FIELD AND WIND TUNNEL EVALUATION OF CFD MODEL PREDICTIONS OF LOCAL DISPERSION FROM AN AREA SOURCE ON A COMPLEX INDUSTRIAL SITE

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INTRODUCTION

Emissions of airborne materials from industrial sites often occur from low level sources as well as from elevated stacks. The determination of near-field environmental impacts from such sites is complicated by the flows generated by site buildings. This study focuses on the Sellafield site, for which atmospheric dispersion of material from elevated stacks has been evaluated previously (*Hill, R. et al.*, 2005; *Jenkinson, P. et al.*, 2006); this paper presents results from wind tunnel and numerical modelling of dispersion from an area source.

METHODS

Wind Tunnel Modelling

A low-speed environmental wind tunnel at the University of Surrey was used to model dispersion from the area source. The tunnel is a suckdown, Eiffel-type installed in a closed room, the air in which providing the return circuit for the flow. The working section of the wind tunnel is 20 m in length and it is rectangular in cross section, measuring 3.5 m in width and 1.5 m in height. A 1:500 scale model of the Sellafield site was used in these tests with two sets of building models being applied (as shown in Figure 1). These building models were used to determine the sensitivity of the wind tunnel dispersion modelling to the specification of detail on the buildings immediately adjacent to the source.

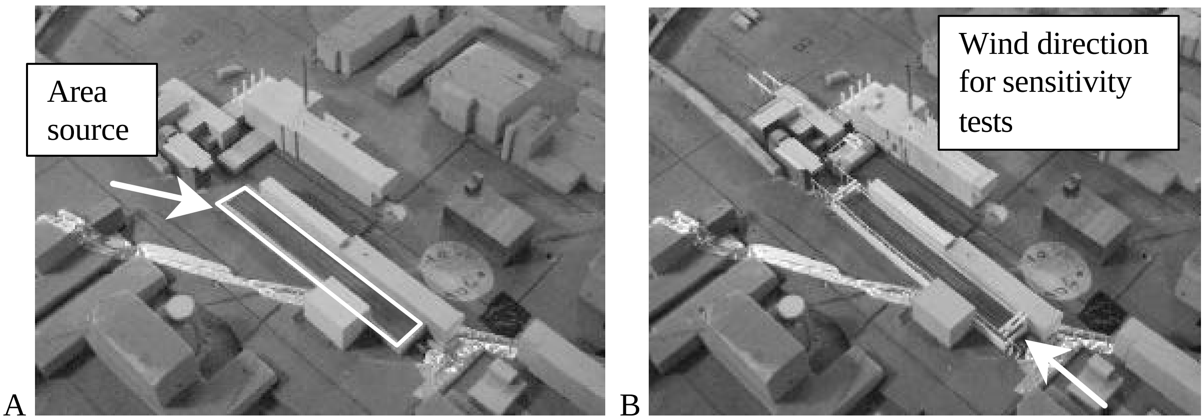

Fig. 1; The Wind Tunnel model of Sellafield showing the simple (A) and detailed (B) building setups and the location of the area source.

Computational Fluid Dynamics (CFD) modelling

The CFD code *"Fluidyn-PANACHE"* was developed by Transoft International for the simulation of atmospheric flows and pollutant emissions from single or multiple sources over short and medium ranges. A finite-volume-based approach is applied in which the governing differential equations for mass, momentum and heat transfer are solved in 3-dimensional space and time. Tests were undertaken to evaluate the sensitivity of the CFD model to the specification of input parameters as detailed in Table 1.

Table 1. Parameter values tested in the sensitivity study on the CFD model.

Parameter	Grid Fineness (Cells)	Time Step (s)	Roughness Length (m)	Numerical Scheme	Turbulence model	Building Configuration
Baseline	$69 \times 61 \times 24$	0.2	0.5	1st order upwind	k-epsilon	Area source flush with building
Variations	$74 \times 68 \times 29$	0.1	0.1	1st order weighed upwind	k-diffusion	Recessed area source
	$83 \times 67 \times 29$		0.3	2nd order	k-L	Upwind building removed
	$86 \times 77 \times 39$		0.7			

Meteorological measurements

Meteorological data were collected on the Sellafield site at a location 235 m downwind of the area source using a conventional wind vane and anemometer and also a Solent ultrasonic anemometer (Gill Instruments Ltd.) located at a height of 10 m. The ultrasonic anemometer enabled collection of high frequency data (5 Hz) on temperature fluctuations (T') and fluctuations in the vertical (w'), lateral (v') and horizontal (u') components of the incident wind. In addition, measurements of the undisturbed upwind meteorology were collected at an off-site meteorological tower, located 850 m north-west of the area source.

