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MODITIC WIND TUNNEL EXPERIMENTS

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Abstract: An extensive series of experiments was conducted in the EnFlo wind tunnel to investigate the behaviour of dense gas emissions in complex flows and provide data for evaluating dispersion models capable of handling gravitational effects. The reference points were passive and dense gas dispersion on level terrain, for which ample data already existed. Increasingly complex scenarios were studied, commencing with a two-dimensional hill, then a simple array of 4 identical obstacles, a more complex, irregular array of 14 obstacles and finally an urban area (central Paris at 1:350 scale). The research treated continuous and finite duration emissions of either air, carbon dioxide or a mixture of the two into a neutrally stable simulated atmospheric boundary layer.

Key words: *MODITIC, dense gas dispersion, wind tunnel modelling*

INTRODUCTION

The objective of the MODITIC project was to conduct a systematic study of the transport of neutral and heavier-that-air gaseous chemicals in complex urban environments. In support of this overall aim an extensive series of experiments was conducted in the EnFlo ‘meteorological’ wind tunnel at the University of Surrey (UK) to generate data for evaluating dispersion models and to aid understanding of the underlying physical processes.

Project planning identified six scenarios, the aim being to ensure gradual progress in complexity that, in turn, would lead to progress in understanding and computational capability, namely:

1. A flat surface
2. A two-dimensional hill
3. A two-dimensional back-step
4. A simple array of obstacles
5. A complex array of obstacles
6. An urban area (central Paris).

Each of these categories was further sub-divided by wind direction, source conditions and measurement requirements. Use was also made of relevant previous EnFlo work, including the PERF project that studied dense gas dispersion in neutral and stable boundary layers (Robins et al., 2001a & b), the DAPPLE studies of dispersion in central London (e.g. Wood et al., 2009) and the DYCE project that investigated inverse modelling for identifying source strength and location (Rudd et al., 2012).

This paper describes the methods use in the wind tunnel simulations, the scaling criteria, the overall strategy, the experiments undertaken, and hence the content of the resulting data-base. Some results are presented and discussed from the simulations of dispersion in central Paris - other examples are to be found in the accompanying MODITIC papers, to which this and the overview paper act as an introduction.

EXPERIMENTAL METHODS

The wind tunnel

The EnFlo wind tunnel was designed specifically to simulate flow and dispersion processes in the atmospheric boundary layer, in particular where density differences are a key factor, either in emissions or the background flow. It is an open circuit wind tunnel with a 20m long working section, 3.5 by 1.5m in cross-section, the capability to heat and cool the flow and the tunnel surfaces, and the ability to operate at low flow speeds of order 1ms^{-1}. Reference flow conditions are measured by two ultrasonic anemometers, one held at a fixed reference location and the other positioned as required. Temperature conditions are recorded by thermistor rakes in the flow and individual thermistors in each tunnel wall, roof and floor panel. Flow conditions through the inlet are also monitored, primarily to indicate the state of the inlet screens. The wind tunnel and all associated experimental equipment and instrumentation operate under full computer control, which allows un-manned and remote operation of the control software. All data collected, including a wide range of environmental and operational information, metadata and web-cam outputs are automatically archived.

Procedures

All velocity and turbulence measurements were made using a two-component Dantec laser-Doppler anemometer (LDA) system with a FibreFlow probe. Data collection durations were selected to control the standard error in the results; achieving a typical standard error in the longitudinal mean velocity of about 2%, and in the turbulence normal stresses between 5 and 10%. Plume concentrations were measured with Cambustion Fast Flame Ionisation Detectors (FFIDs), which respond to hydrocarbon concentrations and have a frequency response of order 200Hz. Small proportions of propane (of order 1%) were added to emissions and acted as the plume tracer. FFIDs were calibrated at regular intervals against standard mixtures of tracer-in-air. Data collection times were again selected to control the standard error in the results, achieving a typical standard error of about 2% in the mean concentration data with a 4 minute averaging time with the tunnel reference velocity at 1ms^{-1}. Positional accuracy was generally ±2mm, but considerably better following reset of the traverse position.

