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INTERPRETATION OF THE THORNEY ISLAND PHASE I TRIALS WITH THE BOX MODEL CIGALE2

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Summary

This paper presents the interpretation of the Thorney Island Phase I trials with the box model DENZ and the consequent development of the improved box model CIGALE2.

The preliminary comparison of the code DENZ with the Thorney Island trials results has shown the necessity to take into account the acceleration of the cloud from the instant of the release. The acceleration phase was supposed to be due to the momentum of the air entrained in the cloud. The code has been modified consequently and was again compared with the experimental results in order to fit the adjustable coefficients. The improved code was recalled CIGALE2.

This work permitted a significant improvement of the realism of the code concerning the mean position of the cloud, the cloud surface, cloud height, and mean concentration in the cloud.

1. Introduction

Atmospheric heavy gas dispersion is one of the important phenomena participating in the risk of external events against nuclear installations or in the hazard represented by the chemical industries against the environment. These problems have been the subject of specific studies by CEA/IPSN for some years. Three different ways of approach of these problems have been developed, or are under development : box modelling, three dimensional modelling and small-scale simulation in a water channel.

The aim of this paper is to present the interpretation of the Thorney Island Phase I trials with the box model DENZ and the consequent development of the improved box CIGALE2.

2. Presentation of the model DENZ

The basic model used in this study is the DENZ code developed by UKAEA/SRD and described in Ref. [1]. Its main features are briefly summarized here.

The behaviour of the heavy gas cloud is schematised in three main phases:
Phase I : formation of the source,
Phase II : gravity slumping of the cloud and air entrainment,
Phase III : passive dispersions.

The initial conditions of the problem are defined in the Phase I. The cloud is supposed to be a cylinder of given initial aspect ratio (height over diameter).

In the Phase II, the gravity collapse of the cloud and air entrainment by the edge and the top of the cloud occur simultaneously.

The radius increase is given by the following formulation:

$$\mathrm{d}R/\mathrm{d}t = K\sqrt{gh(\rho-\rho_a)\rho_a}$$

where R is the cloud radius, t the time, ρ and ρ_a the cloud and air specific masses, g the gravity acceleration, h the height of the cloud and K is a constant (equal to 1 in this study).
The air entrainment is given by the following equation:

$$\mathrm{d}m_a/\mathrm{d}t = \rho_a \pi R^2 U_h + 2\rho_a \pi R\, h\, U_c$$

The edge entrainment velocity is given by:

$$U_c = \alpha^* \mathrm{d}R/\mathrm{d}t$$

α^* being an adjustable coefficient.

The top entrainment velocity is given by the Cox and Roe [2] formulation:

$$U_h = \alpha' U_1 Ri$$

where U_1 is characteristic of the atmospheric turbulence (standard-deviation of the fluctuations of the wind velocity) and Ri is the Richardson number so defined:

$$Ri = (gl_s/U_1^2)(\rho-\rho_a)/\rho_a$$

l_s is a length scale function of the height of the cloud: $l_s = 5.88h^{0.48}$, and α' is an adjustable coefficient.

The coefficient values, adjusted in Ref. [1] on the Porton experiments [3], are the following:

$$\alpha^* = 0.7, \qquad \alpha' = 0.15$$

The cloud is supposed to travel all along with the velocity of the wind (a logarithmic wind speed profile is assumed) at its half-height.

The third phase, occurring when the dilution of the heavy gas is great enough, is treated with a passive dispersions model. This phase, as well as the transition criteria between the Phases II and III, are not relevant to this study and are not detailed here.

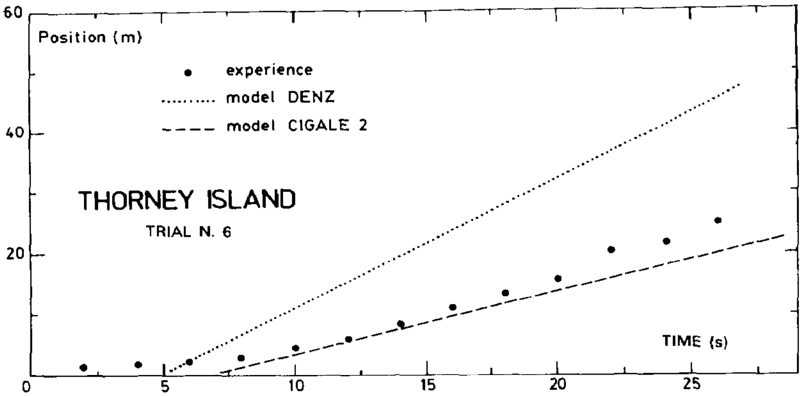


Fig. 1. Position of the cloud center versus time. Trial No. 6.

