is relatively insensitive to the values of the top surface parameters for the Thorney Island Phase I trials. However, a comparison with additional data, previously calculated from records of the trials, shows that this model produces reasonable results. The inclusion of a momentum relationship produces a significant improvement to an earlier British Gas/Cremer and Warner model. It is concluded that other sources of data should be examined to see if the model parameter values deduced here may be used for other release configurations.

1. Introduction

In order to assess the hazards associated with the storage and transmission of flammable gases, it is necessary to consider the consequences of an accidental release of such substances. It is known that in certain circumstances a release of a liquefied fuel, such as liquefied natural gas (LNG) or liquefied petroleum gas (LPG), produces a vapour cloud with a density greater than the surrounding air. Hence it is important to be able to predict the dispersion of such clouds. The Thorney Island Phase I trials [1] simulated effectively instantaneous releases of ambient temperature denser–than–air clouds over flat terrain in a range of atmospheric conditions. They provide information to improve our knowledge of the behaviour of such releases. This paper describes work comparing the results of these trials with previous field and wind and water tunnel

data and also describes how the data have been used to calibrate a simple mathematical model of the dispersion of denser-than-air gases.

Firstly, the maximum downwind distance travelled by the cloud whilst still above a given concentration is examined. It is compared with observations from other experiments involving the dispersion of effectively instantaneously formed denser-than-air clouds. The remainder of the paper then shows how it is possible to use the concentration data collected during all the Phase I trials in the calibration of a simple mathematical model to predict the dispersion of this type of release. The particular model used here was developed jointly by British Gas (BG) and Cremer and Warner (C&W) and is an example of the class of model referred to by McQuaid [2] as 'box-type'. A comparison of the calibrated code with other data from the Phase I trials is then given. The predictions of a previous BG/C&W model [3] are also compared with some of these data. The significance of these results and their relevance to other release configurations are then discussed.

2. The downwind dispersion observed in the trials

The downwind dispersion travel distance to a safe concentration level of a given release is a quantity of great importance to the hazard analyst. In this section, the dispersion distances that resulted from the various Thorney Island Phase I trials are compared, both with each other and with other sources of data for effectively instantaneous releases of denser-than-air clouds. For a cloud of LNG vapour, predictions of the dispersion to the lower flammable limit (LFL) are required – that is, to 5% by volume. Since the cold LNG vapour expands relative to the ambient air as the cloud is diluted, this is approximately equivalent to dilution to 2% by volume of a cloud initially composed of an ambient temperature vapour. Therefore, as ambient temperature Freon–nitrogen mixtures were released at Thorney Island, the downwind dispersion travel distances to the 2% concentration level were estimated for the Phase I trials.

To obtain these estimates a contour that enclosed all sensors detecting concentrations of at least 2% gas was drawn by eye on a plan of the site for each trial. Estimates of the 2% downwind and crosswind dispersion distances were then made from these figures. A partial check on the downwind value was obtained from a plot of the peak concentation detected at a sensor against its distance from the centre of the release. (The peak concentrations were taken from the HSE handbooks [4] and are 0.6 s time-averaged values.) It should be noted that these estimates are subject not only to errors arising from the spatial resolution of the sensor array but also the methods of analysis. This is discussed further by Brighton [5]. The uncertainty in the quoted values of the downwind dispersion distances is of the order of ± 20 m. The dispersion dis-

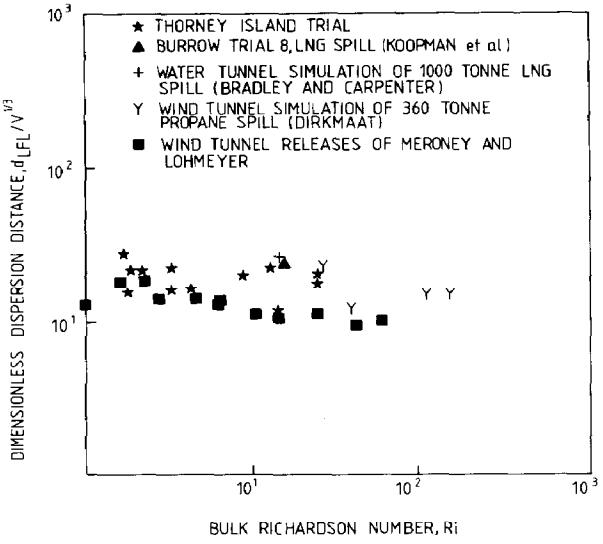


Fig. 1. A plot of the dimensionless downwind dispersion distance to a concentration equivalent to the LFL of LNG vapour against the bulk Richardson number of the release. The Thorney Island Phase I trials are compared with other effectively instantaneous releases.

tances obtained are presented in Fig. 1, where they are shown as a function of the bulk Richardson number Ri of the release. This is defined by:

$$Ri = \frac{g_0' V_0^{1/3}}{u_{10}^2}$$

The dispersion distance has been made dimensionless by choosing a length scale dependent on the volume released in each trial. For a release of a passive contaminant, the dimensionless distance formed in this way should be, to a first approximation, only a function of environmental factors, such as atmospheric stability category and roughness of the underlying surface. As the ratio of the buoyancy forces on the cloud to the inertia of the windfield is increased i.e. the bulk Richardson number is increased, it is possible that some systematic change in the dimensionless dispersion distance might be detected. However, Fig. 1 suggests that the dispersion distances are essentially independent of the Richardson number and are primarily determined by the volume of gaseous material released. The Thorney Island trials give some idea of variability found under similar release conditions.

Puttock, Blackmore and Colenbrander [6] have given a criterion to determine whether the vapour cloud evolving from a liquefied fuel spillage may be regarded as forming instantaneously. In order to compare the Thorney Island trial results with other data we have applied this criterion to the field trial series carried out at China Lake [7]. In these trials, vapour evolved from a

pool of LNG on the surface of an artificially created water pond and dispersed over somewhat uneven terrain. Trial 8, which was carried out in low wind speed conditions, was found to meet the criterion. Sufficient gas sensors were in position to allow an estimate of the downwind travel distance to the LFL to be made and the corresponding data from this trial are shown in Fig. 1. Despite the different mode of release from the Thorney trials, the dimensionless dispersion distance is similar to those found at Thorney Island. The data from the Shell Maplin Sands field trial series [8] were also studied. Unfortunately, the only trials in this series to meet the criterion suffered either from instrumentation problems or significant variability in atmospheric conditions and so no meaningful downwind dispersion travel distances could be obtained.