A standard source diameter of 100mm was used, the source installation extending to approximately 300mm below the tunnel floor and being packed with 3mm diameter beads and covered with a mesh in order to achieve uniform emission conditions; similar arrangements were used in the PERF dense gas dispersion studies (Robins et al., 2001a). In the majority of cases, emissions were either air or carbon dioxide with a trace amount of propane added, as discussed above. Mixtures of air and carbon dioxide were used in some experiments with the Paris model to obtain intermediate densities. A thermal mass-flowmeter and flow-control system was used to regulate emission rates.

Similarity conditions

Neutral boundary layer simulation does not impose any relationships between the wind speeds in the tunnel and at full scale, all that is required is that certain Reynolds number constraints are satisfied to ensure that the surface is fully rough and the flow around buildings Reynolds number independent. These conditions were indeed met. However, scaling of buoyant plume dynamics implies similarity of three parameters (a density ratio, a velocity ratio and a Richardson number; Obasaju et al., 1998) and this leads to an explicit relation between wind speeds at model and full scale (suffices m and fs):

$$\varepsilon_u = \frac{u*_{fs}}{u*_m} = \frac{U_{ref-fs}}{U_{ref-m}} = \left(\frac{h_{fs}}{h_m}\right)^{1/2} = \varepsilon^{1/2} \tag{1}$$

where ε_u if the velocity ration, $u*$ the friction velocity, U_{ref} a reference wind speed, h and length scale (e.g. the mean block height) and ε the geometrical scale ratio. The time scale ratio, ε_T, is:

$$\varepsilon_T = \frac{t_1}{t_2} = \frac{H_1}{H_2}\frac{U_{ref2}}{U_{ref1}} = \varepsilon\varepsilon_u^{-1} = \varepsilon^{1/2} \tag{2}$$

It is sometimes assumed that the density ratio of itself is not a significant parameter away from the immediate vicinity of the source and similarity can be based on just two parameters, the dimensionless buoyancy and momentum fluxes from the source. That approach could be, but has not been, used here.

Strategy

The scenarios of interest were based on emissions that might occur, for example, in the catastrophic failure of a large tank of chlorine in an urban area. However, what could be simulated in the wind tunnel work was tempered by the constraints of the simulation criteria summarised above, which are particularly severe in the case of dense gas dispersion modelling where carbon dioxide is really the only gas that can be used at model scale. The wind tunnel work therefore adopted a strategy that used experimental conditions, controlled by the tunnel speed and the emission rate of carbon dioxide, that produced clear dense gas effects but, at the same time, led to plumes that remained well clear of the wind tunnel side walls. Results obtained in this manner could be used to test models that operate satisfactorily at model scale, in particular CFD-based approaches. However, some operational models only function at full scale and for these the similarity conditions described above were used to convert results from model to full scale. This generally led to emission conditions that were far out of range for the applicability of such models (emissions being far too great to be plausible). Some additional experiments were therefore carried out with considerably reduced emission rates to provide data for more realistic full scale conditions, accepting that dense gas effects would be reduced (but not absent) in such circumstances.

THE DATA-BASE

Existing results from the PERF (Robins et al., 2001) and DYCE (Rudd et al., 2010) projects were used to fill Scenario 1 data requirements, respectively for forward and inverse modelling. For the remaining scenarios, an extensive series of experiments was conducted in the EnFlo wind tunnel to provide data that, again, was suitable for assessing forward and inverse dispersion modelling capability. All the work discussed below made use of the same, neutrally stable boundary layer inflow.

The inflow

The inflow boundary layer was generated in a standard manner using vorticity generators (Irwin spires) and surface roughness. The details and resulting profiles of the mean inflow velocity, turbulent stresses and associated length scales are included in the data-base and summarised here: boundary layer depth, H = 1 m; friction velocity, $u^* = 0.055U_{ref}$; surface roughness length, z_o = 0.088 mm.