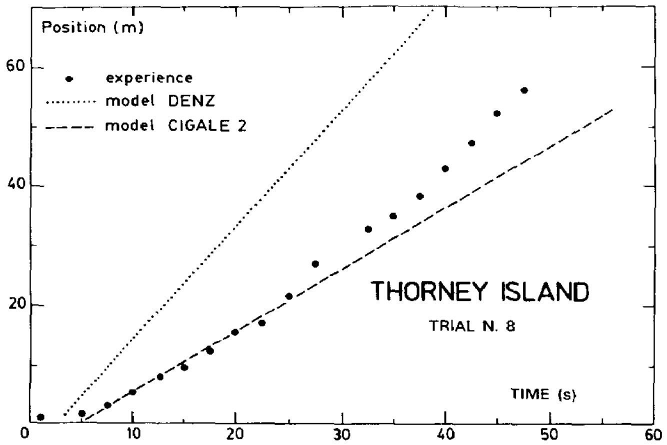


Fig. 2. Position of the cloud center versus time. Trial No. 8.

3. Comparison between the results of the Phase I trials and the code DENZ

Twelve among the fifteen Phase I trials have been used for this comparison. The three remaining trials (No. 5, 10, 12) were not judged fully satisfactory. Comparisons have been performed on the:

— mean position of the cloud versus time,
— cloud area versus time,
— cloud height versus distance,
— mean concentration in the cloud versus distance.

The experimental concentrations were obtained from the graphs reported in the hardcopy books of the trials, the cloud area, height and position, from the photos of the trials and their analysis [4–8].

The comparisons are illustrated here on four representative trials: No. 6, 8, 11, 14. The full results of this work can be found in Ref. [9].

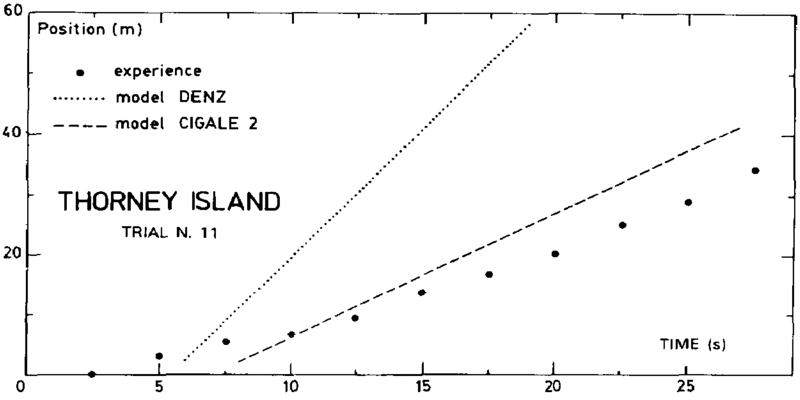


Fig. 3. Position of the cloud center versus time. Trial No. 11.

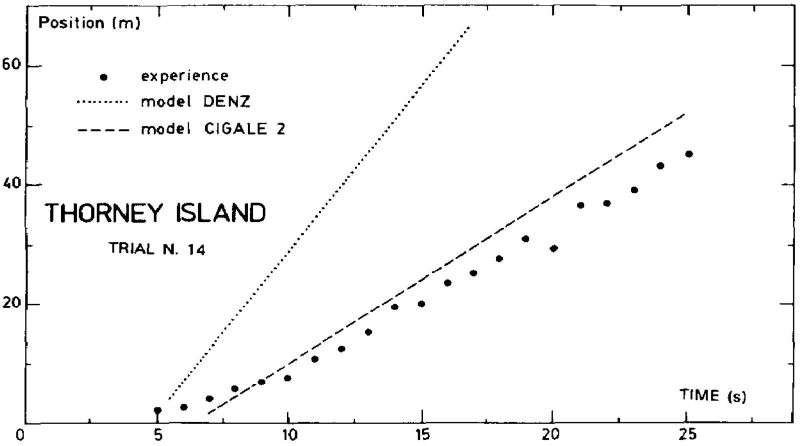


Fig. 4. Position of the cloud center versus time. Trial No. 14.

3.1 Comparison of the positions of the cloud

On Figs. 1–4, it is clear that the theoretical velocity of the cloud is much greater than the observed one. It can be observed that this phenomena persists all the time during which the cloud remains visible.

3.2 Comparison of the cloud areas

On the Figs. 5–8, we can notice that the results of the code are very near by the experimental ones. The linear growth of the cloud surface versus time is an hypothesis of the modelling which is confirmed by the experiments.

