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A WIND TUNNEL SIMULATION OF THE THORNEY ISLAND PHASE II TRIAL 20

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Summary

The Thorney Island Phase II Trial 20 has been simulated with respect to bulk Richardson number in a wind tunnel. The model scale was 1:50.

The experiment reproduces the front concentration peaks satisfactorily, but when taking a mean of the maximum concentration of 5 different runs, the concentration is somewhat lower than the full scale readings. The duration of the dispersion process was found to be somewhat longer in the model tests than what can be deduced from the full scale experiments.

1. Introduction

Severe environmental problems can be caused by the release of hazardous and toxic gases. It is therefore of importance to be able to determine the behaviour of these gases within the framework of risk-analysis studies associated therewith.

In quite a number of cases, accidental releases of hazardous or toxic gases are complicated by the fact that the gases are heavier than the ambient air. Such heavy gases spread widely and thus the effects on this spreading of the gas by geographical features and obstructions are of importance.

A wind tunnel model needs to be evaluated with a large scale experiment to see if the small scale model reproduces the large scale experiment satisfactorily.

It is also of interest to study the effect of improved measurement techniques and see how this effects the wind tunnel model performance.

There have been many large scale releases of heavy gas, the most famous of which are the experiments at Maplin Sands, Porton Down and Thorney Island. Britter and Simpson [1–3] have studied the front wave in a gravity current and found the vortex at the gravity current head.

The Porton Down heavy gas release has been successfully modelled by Hall et al. [4,5]. They found that large scale heavy gas releases could be scaled down by Froude number and density difference ratio. They also found that modelling with densimetric Froude number or bulk Richardson number could successfully be applied. This is favourable because it allows model tests to be performed at different speeds by changing the density ratio accordingly.

At TNO Apeldoorn, van Heugten and Duijm [6] simulated the Thorney Island Phase I trials. A simulation of Trial 008 scaled with bulk Richardson number indicated that the peak concentrations were underestimated.

Duijm et al. [7] modelled Trial No. 013 in the Thorney Island series and used both bulk Richardson and the Froude number scaling. They found that the wind tunnel experiment underestimated the maximum concentration with approximately a factor of two and that the bulk Richardson number model performed slightly better than the scaling with Froude number and density difference ratio.

It may be that the differences observed by Duijm et al. in maximum concentration was an effect of low frequency response of the concentration measurement equipment. This paper looks into this effect.

2. The geometrical layout of Trial 20 in the Thorney Island Phase II

The container of gas has 12 sides, height 14 m and base cord 14 m. Filled up to 13 m it contains 2000 m^3.

The obstruction is a 6 m high impermeable fence. It is formed in a semi circle with radius 50 m, placed around the center of the container. The gas sensors were placed in semi circles with radius 20, 40, 75, 100, 150 and 200 m from the source center.

Inside the fence there were 3 sensor masts per semi circle, and the sensors were placed 0.4, 2.4 and 4.4 m above the ground. Outside the fence there were 5 sensor masts per semi circle with sensors at 0.4, 2.4, 4.4, 6.4 and 10.4 m. For further layout see Fig. 1.

The Thorney Island Trial 20 Phase II full scale parameters were

Freon/nitrogen density ratio $\Delta\rho/\rho$	1.92
Mean velocity at 10 m (U_{ref}): Over main data collection period	5.7 m/s
Over 5 minutes cycle immediately before release	5.6 m/s
Bulk Richardson number based on the fence height	3
Mean wind heading (relative to the center line of the array)	−6.5°
Relative humidity (at 10 m height)	70%
Insolation	686 W/m^2
Ambient air temperature	23°C

3. Choice of modelling parameters

The fundamentals of modelling of heavy gas dispersion at reduced scale is discussed at some length in earlier work [8].