Turning to reduced-scale physical modelling, Bradley and Carpenter [9] reported a simulation of a 1000 tonne LNG release onto the sea. This was carried out on a scale of 1:500 in a water flume. Again, according to the criterion of Puttock et al [6], the simulated vapour cloud produced in the water flume to model this situation was released effectively instantaneously and we have included these data in Fig. 1. The closeness of the data point representing it to the point for Trial 8 of the Burro series gives us some confidence in the validity of this particular simulation. Four further data points are shown in Fig. 1 that were derived from a paper by Dirkmaat [10] of TNO. He simulated the dispersion of a propane cloud produced following a double-ended guillotine break in a pipeline carrying liquid propane under pressure. The combination of low wind speeds ($2–4\ m\ s^{-1}$) and rapid release rates makes these effectively instaneous releases. The results overlap and extend the previous trend.

We also show data points in Fig. 1 representing the results reported by Meroney and Lohmeyer [11] in 1981 for idealised instantaneous releases. In their experiments a known volume of denser-than-air gas was suddenly released into a turbulent boundary layer in a wind tunnel. The method of release involved a rotating gas-filled cup mounted flush with the tunnel floor. All of the above sources of data suggest a common trend for downwind dispersion distances that is independent of the details of the mode of release.

We conclude that the data from the Thorney Island trials may be used to help develop or validate mathematical models for dispersion of instantaneous releases of denser-than-air vapour clouds. In particular, it may be used to help specify the values of the coefficients in a simple box-type model. The remainder of this paper addresses this topic.

3. Brief description of a simple mathematical model

The model described in this paper was developed for effectively instantaneous releases and is based on the work of Bradley et al. [12]. It assumes an idealised geometry for the dispersing cloud, as illustrated in Fig. 2. It attempts to follow the bulk cloud advection and dilution in the given atmospheric con-

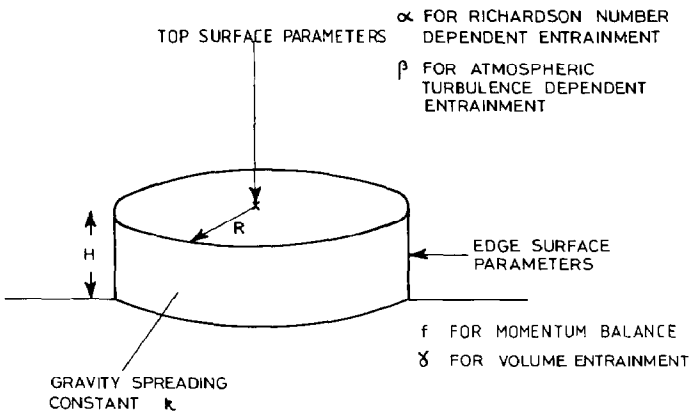


Fig. 2. Idealised shape of dispersing cloud assumed by the simple model. The parameters to be determined in the calibration procedure are indicated.

ditions. The equations that are used to model this process are outlined below. This also introduces the various parameters of the model whose values are to be assigned in the calibration procedure.

The gravity spreading of the cloud is expressed by:

$$\frac{dR}{dt} = k(g'H)^{\frac{1}{2}} \tag{1}$$

Entrainment into the cloud is considered to be made up of two terms:

$$\frac{dM}{dt} = \frac{dM_E}{dt} + \frac{dM_T}{dt} \tag{2}$$

where the entrainment due to the gravity spreading is given by:

$$\frac{dM_E}{dt} = \gamma \frac{dR}{dt} 2\pi RH\rho_a \tag{3}$$

and the entrainment due to atmospheric turbulence is given by:

$$\frac{dM_T}{dt} = \text{Min}\left(\alpha \frac{u_1^2}{g'l}, \beta\right) u_1 \pi R^2 \rho_a \tag{4}$$

The volume of the cloud is given simply by:

$$V = \pi R^2 H \tag{5}$$

and its advection is determined from a simplified horizontal momentum balance:

$$M\frac{dU}{dt} = \frac{dM_E}{dt}(f\bar{u}_H - U) + \frac{dM_T}{dt}(u(H) - U) + D - F \tag{6}$$

where the drag D, due to the relative motion of the atmosphere and the cloud is given by:

$$D = C_D \rho_a R \int_0^H |u(z) - U| \ (u(z) - U) \ dz \tag{7}$$

and the friction F experienced by the cloud as it passes over the ground is given by:

$$F = \rho_c \pi R^2 u_{*c}^2 \tag{8}$$

where u_{*c} is the friction velocity appropriate to cloud motion over the ground. It is approximated by:

$$u_{*c} = u_* \ (U/u_{10})$$

This is only a valid approximation provided the cloud height is not substantially different from 10 m.

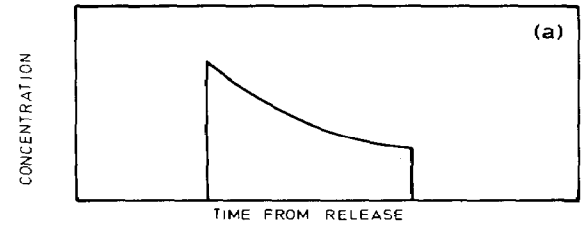
Of interest here are the edge mixing parameters γ and f, the top surface mixing parameters α and β, the gravity slumping constant k and the drag coefficient C_D. The edge momentum factor f was not present in the equations of Bradley et al. [12]. It can be viewed as a term to account for the tendency for preferential entrainment into the cloud of low velocity air from close to the ground. It should be noted that this model differs from several earlier box models in that a momentum equation (eqn. 6) is included to determine the mean translational speed of the cloud. In the next section, a method of calibrating this model with data collected during the Thorney Island trials is proposed.

4. Method of calibration

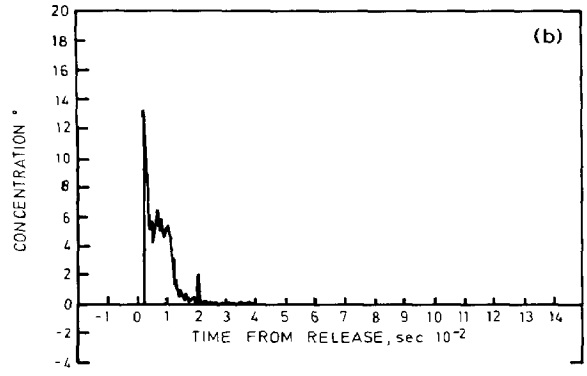
The shape of a typical concentration–time record predicted by the simple 'box model' described in Section 3 is illustrated in Fig. 3(a) for a fixed position downwind of an instantaneous denser-than-air gas release. As the model does not consider variation of concentration within the cloud, it predicts discontinuous changes on arrival and departure of the cloud. This may be compared with two typical traces obtained from the gas sensors at Thorney Island [4] in Fig. 3(b) for a 'near-field' point (about 70 m from the centre of the release) and Fig. 3(c) for a 'far-field' point (about 430 m from the release point). This illustrates a problem to be confronted when an attempt is made to fit a simple model to field data. Namely, precisely what measures should one us to define the goodness of fit of the model?