It must be noticed that if the areas were presented as function of the travel distance and not the travel time as it is here, a disagreement between the code and the trials would be concluded, due to the divergences mentioned hereabove. In this case, the code would underestimate the actual area of the cloud.

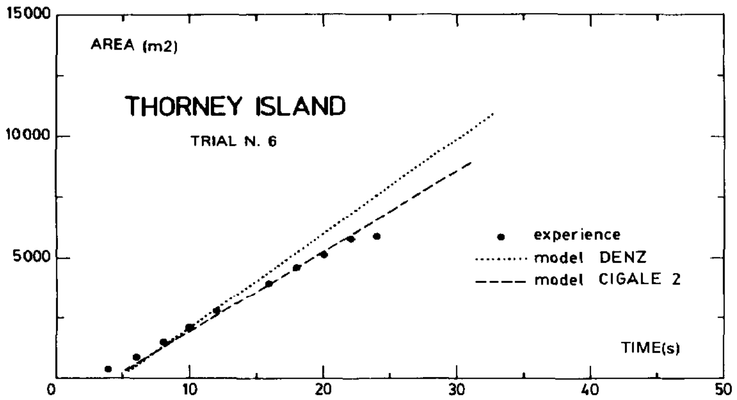


Fig. 5. Cloud area versus time. Trial No. 6.

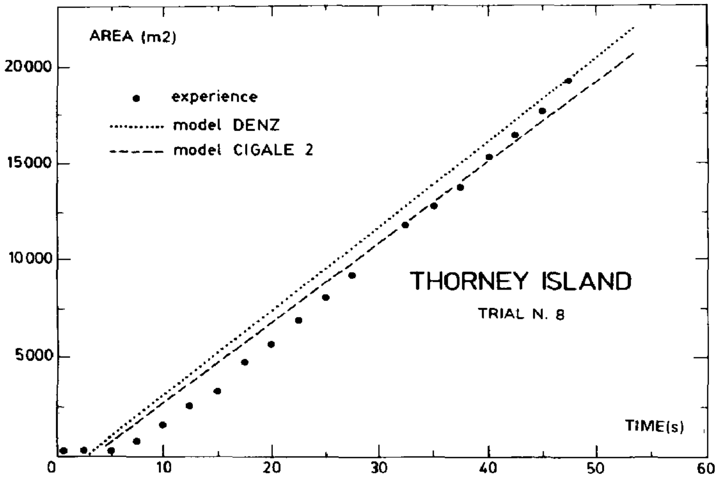


Fig. 6. Cloud area versus time. Trial No. 8.

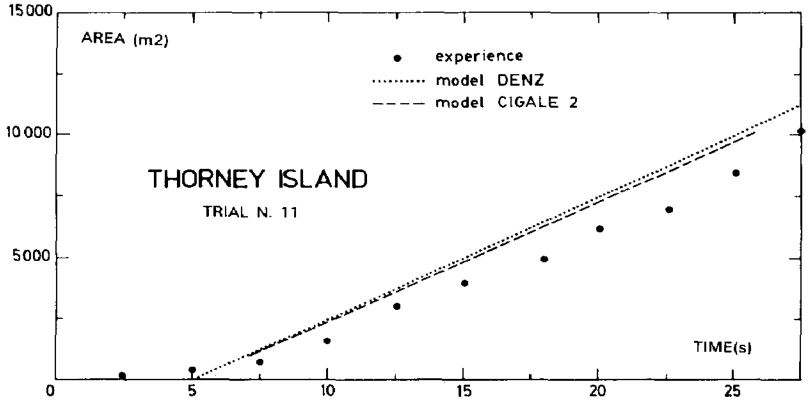


Fig. 7. Cloud area versus time. Trial No. 11.

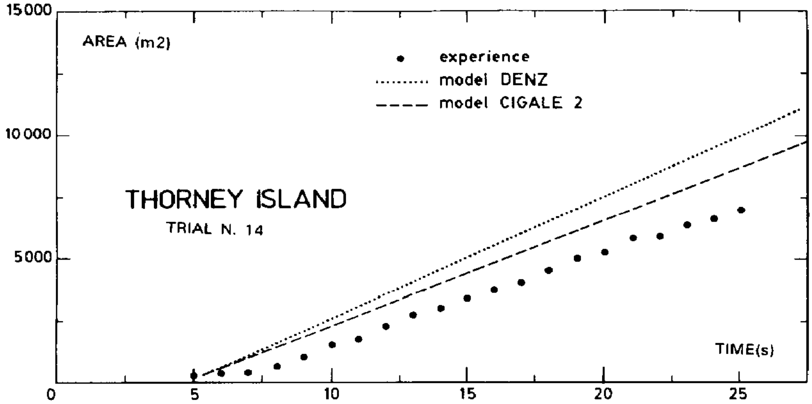


Fig. 8. Cloud area versus time. Trial No. 14.