RESULTS

Sensitivity of the CFD model to input parameters

The sensitivity of the CFD model to the specification of the input parameters detailed in Table 1 was evaluated for a wind direction along the axis of the area source (shown in Figure 1) at 6 downwind distances. Coefficients of variation were determined from the mean and standard deviation (σ) of the CFD predictions at each downwind distance. The results of this analysis are shown in Table 2, illustrating that the highest sensitivity was for the specification of turbulence model. In general, the sensitivity of the CFD model to changes in input data declined with downwind distance due to mixing of material within the plume.

Table 2. Sensitivity of downwind centreline concentrations (c) to specification of parameter values in the CFD model.

Distance (m)	Coefficient of variation ($s_C / \bar{c}$) Grid Fineness	Time Step	Surface Roughness	Building Geometry	Numerical Scheme	Turbulence Model
95	0.27	0.10	0.24	0.25	0.47	0.93
175	0.12	0.01	0.27	0.04	0.14	0.55
225	0.10	0.00	0.18	0.08	0.14	0.63
235	0.12	0.00	0.18	0.08	0.14	0.63
262	0.07	0.00	0.13	0.06	0.14	0.63
350	0.07	0.00	0.16	0.06	0.13	0.62
395	0.06	0.00	0.15	0.05	0.11	0.63

Comparison of the CFD modelling with on-site meteorological data

The flow field downwind of the area source was evaluated by comparison of the CFD results with the on-site meteorological measurements collected using the ultrasonic anemometer.

These measurements included turbulent kinetic energy (TKE), wind speed and wind direction. In addition, measurements of upwind flow, collected at the Sellafield meteorological tower, were used to define the boundary conditions of the CFD model and allow a comparison between measured and modelling deceleration of flow and the deviation in wind angle across the site. Data were extracted from the CFD model, from the grid cell containing the 10 m height level at the location of the on-site meteorological equipment.

Comparative hourly on-site meteorological data from the ultrasonic anemometer were extracted from the meteorological database for periods when measured off-site wind directions were within +/- 5° and wind speeds were within +/- 0.5 m s^{-1} of the data specified as upwind boundary conditions for each of the CFD simulation periods. Each set of measured hourly meteorological data was averaged to allow a direct comparison with the CFD data; the results are shown in Figure 2.