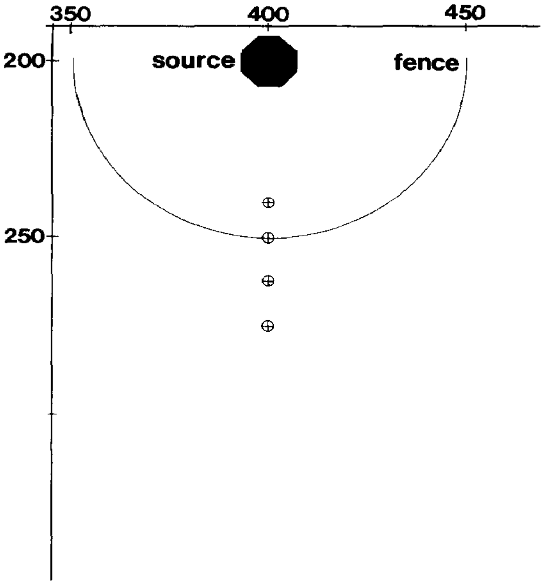


Fig. 1. The geometrical layout of the experiment.

The most important parameters involved in the modelling is the size of the release represented by a characteristic length L, the relative density ratio $\Delta\rho/\rho = (\rho_{gas} - \rho_{air})/\rho_{air}$, and the velocity at a reference height (U_{ref}).

This leads to the following dimensionless parameters:

Reynolds number $$\frac{U_{ref}L}{\nu}$$

Density difference ratio $$\frac{\Delta\rho}{\rho} = \frac{\rho_{gas} - \rho_{air}}{\rho_{air}}$$

and

Froude number $$\frac{U_{ref}}{\sqrt{gL}}$$

At the reduced wind tunnel model scale the Reynolds number is unavoidably much smaller than the full scale value. The Reynolds number is, however, high enough for the simulated atmospheric boundary layer to be fully turbulent and thus the model is realistic in spite of the difference in Reynolds number. The Reynolds number in the model was 70,000.

In cases of heavy gas dispersion the heavy gas has a strong negative buoyancy. This has a stabilizing influence on turbulence. When running at a lower Reynolds number in a wind tunnel the flow can get locally laminar. This is not the case in the full scale trials, but in the experiment the fence introduces new turbulence into the flow and this opposes the stabilizing effect.

The other two groups are normally easy to scale. Since the full scale experiments have a relatively small velocity, the wind tunnel velocity gets impractically small. (The velocity reduces as the square root of the characteristic length scale.)

To avoid this the scaling was done with a densimetric Froude number or bulk Richardson number which is a combination of relative density ratio and Froude number.

$$Ri_{\mathrm{bulk}} = \frac{\Delta\rho}{\rho}\frac{Lg}{U_{\mathrm{ref}}^2}$$

This scaling allows the wind tunnel model to operate at a higher velocity, when the difference density ratio is scaled accordingly.

The scaling with bulk Richardson number is not strictly correct for differences in density larger than about 5% according to the Boussinesq approximation. This is the case when the gas cloud has spread out and the gas concentration has become low. But the error made by applying this approximation to the near field is indicated to be small [8].

4. The experiment

The reason why Trial 20 Phase II was chosen was that a rather complete set of data were collected from the full scale trials, and that the wind direction was in good agreement with the layout of the gas sensors.

Trial 20 Phase II has a relatively low density difference ratio and a relatively high mean wind speed, which is preferable for modelling conditions.

Because of the stochastic nature of transient trials more than one release had to be taken per measuring position. This put a limitation to how many concentration profiles that could be determined. Five repeated runs were made at each position, and 4 vertical profiles were measured. The position of two of the profiles coincide with the full scale trial.

The profiles measured were at (400, 240), (400, 250), (400, 262.5), (400, 275) in the full scale coordinates. The two profiles that coincide were at (400, 240) and (400, 275).

The scale of the modelling was 1:50, and the gas release was pure Freon 12.

The relative density ratio was

$$\rho_{\mathrm{Freon}} = 5.22 \text{ at } 20\,^\circ\mathrm{C}$$

$$\rho_{\mathrm{air}} = 1.2 \text{ at } 20\,^\circ\mathrm{C}$$

$$\frac{\Delta\rho}{\rho} = 3.35$$

From the bulk Richardson number similarity a model velocity of 1.04 m/s is deduced.