3.3 Comparison of the cloud heights

The agreement, Figs. 9–12, is reasonable, with a slight tendency of the code to overestimate the experimental results at small times. The prediction of the height of the cloud at longer times is in close agreement with the experimental results. It tends to confirm the validity of the models of slumping and edge air entrainment in the code, dominant processes at this moment of the behaviour of the cloud.

3.4 Comparison of the concentrations

The comparison concerns the distribution of the mean concentration with downwind distance, where the mean is taken over the time when gas was detected at the sensor of interest. The sensors chosen are those located near the mean wind direction. For the sensors at 0.4 m above the ground, the Figs. 13–16 show that DENZ generally overestimates significantly the concentration. The probable reason for this discrepancy is the following: as already observed, the theoretical cloud moves more rapidly than the experimental one. The time during the air entrainment occurs is too short and the concentration in the cloud too high. Improvement of the model of cloud motion should then correct this point.

As regards the sensors located at 2.4 m, the comparison is presented on Figs. 17–19. Here again, the model overestimates the concentration, probably for the same reasons as hereabove.

At higher altitudes, only few results are available and no comparison is made.

4. Improvement of the code DENZ

4.1 Improvement of the modelling

It has previously appeared that the main disagreement between the code and the experiments comes from an erroneous modelling of the motion of the cloud,

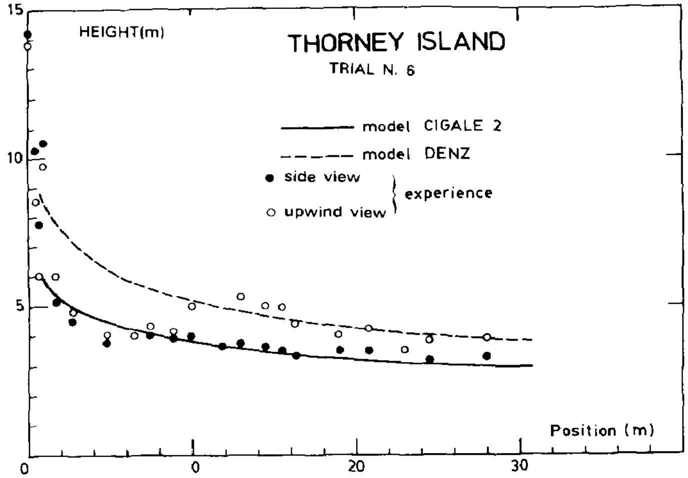


Fig. 9. Cloud height versus distance. Trial No. 6.

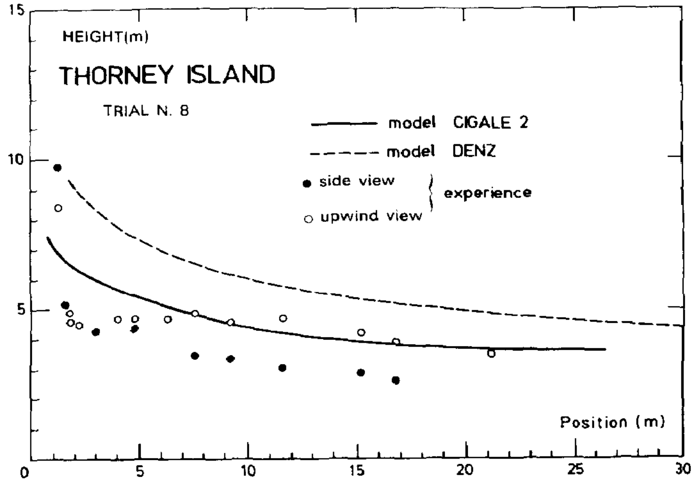


Fig. 10. Cloud height versus distance. Trial No. 8.

leading to a much faster cloud travel (i.e. shorter time to reach a given distance) than is observed. The assumed reason for this is the omission by the code of a significant inertia effect of the cloud, accelerating from its initial position to reach a constant advection velocity after a certain time. The inertia of the cloud obviously does not affect this advection velocity, but the time to reach this velocity.