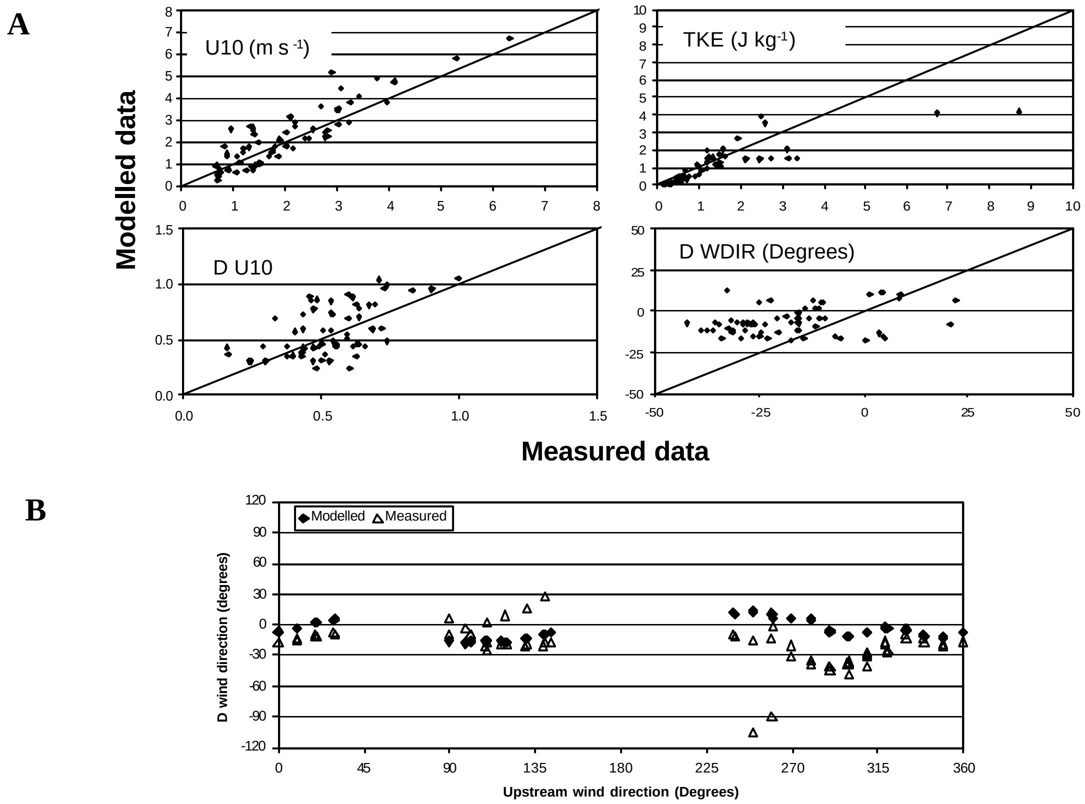

*Fig. 2; Comparison between measured on-site meteorological data and calculations from the CFD model showing **A**: scatterplots of measured and modelled data and **B**: the variation in the deviation in wind direction (D WDIR) with upstream wind direction.*
Note: D U 10= on-site wind speed / upstream wind speed (at 10 m)
D WDIR= on-site wind direction - upstream wind direction

The data in Figure 2 show a good correlation between the measured and modelled TKE data, with an R^2 value of 0.72. The modelled TKE data also closely matched the magnitude of the measured data below 2 J kg^{-1}, though the model tended to both under and over-predict TKE values above this value. The over-prediction corresponded to periods when wind speeds were above 8 m s^{-1}. It is therefore likely that during such periods the CFD model may over-predict turbulence somewhat and thus under-predict air concentrations.

Linear relationships were also found in Figure 2 between the modelled and measured values of on-site U_{10} and the ratio of downwind wind speed to upwind wind speed (termed D U10), a measure of the deceleration in wind speed caused by the site buildings. However, the comparison between the CFD predictions of the variation in wind direction between the upstream and on-site measurements (termed D WDIR) showed a considerable scatter. A detailed comparison of trends in D WDIR with wind direction measured at the Sellafield meteorological station is also shown in Figure 2. This showed that the CFD model estimated the trends in D WDIR well, in particular the veering in wind direction between 0-40^o and the variability found between 270^o and 360^o.

Comparison of the CFD modelling with wind tunnel data

The dispersion estimates from the CFD model, determined for the input parameters specified in Table 1, were compared with wind tunnel data collected along a centreline transect downwind of the area source. In addition, vertical and crosswind profiles were compared at a location corresponding to the position of the on-site meteorological measurements (235 m downwind of the source).

Figure 3 shows the comparison between the wind tunnel data, for simple and detailed building models, and the CFD data for the baseline case (see Table 1). The ranges of data from the sensitivity trial are shown as vertical error bars. The wind tunnel data collected for the two sets of building models illustrate the same pattern of reducing uncertainty with distance from the source as found in the CFD sensitivity trials (Table 2). The magnitudes of the coefficients of variation, due to the use of differing building complexities, that were measured in the wind tunnel were well matched by CFD model, with values of 0.25 (CFD) and 0.30 (wind tunnel), in the near-field, reducing to values of 0.05 (CFD) and 0.03 (wind tunnel) at 395 m.