The time scale between the full scale release and the model scale release then becomes:

$$\frac{U_{\text{model}}}{U_{\text{full scale}}} = \frac{(L_{\text{model}}/t_{\text{model}})}{(L_{\text{full scale}}/t_{\text{full scale}})} \Leftrightarrow \frac{t_{\text{full scale}}}{t_{\text{model}}} = 9.28$$

In order to ensure comparable frequency response between model and full scale releases the frequency response of the concentration measurement equipment had to be about 10 times the frequency response of the full scale equipment. This means 10 and 100 Hz.

The Thorney Island trials were logged at 20 Hz. Therefore the model data were collected at 250 Hz.

The instrumentation of the model experiments was for velocity measurements a pulsed hot-wire and for concentration an aspirating hot-wire. The aspirating hot-wire was tuned for a high frequency response at about 200 Hz. The frequency response was checked by hanging the probe on a pendulum that was allowed to swing through a Freon jet.

The trial was simulated in the SINTEF/NTH off-shore wind tunnel. The test section is 2.7 m wide and 2 m high. At a scaling factor 1:50 the fence is 0.1 m high, with a radius of 1 m.

The release mechanism was an 8 sided box with a lid. The box and lid were connected to a spring so that when released, the lid would be pulled over to the wind tunnel side very quickly, and the box pulled down underneath the wind tunnel floor. This took approximately 1/20 of a second.

The simulated boundary layer is shown in Fig. 2.

The reference velocity was monitored by a separate pulsed hot-wire placed upstream of the working section.

The concentration data were collected at 250 Hz, and 6,500 samples were taken for each time series, giving a duration of 26 s model time or about 240 s equivalent full scale time. This was adequate time for the gas to pass the sensors. The data were collected on a PDP 11/23+. The lower limit of resolution of the gas sensor was 0.15%.

5. Results

To be able to compare full scale results with model scale results the model scale results have been scaled to full scale.

To determine the relevant averaging time the effect of averaging has to be determined. The averaging time for the full scale trials has been discussed in

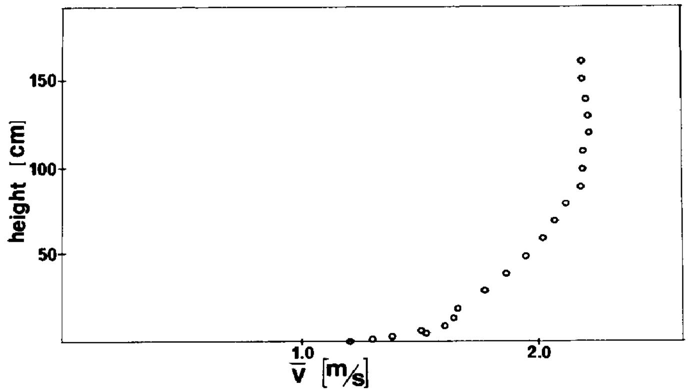


Fig. 2a. Simulated boundary layer.

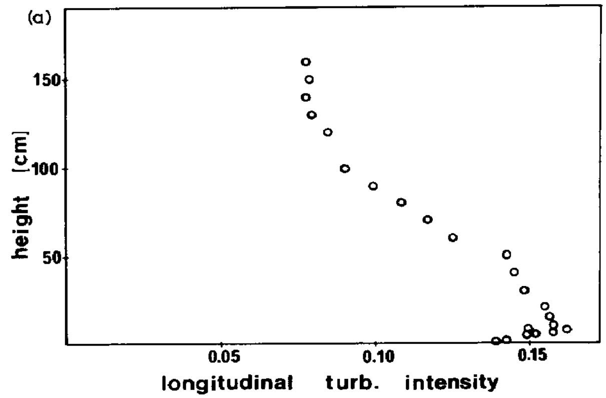


Fig. 2b. Longitudinal turbulence intensity.

Ref. [9]. To determine the effect of the model measurements a plot of maximum concentration versus averaging time was developed (Fig. 3). The plot shows little effect on maximum concentration up to 1 s averaging time. This is in good agreement with what was found in Ref. [9]. The averaging time chosen was 0.6 s.

The time lapse rate of the release is shown in Fig. 4 and Table 1. To determine when the gas has reached the sensor is easy because of the sudden change in concentration level, but to determine when the gas has passed the sensor is not so easy because of the flatness of the curve so this point in the curve can not be accurately determined.