In the DENZ code, the cloud is supposed to travel with the wind velocity at half height from the instant of release. The idea is to model this acceleration by assuming that it is entirely due to the momentum of the air entrained into the cloud. Thus, $dM(T)/dt=\xi U(dm_a/dt)$, and $M(O)=M_o$, with $M(t)$

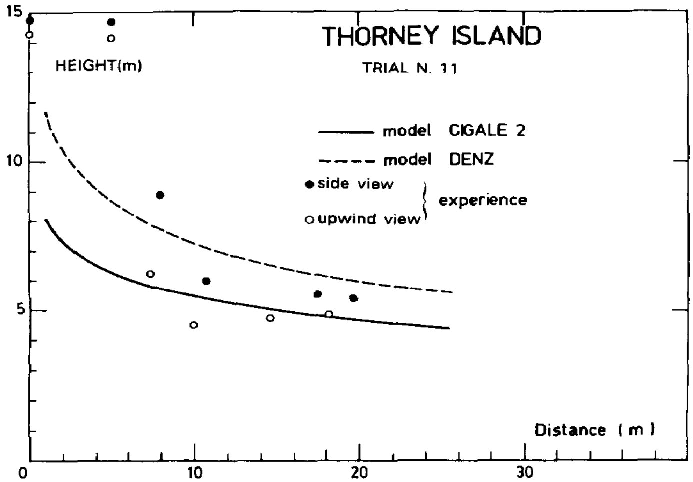


Fig. 11. Cloud height versus distance. Trial No. 11.

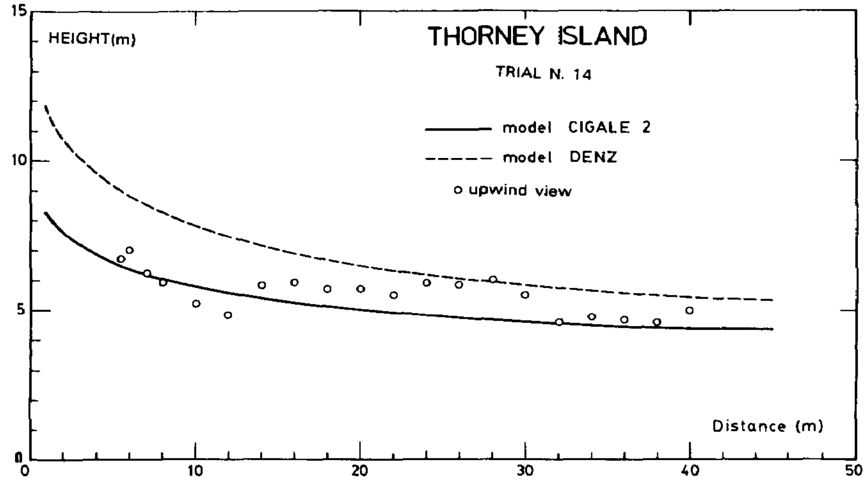
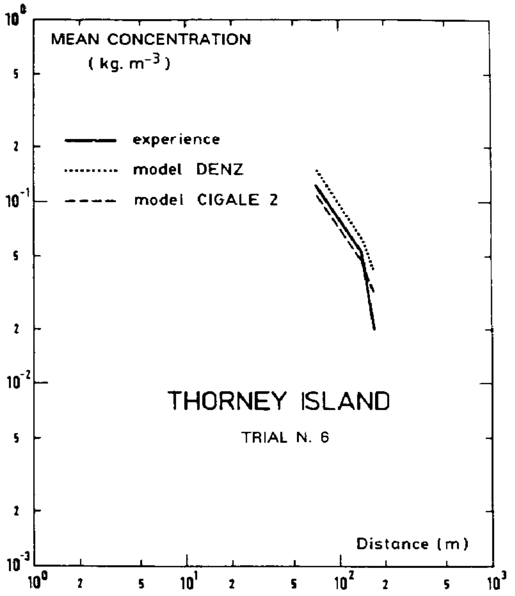


Fig. 12. Cloud height versus distance. Trial No. 14.

momentum of the cloud at the time t, M_0 initial momentum, m_a mass of air entrained at t, U wind speed at half height of the cloud, and ξ ajustable coefficient expressing that the transfer of momentum from the air into the cloud is not total. It means that ξ lies between 0 and 1.

4.2 Adjustment of the coefficients of the code

There are three adjustable coefficients in the improved code: α' and α^* air entrainment coefficients, ξ acceleration coefficient. They have been fitted to the experimental data for each trial. The acceleration coefficient has been obtained by fitting the calculated and observed positions of the cloud. The