One approach is to make direct use of the individual sensor records, such as those shown in Figs. 3(b) and (c). The minimum information that adequately characterises such a trace is considered to be:

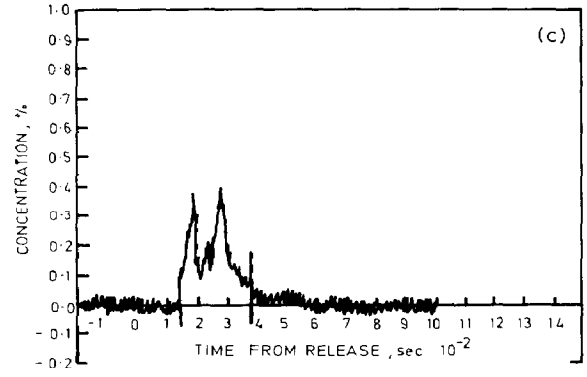
- the time of arrival of the gas t_a,



TYPICAL RECORD PREDICTED BY SIMPLE BOX-MODEL PROPOSED IN SECTION 3



RECORD FROM SENSOR AT (450., 250., 0·4) IN TRIAL 07



RECORD FROM SENSOR AT (700., 500., 0·4) IN TRIAL 07

Fig. 3. A comparison of the shape of a typical concentration–time record predicted by the model (a) with two records observed in the Thorney Island Phase I trials; (b) is a near-field point whilst (c) is for a far-field point.

- the maximum gas volume concentration detected C_p (0.6-s time average is plotted in the hard copy data books),
- and the time of departure of the gas t_d.

Depending on the predicted values for these quantities, a numerical 'measure of error' can then be assigned to the model for each sensor record. The aim of

the calibration procedure is to find that set of model parameter values that produces the least overall error.

In practice, there were large uncertainties in estimating t_d from the experimental data, reflecting the fluctuating tails of some of the traces. Hence, these values were not used in the subsequent analysis, although a comparison of them with the predictions of the model is included in Section 6. Also it proved difficult to estimate t_a from the hardcopy plots for traces with peak concentrations below about 0.5%. Consequently, only those sensors at the 0.4 m elevation for which reliable estimates of both t_a and C_p could be made were included. This gave a total of 146 admissible traces for Trials 7–19 inclusive with which the predictions of the model could be compared. The following measures of error were then defined for each sensor trace:

$$E_a = \frac{|t_{ae} - t_{am}|}{t_{ae}} \qquad S_a = \frac{t_{ae} - t_{am}}{t_{ae}}$$

and (9)

$$E_p = \frac{|C_{pe} - C_{pm}|}{\text{Max } (C_{pe}, C_{pm})} \qquad S_p = \frac{C_{pe} - C_{pe}}{\text{Max } (C_{pe}, C_{pm})}$$

where the subscripts e and m denote an experimental observation and model prediction, respectively. An overall error estimate for Trials 7–19 was then defined for a particular set of values of the parameters of the model by:

$$G = \sum_s (E_a + E_p) \tag{10}$$

where the summation s is over those sensors at 0.4 m elevation which both during the experiment and according to the prediction of the model saw gas. Equal weighting was selected for the error estimators E_a and E_p to reflect our aim of producing a simple box-model capable of predicting the bulk advection and dilution of the cloud to the same level of accuracy. We examined the effects of giving greater weighting to those sensors with peak detected concentrations in the range of 1% to 10%, but this modification did not make a significant difference.

For the calibration, use was made of the analysis of Brighton et al. (see Ref. [1]) of the photographic records taken during the trials. In accordance with their eqn. (5), the gravity slumping constant was given the value:

$$k = 1.05 \tag{11}$$

For an ambient temperature release, according to the equations of the model, the spreading with time is independent of the amount of entrainment and so the spreading constant may be specified at this stage independently of the other parameter values. Further, a constant value was taken for the drag coefficient. For all the calculations reported here

$$C_D = 0.3 \tag{12}$$

was used. A limited sensitivity study showed the results were relatively insensitive to realistic variations in its value.

Thus in the subsequent analysis, G may be regarded as a function of the four remaining model parametes. That is:

$$G = G(\alpha, \beta; \gamma, f).$$

5. Results of the calibration exercise

The value of G was found to be more sensitive to changes in the edge mixing and momentum parameters γ and f than the top surface parameters α and β. A narrow region centred on

$$\gamma = 0.65 \pm 0.05 \qquad f = 0.55 \pm 0.05 \tag{13}$$

defined the approximate location of the minimum. Considering a total of 52 different sets of parameter values it was found that, for these values of γ and f, there is a range of values of α and β which give similar values of G. Namely, appropriate combinations of α and β from within the ranges of:

α from 0.06 to 0.25

and β from 0.10 to 0.50.

To consider why this should be the case, it is necessary to consider firstly the definition of G itself. It is expressed as the sum of two separate terms, which are affected differently by variations in α and β. Larger values of these entrainment parameters increase the cloud speed predicted by the model and so decrease the predicted time of arrival. Also they cause the cloud to be diluted more quickly and so decrease the predicted peak concentration. It so happens that these effects reduce E_p and increase E_a by virtually identical amounts when γ and f take values in the range specified in eqn. (13). Secondly, and more importantly, however,the nature of the trials themselves should be considered. The clouds were released with height to width ratios of approximately one, giving what Fay and Zemba [13] have referred to as 'compact' source conditions. They have argued that such releases are characterised by rapid initial mixing, dominant in the near-field. As formulated, the model attributes this mixing to the spreading front edge of the cloud (as in eqn. (3)). This explains why such a narrow range of edge coefficients are found. It is only after sufficient dilution has occurred to produce a 'non-compact' cloud that the top surface mixing, specified in eqn. (4), becomes important. According to our model formulation, this appears to occur in the Thorney Island trials for concentrations of the order 1% (varying according to the initial bulk Richardson number). Consequently it is not too surprising that the values of α and β are