From Fig. 4 it is seen that the arrival of the cloud is in good agreement between model and full scale. There are some differences but considering that there is a time factor of 10 between the two the agreement is good.

The cloud is longer present in the model experiment than at full scale at the 75 m measuring position i.e. 25 m downwind of the fence. The differences are

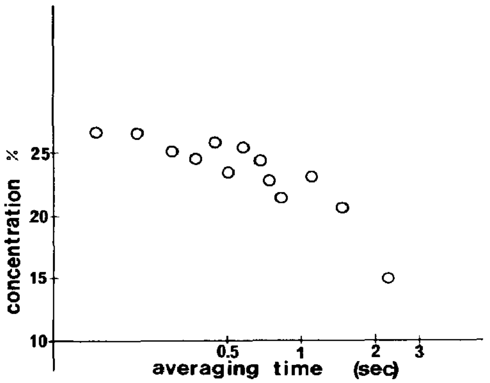


Fig. 3. Maximum concentration versus averaging time.

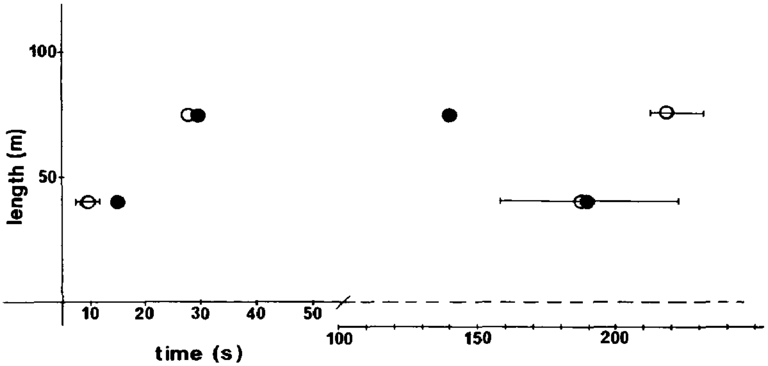


Fig. 4. Arrival and departure times at height 0.4 m at a distance from the source 40 m (coordinate 400,240) and 75 m (coordinate 400,275): • full scale, and o model scale.

so significant that the uncertainty in determining the time cannot account for this. One reason for the difference may be the difference in Reynolds number and thus the wake behind the fence may be different.

When comparing the maximum concentration in the full scale and model experiments, the stochastic nature of the heavy gas dispersion must be taken into consideration. Figure 5 shows the differences between the model results and full scale at the same location. There are measurements that have a higher concentration peak than the full scale results. But when averaging over 5 repeated runs the model seems to underestimate the maximum concentration at all heights. This indicate that the full scale trial could be in the upper range of the spectrum. When the gas has passed the fence the maximum concentration is relatively constant with height from 1–1.5% in the model scale and 2.2–2.8% in the full scale trials, Fig. 6.

To further map the near field two additional profiles were measured, one at

TABLE 1A

The time span of the gas cloud at (400, 275)

Arrival and end times are measured from the instant of release. The model's time is converted into full scale time

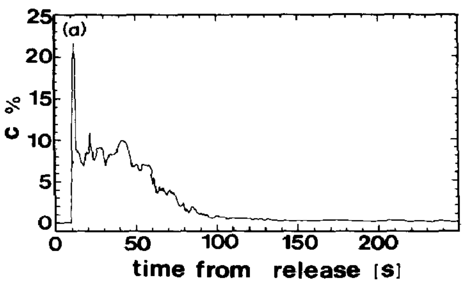
Height (m)	Model				Full scale		Time span (s)
	Arrival (s)	End (s)	Time span (s)	Mean time span (s)	Arrival (s)	End (s)	
0.4	28	232	204				
	28	213	185	191	30	140	110
	28	213	185				
2.4	23	227	204				
	18	195	177	198	25	185	160
	18	232	214				
4.4	32	199	167				
	25	195	170	179	25	235	215
	37	237	200				
6.4	23	195	172	183	20	120	100
	28	223	195				
10.4	19	232	213	180	20	160	140
	28	176	148				

TABLE 1B

The time span of the gas cloud at (400,240)