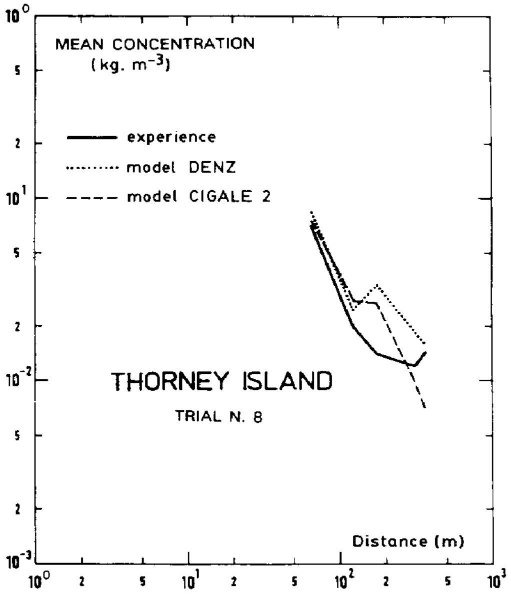
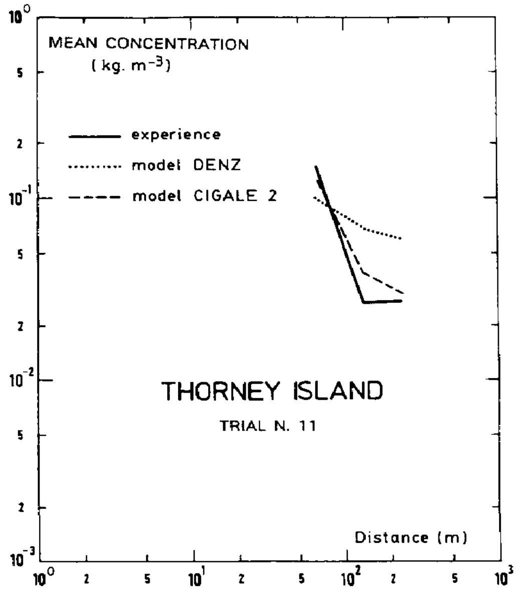


Fig. 13. Mean concentration versus distance ($H = 0.4$ m). Trial No. 6.

Fig. 14. Mean concentration versus distance ($H = 0.4$ m). Trial No. 8.



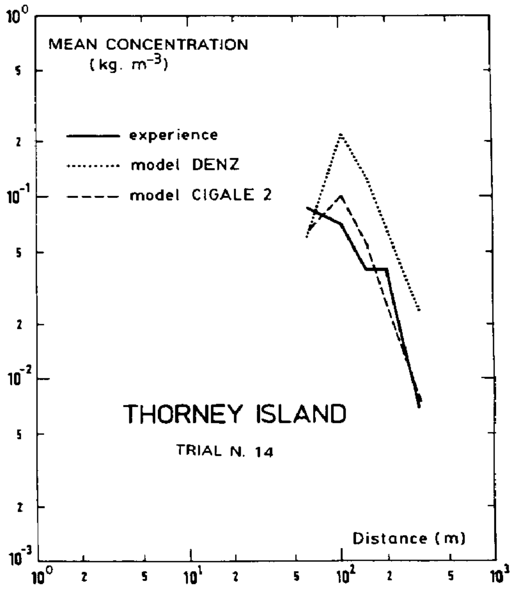
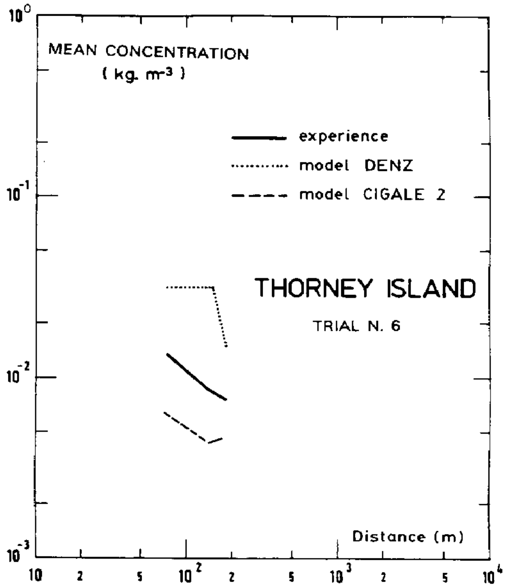


Fig. 15. Mean concentration versus distance ($H = 0.4$ m). Trial No. 11.

Fig. 16. Mean concentration versus distance ($H = 0.4$ m). Trial No. 14.



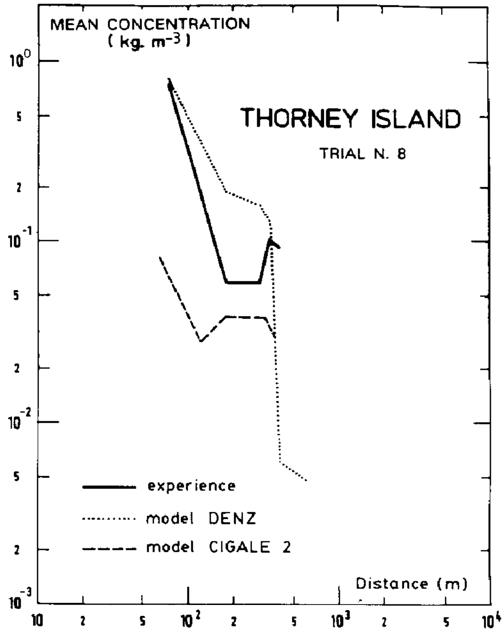


Fig. 17. Mean concentration versus distance ($H=2.4$ m). Trial No. 6.