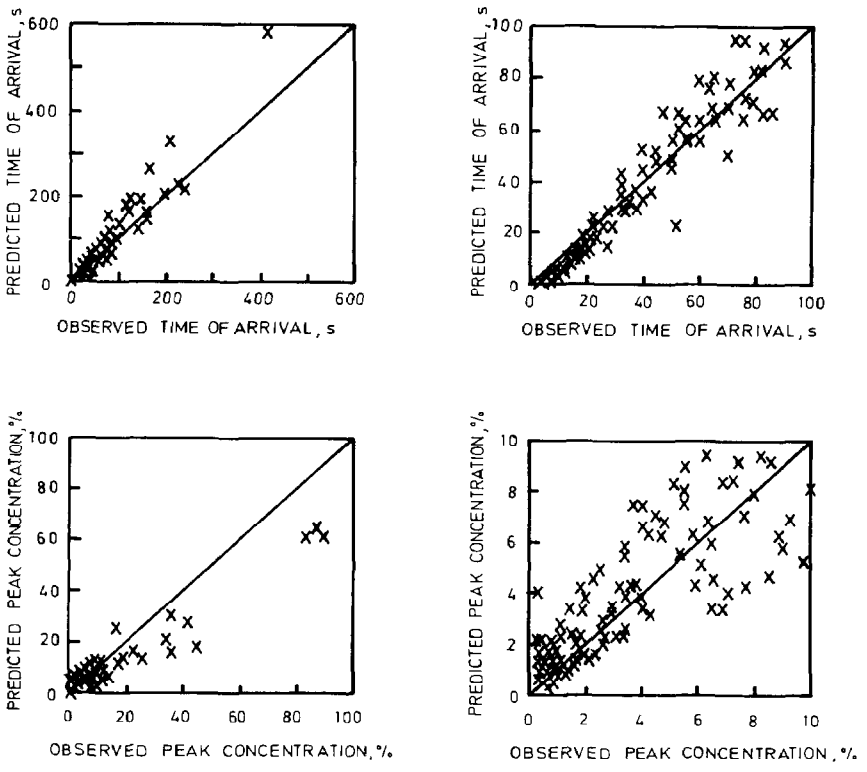


Fig. 4. A comparison of the predictions of the model using the optimum values for its parameters with the observations at selected gas sensors (at the 0.4 m elevation) in Trials 7–19. The left hand graphs show the full data set, whilst the right hand ones show the region near the origin in more detail.

not particularly well-defined. This supports the conclusions of Wheatley et al. [14], who found a similar indeterminancy in the value of the parameters controlling top entrainment despite investigating several alternative formulations for it.

In order to select a final set of parameter values, the signed errors S_a and S_p defined in eqn. (9) were examined. The following parameter values were found to produce the smallest numerical values of S_a and S_p:

$$\alpha = 0.08 \qquad \beta = 0.30 \qquad f = 0.55 \qquad \gamma = 0.65 \tag{14}$$

With this choice the average value of each error estimate was as follows:

$$E_a = 0.24 \qquad E_p = 0.31 \qquad S_a = -0.06 \qquad S_p = 0.05$$

Figure 4 compares the predicted values of the time of arrival and peak concentration with the experimental observations for the choice of parameters given

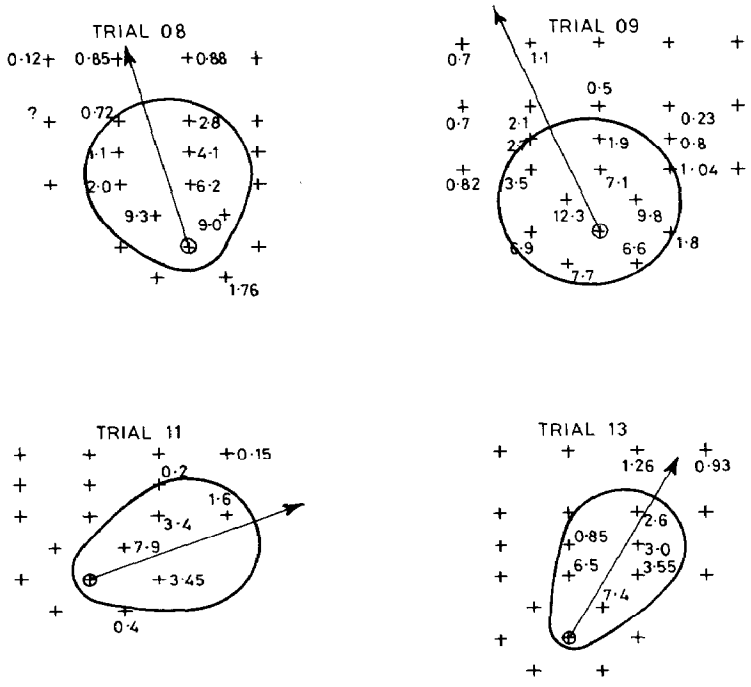


Fig. 5. A comparison of the predicted 2% cloud envelopes with the peak concentrations detected at the sensors at 0.4 m elevation for four selected Phase I trials. The mean wind direction for each trial is indicated by an arrow.

by eqn. (14). In all of the remaining calculations reported in this paper, the model is used with this choice of parameter values.

6. Further comparisons with data from the trials

Although the above calibration exercise has produced a set of values for the parameters of the model that minimise the stated 'measure of error', there remains the possibility that some important aspect of the behaviour of the cloud may have been overlooked in this process. For example, the actual hazardous area covered by the cloud (its 'flammable footprint') has not been compared with the predictions of the model. Also the experimental data used in the above analysis were recorded at an elevation of 0.4 m. The actual height of the cloud has not been considered. For this reason, a comparison with other data obtained from the Phase I trials is given in this section. Results are presented here for four trials that are representative of the range of initial bulk Richardson numbers.