Arrival and end times are measured from the instant of release. The model's time is converted into full scale time

Height (m)	Model				Full scale		Time span (s)
	Arrival (s)	End (s)	Time span (s)	Mean time span (s)	Arrival (s)	End (s)	
0.4	9.3	167	158				
	8.3	223	215				
	12.1	176	164				
	7.4	167	160	179	15	190	175
	10.2	213	203				
	10.2	158	148				
	10.2	213	203				
2.4	9.3	176	167				
	9.3	158	149				
	9.3	176	167	167	15	115	100
	9.3	195	186				
	9.3	176	167				
4.4	9.3	195	186	186	20	160	140
	9.3	74					



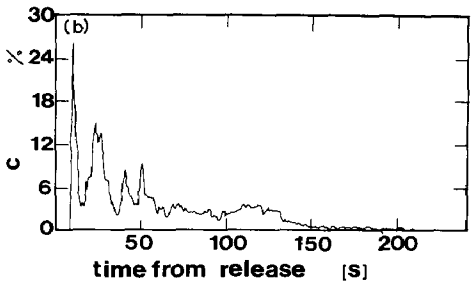


Fig. 5a. Full scale measurements at the location (400,240,0.4).
Fig. 5b. Model scale measurements at the location (400,240,0.4).

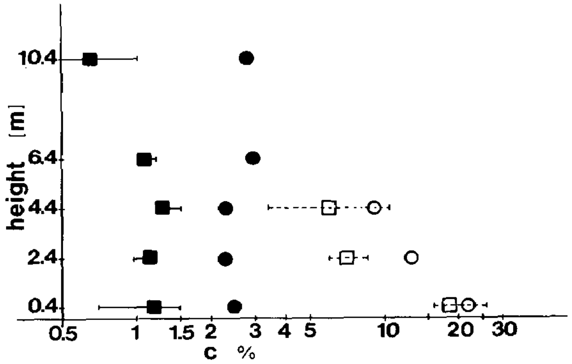


Fig. 6. Maximum concentration with height: o full scale measurements (400, 240), ● full scale measurements (400, 275), □ model scale measurements mean (400, 240), ■ model scale measurements mean (400, 275), - - - - indicates the span of the model measurements (400, 240), and —— indicates the span of the model measurements (400, 275).

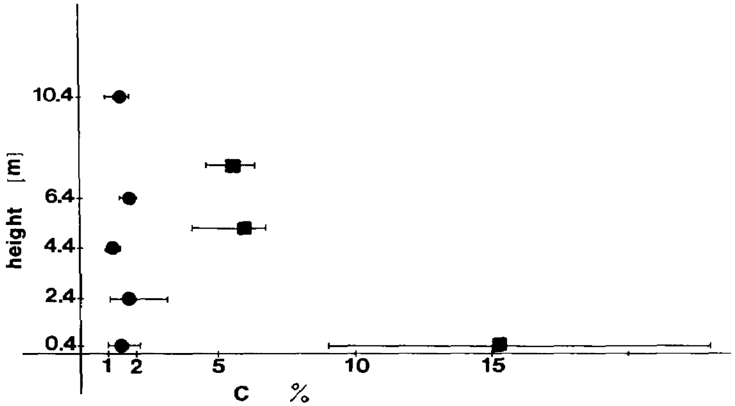


Fig. 7. Maximum concentration plotted with height: ● (400, 262.5) and ■ (400, 250) (in front of fence).

the inside of the fence (400,250) and one at (400,262.5). The distribution of the maximum concentration with height is plotted in Fig. 7.

These additional measurements match the others well and verify the expected dilution process.

6. Conclusions

This experiment has shown that it is possible to scale the Thorney Island Phase II trials with a bulk Richardson number scaling.

When the modelling with bulk Richardson number is applied there is a longer period that gas is present in the model experiment than in full scale. This could be due to the differences in Reynolds numbers. The experiments indicate that the maximum concentration level in the model is under estimated and that the dilution of gas tends to be faster than in the full scale tests.

Because of the high frequency response of the concentration measurement equipment the reproduction of the data has been satisfactory and in front of the fence the peak concentrations have been reproduced.

Acknowledgements

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