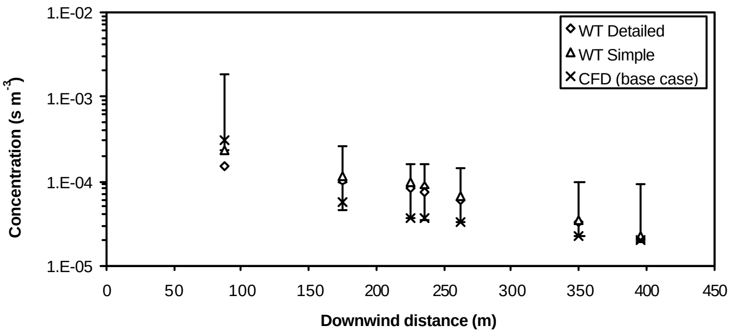

Fig. 3; Comparison between wind tunnel measurements (WT) of downwind centreline air concentrations (normalised by release rate) with baseline data from the CFD model. Error bars show the range of data from all the CFD sensitivity tests listed in Table 1.

The centreline concentrations modelled in the wind tunnel at 95 m, 350 m and 395 m were well matched by the CFD model, run using the baseline parameter set. However, the numerical model estimated concentrations that were approximately a factor of two lower than those determined in the wind tunnel at downwind distances of 175 – 262 m. A comparison of the standard deviations of the plume in the vertical and crosswind directions (σ_z and σ_y), at 235 m, illustrated that higher rates of dispersion were estimated by the numerical model (σ_z = 47 m, σ_y = 40 m) than the physical model (26 m for both σ_z and σ_y).

Figure 3 also compares the wind tunnel results with the range of concentrations predicted by the CFD model for the simulations listed in Table 1. These data show that the majority of the wind tunnel measurements were within the range of data from the CFD model, though it should be noted that the range of predictions from the CFD model was strongly influenced by the selection of turbulence model (Table 2).

An analysis of the Normalised Mean Squared Error (NMSE) between the CFD and wind tunnel models was undertaken to evaluate each of the CFD simulations (Figure 4). These data illustrate that attempts to find a best fit between the CFD and wind tunnel data were location specific for many parameters. For example, reducing the roughness length improved the comparison between the models when vertical and crosswind profile data were considered (at 235 m downwind) though such effects were not apparent when centreline data were considered. Improvements in the performance of the model were found when a second-order numerical scheme was applied, that were likely to be due to a reduction in numerical diffusion in the CFD model. However, the use of the k-L or k-diffusion turbulence models were found to consistently increase NMSE values, showing that the k-epsilon model, applied in the baseline simulations, provided the closest agreement with the wind tunnel data.

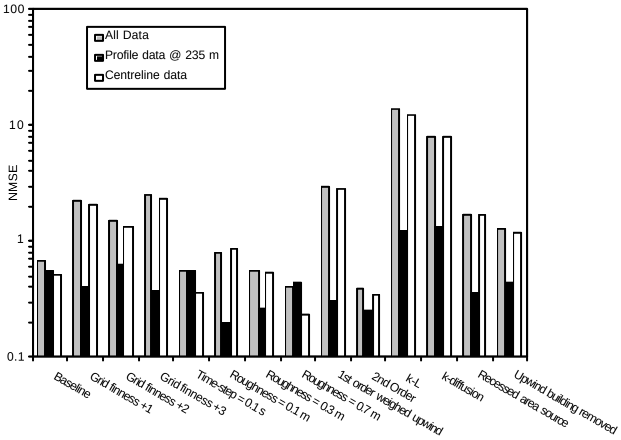

Fig. 4; Normalised Mean Squared Error (NMSE) of each of the CFD simulations when compared with the wind tunnel data. The entire dataset has been considered (All Data) as well as subsets corresponding to the vertical and crosswind profiles (at 235 m downwind of the source) and the centreline transect.

CONCLUSIONS

The CFD model *"Fluidyn-PANACHE"* was found to provide realistic estimates of near-surface level on-site meteorology and atmospheric dispersion through comparisons with monitoring data and wind tunnel experiments. The concentrations predicted by the numerical model were found to be particularly sensitive (by more than a factor of 5) to the specification of turbulence model, with the k-epsilon model providing dispersion estimates that were closest to the wind tunnel data. Uncertainties in wind tunnel and numerical modelling of local dispersion from an area source on a complex site were found to be highest close to the source and to decline with distance from the source due to mixing of the plume. Consequently, consideration of detailed fine scale features in either model was only found to be necessary to estimate dispersion in the near-field (less than 100 m from the source in this study).

REFERENCES

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