In Fig. 5, the envelopes of all ground level points that are predicted to have seen gas concentrations in excess of 2% are superposed on a plan of the site for

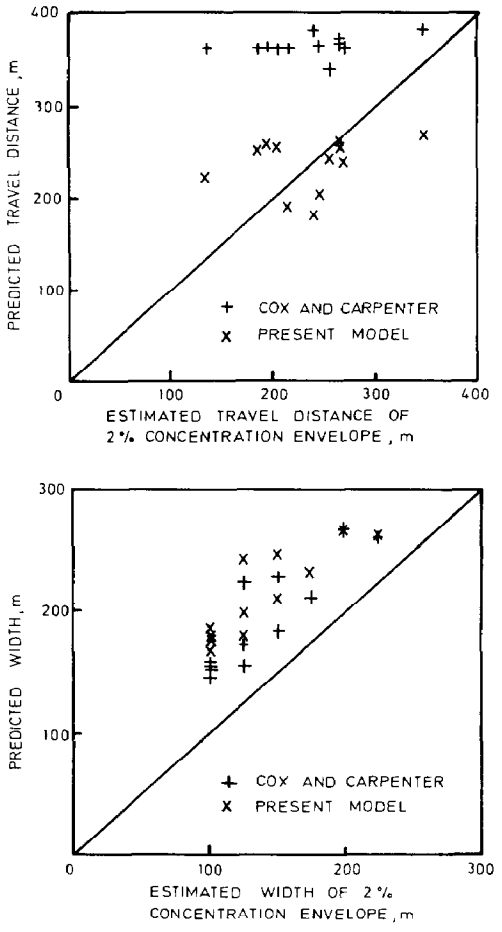


Fig. 6. A comparison of data from the Thorney Island Phase I trials with the predictions of the calibrated model described in section 3 and a previous BG/C&W model for the dispersion of a denser than air vapour cloud.

these trials. The fixed mast sensor locations are marked by a cross in these figures and written alongside each point that detected gas are the maximum (0.6-s time-averaged) observed concentration. These plots suggest that, on average, the downwind dispersion distance to 2% is correctly predicted but that the width of the cloud is perhaps overestimated.

Confirmation of this is given in Fig. 6, where the predicted dispersion distances and widths are compared with our estimates of the maximum observed values for all Trials 7–19. As noted in Section 1, our estimated values for the trials are subject to some uncertainty. This may amount to ± 50 m in trials where the mean wind direction was significantly different from the axis of the sensor array. The predictions of the earlier BG/C&W model [3] are also shown

in this figure. This model uses a constant advection speed, set to be the mean-wind speed at 10 m. Although this model gives similar agreement with the observed cloud widths, it overestimates the cloud advection speed and the downwind dispersion distance for this size of release.

Figures 7–10 show a comparison of the predictions of the model with direct visual observations of the cloud in its early stages of motion. The observations are reproduced from the reports by the UKAEA Safety and Reliability Directorate [15–17] analysing the photographic records obtained during the trials. They generally cover the period before the cloud drifted through the array of fixed sensors. The agreement between the predicted and observed cloud areas is a reflection on the value recommended for the gravity spreading constant k in eqn. (1) by Brighton et al. [1] in the light of their analysis of the same visual records. The comparisons with the observed cloud centroid and height, however, do provide a check on our calibration exercise. In particular, the agreement with the cloud height is satisfactory and gives added confidence in the ability of the model to predict the behaviour of this type of release.

Figure 11 compares observed and predicted values of the time of departure of the cloud from the fixed mast sensors. As mentioned earlier there is considerable uncertainty in defining the value observed in the experiments. Nevertheless, there appears to be, on average, a tendency for the model to underpredict the actual time of departure slightly at the earlier times.

The chosen method of calibration used the time of arrival of gas and the peak observed concentration at the fixed sensor locations. Brighton (see Ref. [1]) has processed the original data recorded on magnetic tape to obtain a spatial average of the (time-averaged) concentrations detected by those sensors at an elevation of 0.4 m that were within the cloud at any given time after the release. This gives a record of the mean concentration within the cloud at the given horizontal level, subject to limitations imposed by the spatial resolution of the sensor array. These data are reproduced in Figs. 1–13 of Wheatley et al. [14], where they present plots of all the concentration data from mast points at an elevation of 0.4 m inside the cloud at discrete intervals of time. The area-averaged concentration was specified by them simply as the average of all these values. In Figs. 12–15,we reproduce the original data for the four chosen trials and compare it with the predictions of the calibrated model. The level of agreement between the predictions of the calibrated model and the data is of the same order as that shown by Wheatley et al. [14] as a result of their calibration procedure using the area-averaged data.

7. Discussion

The calibration procedure defined in Section 4 has produced an edge mixing parameter γ of 0.65. This is higher than values that have been deduced from the laboratory density driven flows of Simpson and Britter [18]. However, it

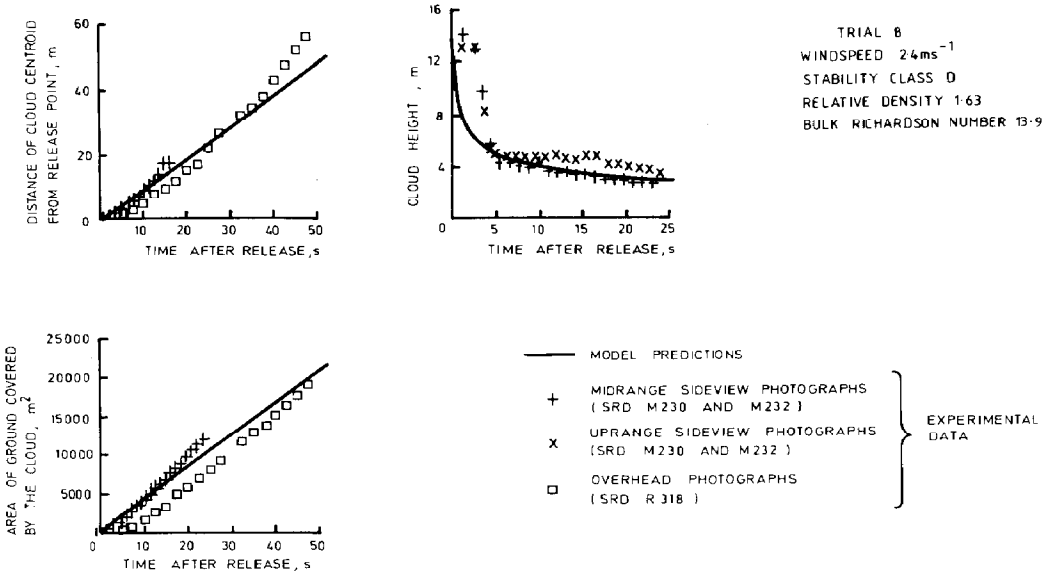


Fig. 7. A comparison of the calibrated model with data derived from the photographic records of Trial 8 by the UKAEA SRD.