Fig. 18. Mean concentration versus distance ($H=2.4$ m). Trial No. 8.

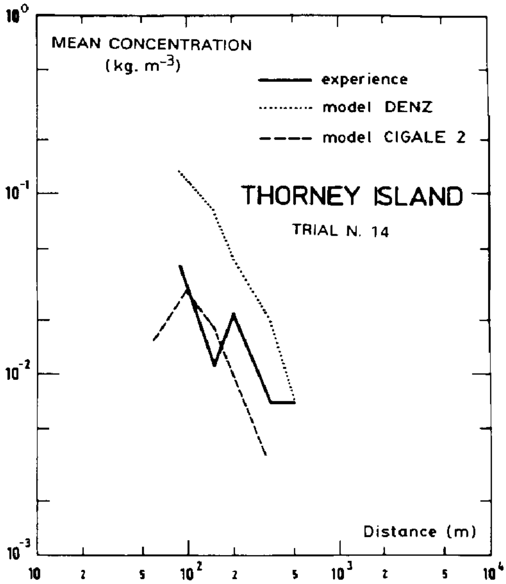


Fig. 19. Mean concentration versus distance ($H=2.4$ m). Trial No. 14.

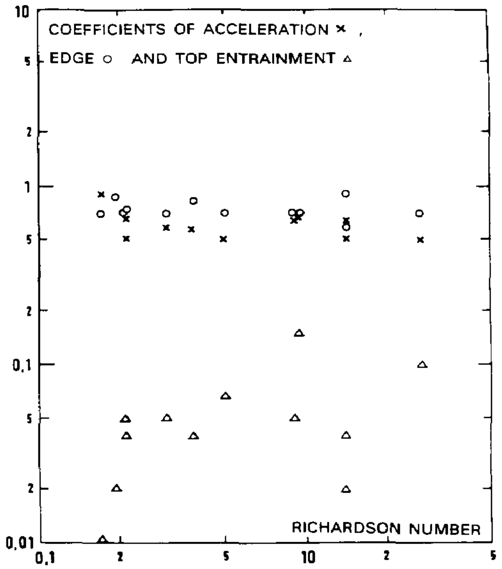


Fig. 20. Best adjustment of the acceleration, edge and top entrainment coefficients as function of the initial Richardson number.

values determined for each trial are reported on Fig. 20 as function of the Richardson number of the trial (the Richardson number is calculated here with the wind velocity at 10 m height, the initial height of the cloud and the initial relative density).

Figure 20 presents the best adjustment obtained specifically for each trial. Values of ξ are found between 0.5 and 0.9. No clear correlation with the Richardson number appears. The mean value of 0.58 has been adopted.

We notice a high scatter on the value of α' (the extreme values are 0.01 and 0.15), but no clear dependance on the Richardson number. The mean value 0.05 has been retained. On the contrary, the value 0.7 for α^* is characteristic of eight of the twelve trials. The code with these new coefficients $\xi = 0.58$, $\alpha' = 0.05$ and $\alpha^* = 0.7$ has been called CIGALE2.

An interesting feature of this code is that it is rather insensitive to the values of the coefficients. For example, an increase of ξ reduces the time to reach a given distance and therefore reduces the amount of air entrained. This in turn leads to a lesser acceleration, opposite in effect to the variation of ξ. Similarly, an increase of the air entrainment coefficients increases the acceleration of the cloud and reduces the time to reach a given distance. A similar reasoning could be applied to the reduction of these coefficients.

4.3 Comparison of the code CIGALE2 with the experiments

In order to assess the improvement brought by the present work, the results have been reported on the same graphs as those of the comparison with DENZ.