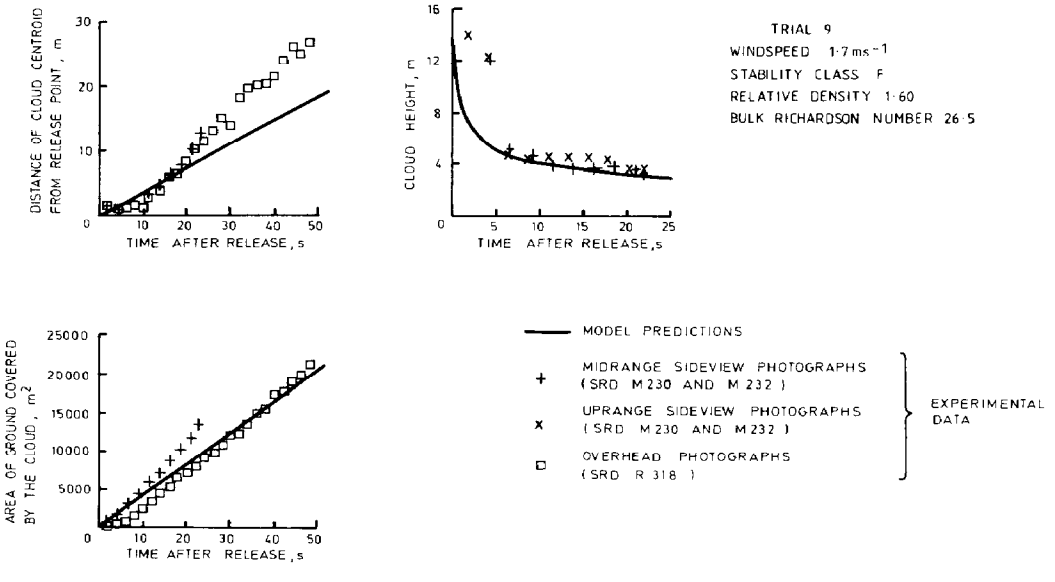


Fig. 8. A comparison of the calibrated model with data derived from the photographic records of Trial 9 by the UKAEA SRD.

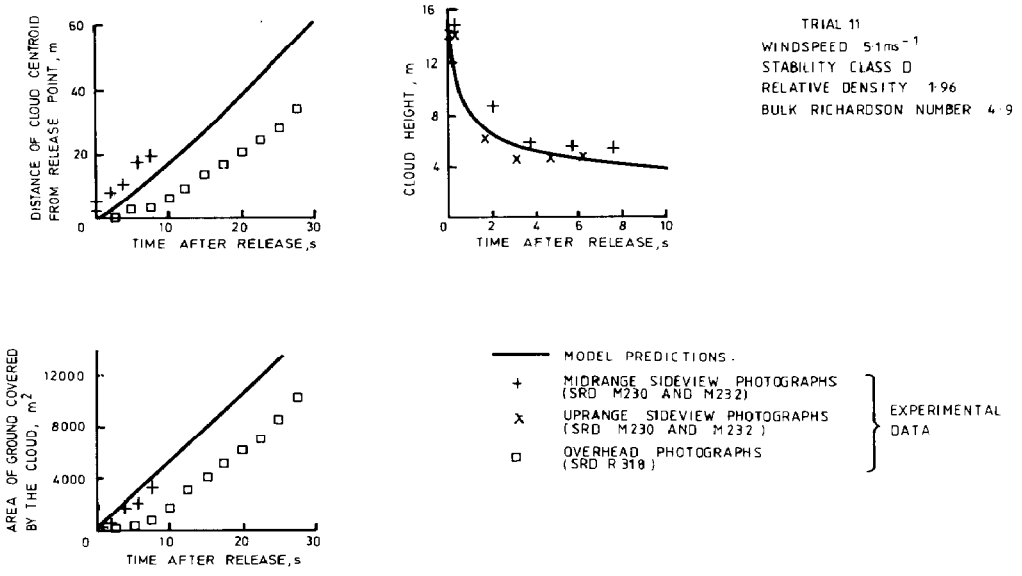


Fig. 9. A comparison of the calibrated model with data derived from the photographic records of Trial 11 by the UKAEA SRD.

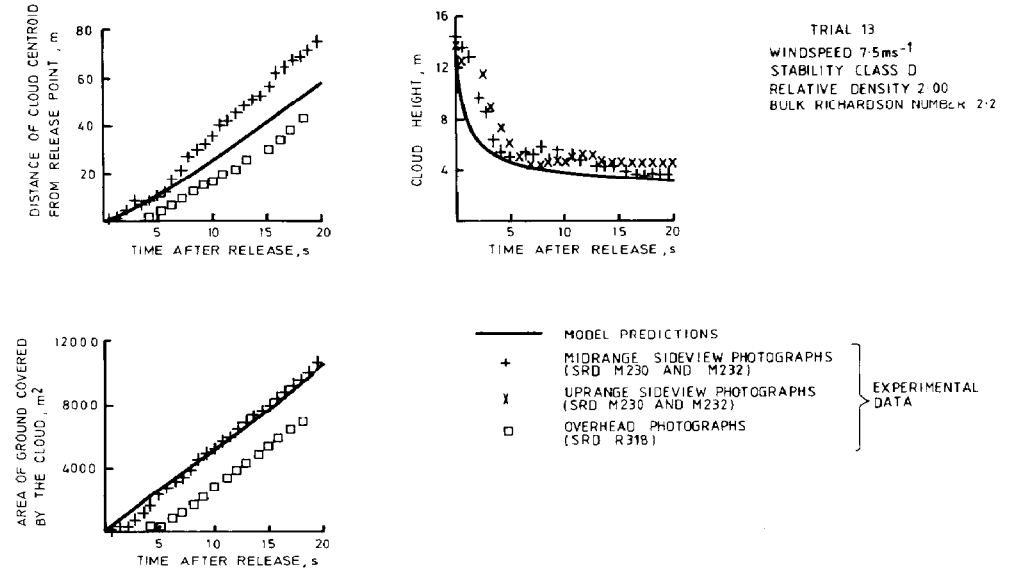


Fig. 10. A comparison of the calibrated model with data derived from the photographic records of Trial 13 by the UKAEA SRD.

is of the same order as values deduced by other authors from the Thorney trials data (see e.g. Crabol, Roux and Lhomme [19]). It is possible that the magnitude of this value may be linked to a physical process that is dependent on