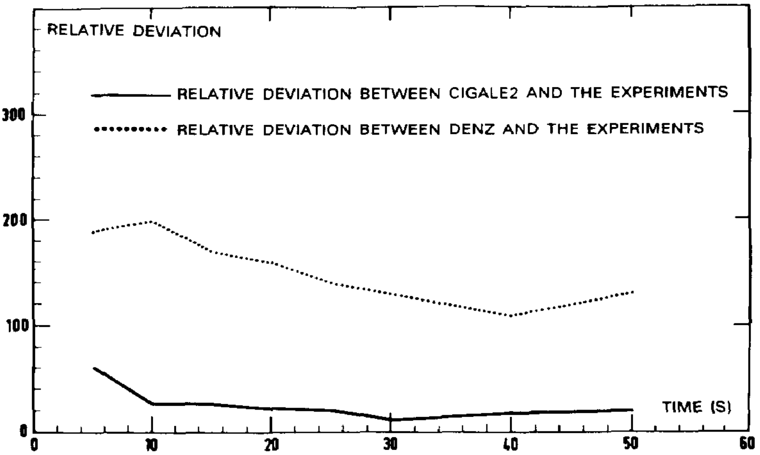


Fig. 21. Mean relative deviation between the theoretical and experimental positions of the center of the cloud versus time.

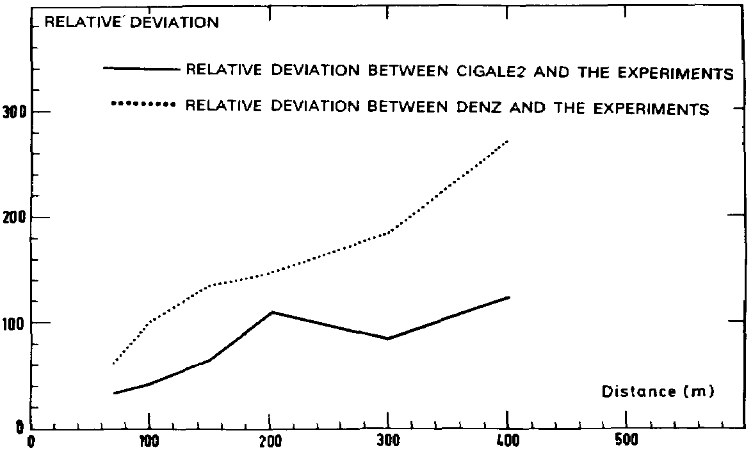


Fig. 22. Mean relative deviation between the theoretical and experimental concentrations versus distance.

As regards the cloud area, we notice a good agreement with the experiments, and no great change compared with DENZ. In a different presentation of the results, as function of the distance and not of the time, the improvement would been noticeable.

Figs. 9–12 show that the cloud height is correctly predicted by the code CIGALE2. Particularly, the tendency of DENZ to overestimate the height at small times has vanished. As regards the concentration at 0.4 m (cf. Figures 13–16), we notice a satisfying agreement between the code and the experiments. The ratio between the two is generally less than 2, seldom or order of 3.

As the higher level (2.4 m), CIGALE2 slightly underestimates the concentration, result opposite to the tendancy of the code DENZ. It could be due to a certain underestimation of the height of the cloud far from the source, as it is correctly estimated near the source (cf. Figs. 9–12). It could be also due to the vertical distribution of the concentration in the cloud different from the Gaussian one assumed in the code. This last hypothesis seems to be supported by the measurements performed in the Trial 17 where a complex vertical concentration profile was observed [9].

4.4 Assessment of the improvement of the modelling

In order to assess the global improvement brought by the work, the mean relative deviation (in absolute value) for all the trials between, on the one hand, DENZ and the experiments, on the other hand, CIGALE2 and the experiments, has been calculated.

Two quantities have been considered: the position of the cloud and the concentration at 0.4 m. The results are presented in Figs. 21 and 22.

On the second one, we observe that the mean deviation between DENZ and the experiments increases with the distance from 60 to 300%. The deviation with CIGALE2 only increases slightly and is never greater than 100%.

It is to be noticed that the codes DENZ and CIGALE2 have also been tested against the Porton trials data [3]. The detailed results of the work are not reported here, but can be found in Ref. [10]. It was concluded that most of the improvements brought by the present work and highlighted by the Thorney Island trials also apply to the Porton data.

5. Conclusions

The preliminary comparison of the code DENZ with the Thorney Island trials results has shown the necessity to take into account the acceleration of the cloud from the instant of the release. This acceleration phase was supposed to be mainly due to the momentum of the air entrained in the cloud. The code has been modified consequently and was again compared with the experimental results in order to fit the adjustable coefficients.

A unique triplet of values of these coefficients (acceleration coefficient, top and edge entrainement coefficients) has been drawn. The improved code was recalled CIGALE2.

This work permitted a significant improvement of the realism of the code concerning the mean position of the cloud, the cloud surface, cloud height, and mean concentration at 0.4 and 2.4 m high. Particularly, the mean deviation between the code and the experiments was reduced to 10% concerning the position of the cloud versus time and less than a factor 2 for the ground concentration versus distance. The validity of this work was confirmed by a test of the code on the Porton trials data.

Acknowledgement

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