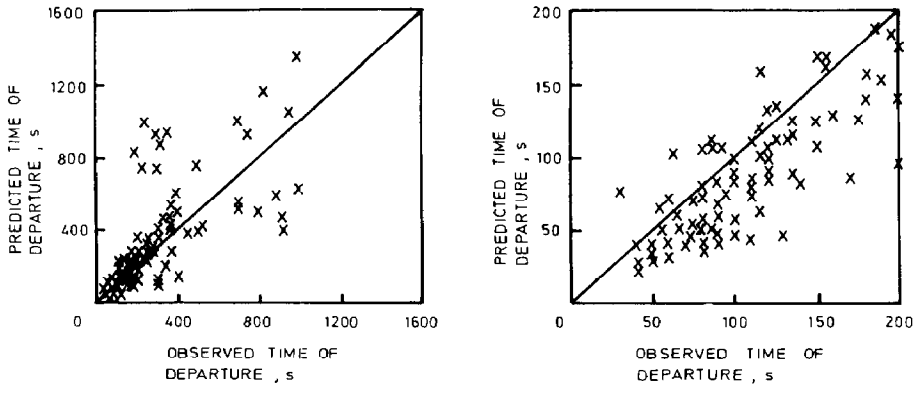


Fig. 11. A comparison of the predictions of the calibrated model with the estimated time of departure of the cloud from selected sensors at 0.4 m elevation in Trials 7–19. The left hand side graph shows the full dataset, whilst the right hand one shows the region near the origin in more detail.

the initial aspect ratio or density of the release. Thus the model needs to be compared with data obtained from instantaneous releases with smaller initial aspect ratios. Spillages of liquefied fuels may produce such clouds, especially if the release is unconfined. The evidence shown in Fig. 1 tentatively suggests that, as far as the downwind dispersion distance to the LFL of LNG vapour is concerned, such releases behave similarly. Further Webber and Wheatley [20] and Van Ulden [21] argue that the density driven entrainment we defined in eqn. (3) is best regarded as edge-induced top entrainment. Webber and Wheatley conclude that from a practical viewpoint, the parameterization in eqn. (2) is adequate, being independent of the aspect ratio and density of the material released. However, Van Ulden argues that using concentration data from the 0.4 m elevation sensors may lead to too large a value of γ being deduced, owing to a non-uniform vertical concentration gradient. This requires further examination.

It is anticipated that for releases that are not effectively instantaneous, the top surface mixing contributes a higher proportion towards the cloud dilution than for instantaneous releases. Indeed it is likely to be the dominant mechanism for cloud dilution. This is discussed further by Brighton [5]. As noted in Section 5, our calibration procedure did not produce a precise determination of the top surface mixing parameters α and β. The three continuous release trials at Thorney Island, as well as the Maplin Sands and China Lake field trial series, may provide data to check or improve upon the values deduced here.

The model was calibrated with data on the time of arrival of gas and the peak observed concentration (albeit 0.6-s time-averaged values) observed at a series of isolated points. The comparison throughout the duration of the release with the 'whole cloud' concentration data of Brighton [1], shown in Figs. 12–15,

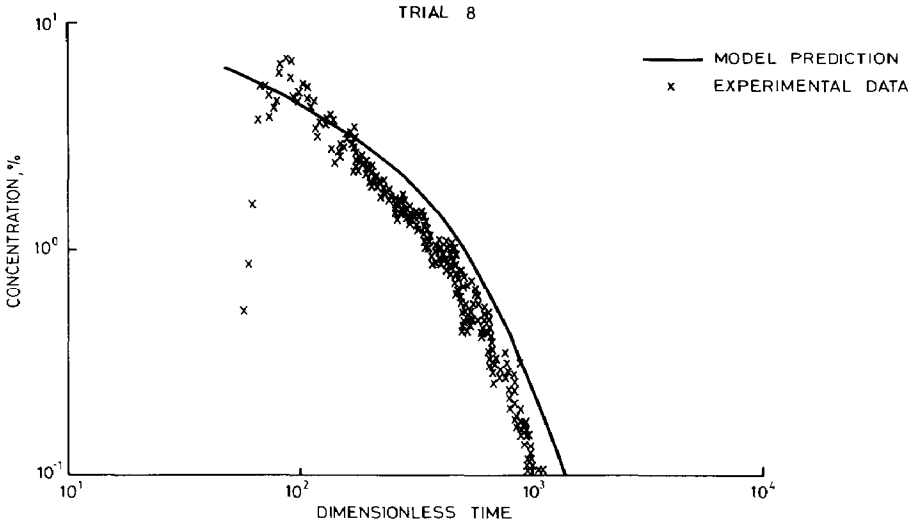


Fig. 12. A comparison of the predictions of the calibrated model with the experimental data given by Wheatley et al. [14] for Trial 8 (the concentration values are 1-s time averages).

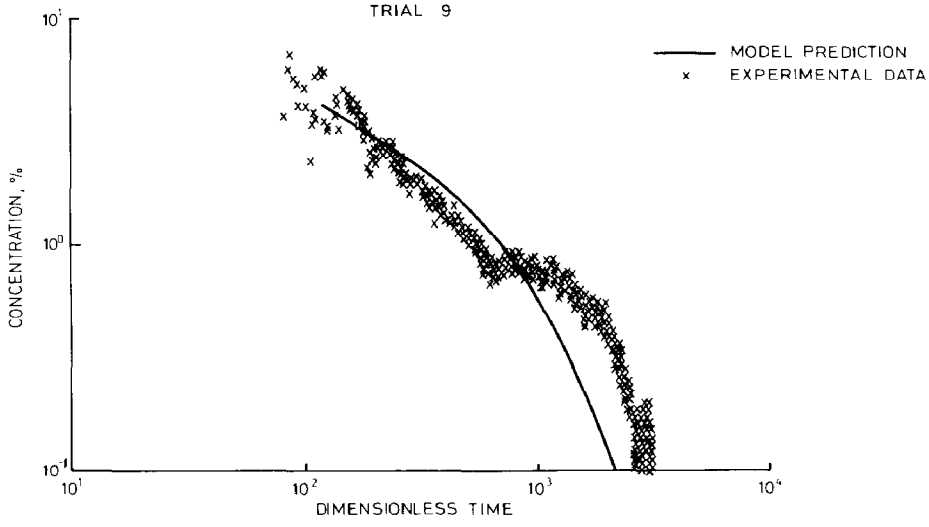


Fig. 13. A comparison of the predictions of the calibrated model with the experimentaldata given by Wheatley et al. [14] for Trial 9 (the concentration values are 1-s time averages at early times and 3-s time averages at later times).

suggests that our use of a limited amount of data to characterise the cloud behaviour produces acceptable results.

Finally, it is noted that the incorporation of a momentum equation to determine the speed of travel of the cloud has resulted in a significant improvement in modelling this type of release. The resulting calibrated model does appear

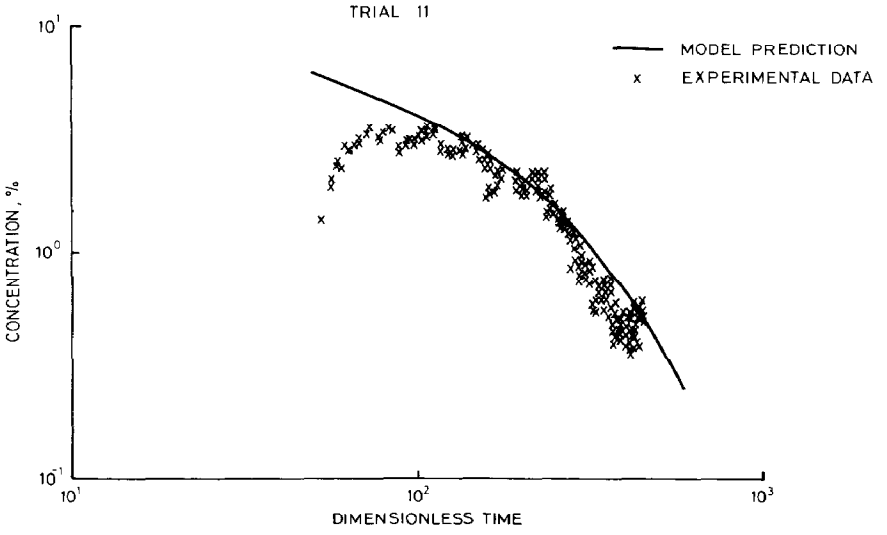


Fig. 14. A comparison of the predictions of the calibrated model with the experimental data given by Wheatley et al. [14] for Trial 11 (the concentration values are 1-s time averages).

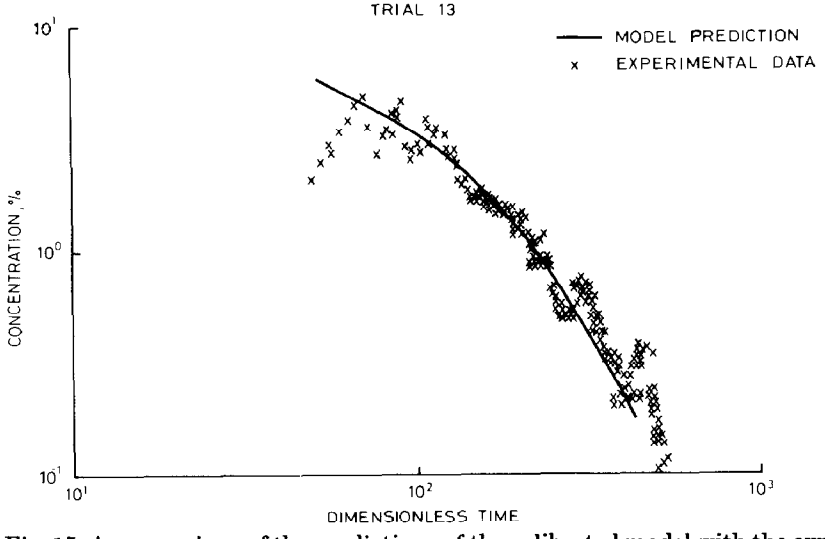


Fig. 15. A comparison of the predictions of the calibrated model with the experimental data given by Wheatley et al. [14] for Trial 13 (the concentration values are 1-s time averages).

to capture the bulk behaviour (dilution and advection) witnessed in the Thorney Island trials.

8. Conclusions

It has been shown that the data collected during the Thorney Island trials may be used to calibrate a simple mathematical model for the dispersion of an instantaneous release of a denser than air vapour cloud. This has been illustrated for a model similar to the one proposed by Bradley et al. [12]. The results of the model were found to be relatively insensitive to the values of the top surface mixing parameters for this type of release. However, the edge mixing and momentum parameters were well defined. A comparison with additional data, previously calculated from records of the trials, shows that this model produces results that are in reasonable agreement. Further, the inclusion of a momentum equation to determine the bulk advection speed of the cloud produces a significant improvement to an earlier BG/C&W model.

Finally, it is concluded that other sources of data should be examined to see if the model parameter values deduced here may be used for other release configurations. The continuous release trials at Thorney Island and the Shell Maplin Sands and Burro series of trials at China Lake may be useful in this respect.

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List of symbols

C_D drag coefficient for air flow around the cloud
C_p peak gas concentration detected at a fixed sensor position
d_{LFL} downwind dispersion travel distance to a concentration level equivalent to the lower flammability limit of LNG vapour (5%)
D total drag force in downwind direction experienced by the cloud
E_a measure of error in estimated time of arrival of gas at a fixed sensor location
E_p measure of error in estimated peak gas concentration detected at a fixed sensor location
F friction force opposing downwind motion of cloud due to underlying surface
f parameter for entrainment of momentum through cloud edges
G overall error estimator for a given set of model parameter values
g' the reduced gravity experienced by the cloud. Defined by $g' = g(\rho_c - \rho_a)/\rho_a$
g'_0 initial value of g'
H cloud height

k gravity slumping constant
l representative length-scale for the size of the turbulent eddies in the atmosphere
M total mass in the cloud
M_E mass of air entrained through the cloud edges
M_T mass of air entrained through the cloud top surface
R cloud radius
Ri bulk Richardson number of the cloud
S_a signed error in estimated time of arrival of gas at a fixed sensor location
S_p signed error in estimated peak gas concentration detected at a fixed sensor location
t time measured from the instant of release of gas
t_a time of arrival of gas at a fixed sensor location
t_d time of departure of gas from a fixed sensor location
U advection speed of the centre of the cloud
u_1 horizontal rms turbulent velocity of the atmosphere
$u(z)$ mean wind speed at height z m above the ground
$\bar{u}_H$ average of the mean wind speed over a height H above the ground
u_* friction velocity at the ground due to the wind
u_{*c} friction velocity at the ground due to the cloud motion
u_{10} mean wind speed at a height 10 m above the ground
V volume of cloud
V_0 initial value of V
z elevation above ground level
α topsurface entrainment parameter for gravity dominated phase of dispersion
β top surface entrainment parameter for atmospheric turbulence dominated phase of dispersion
γ edge entrainment parameter
ρ_a density of air (assumed constant)
ρ_c density of cloud

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