The two-dimensional hill

The hill shape was scaled from the WALLTURB ‘bump’, which itself was designed to generate a small separation bubble on the downwind face and for which high quality LES flow simulations already existed within the MODITIC group. Two source positions were used, one on the upwind face and the other on the downwind face, and initial experiments settled on U_{ref} = 1ms^{-1}, $Q_{(CO2)}$ = 100litre.min^{-1} as the operating conditions; the same emission rate being used for the neutral density (air) cases. Extensive, simultaneous LDA and FFID measurements made in all four cases (2 sources, 2 gases). Buoyancy effects in the dense gas plumes led to local flow deceleration near the upwind source and acceleration near the downwind source. The associated plume showed significant upwind spread and greatly enhanced lateral spread (relative to the neutral density cases).

The two-dimensional back-step

The back-step was formed by removing the downwind section of the hill model, separating the two parts at the crest. This gave a step aspect ratio (width, W, to height, h) of just 10, which was clearly too small as it implied that the length of the recirculation region, L_R, formed downwind of the step was similar in magnitude to step width (3m). The floor level downwind of the step was therefore built-up to reduce the step height to 0.1m, increasing W/h to 30 and implying that $W/L_R \sim 5$. The source was located with its centre 0.1m from the step. Experiments were conducted with the floor downwind of the step either smooth or covered in the roughness elements that were used to simulate the approach flow boundary layer. The reference speed and emission rate were kept at the values used with the hill model. The most dramatic results were seen in the mean concentration field. In comparison with the neutral density plume, the heavier than air plume was much shallower, as expected, but essentially two-dimensional, spreading across the full extent of the recirculation region. Vertical turbulence intensities were greatly reduced and associated vertical mass fluxes much smaller, in keeping with the reduced rate of vertical spread. Differences between results over the smooth and rough wall were very small. Variants on the basic experiments with the back-step saw two-dimensional arrays of obstacles installed on the downstream surface. These comprised three rows of 0.11m cubes, separated laterally and longitudinally by 0.11m. In the first case, the obstacle array commenced at 0.8m from the step and downstream of the recirculation region; in the second at 0.36m and well within the recirculation region.

The simple array of obstacles

The small array comprised four h = 110mm cubes in an aligned 2x2 array, with a separation of 110mm. Experiments were carried out with the array either aligned normal to the approach flow, defined as 0˚, or at 45˚. Sources were located upwind, on the centre line, or upwind and to one side (y = 1.5h). Initial tests with the array at 0˚ examined the effect of carbon dioxide emission rate on the plume width around and downwind of the array. The concentration field was judged to be too wide relative to the tunnel cross-section with Q = 100litre.min^{-1}, U_{ref} = 1ms^{-1}, as in the hill experiments, and a lower emission rate of 50litre.min^{-1} was therefore adopted in this work and also that with the complex array. Measurements were made both upwind and downwind of the array. The most obvious difference between the air and carbon dioxide plumes was that the former passed through the array whilst the latter were deflected around it.

The complex array of obstacles

This model comprised fourteen rectangular blocks of differing sizes arranged in an irregular manner, all constructed from 110mm cubes. 'Tree' simulators were used in some of the experiments to study their impact on dispersion behaviour. The array was aligned either normal to the approach flow, defined as 0˚, or at 45˚. Sources were located within the array, upwind on the centre line, and upwind to one side at y = 3h; the emission rate were again 50litre.min^{-1} with U_{ref} = 1ms^{-1}. Measurements were made within the array and downwind from it.

Data for inverse modelling studies

Four FFIDS were operated simultaneously to generate long concentration time series that could be used in inverse modelling studies. Experiments ran for 16 minutes, with the emission initially off, then on and, finally, off again so that concentrations fell to background levels by the end of the whole period, providing a period of approximately 13 minutes of steady emission. Both the raw data, sampled at 400 Hz, and equivalent full scale data were made available to test the ability of inverse modelling systems to detect the location of the source, the emission rate and the emission profile. A geometrical scale of 1:200 was assumed in converting the results to full scale, the data being first down-sampled to 100 Hz.

The urban area (central Paris).

By far the greatest effort was devoted to simulations with the Paris model. A geometrical scale of 1:350 was selected in order to encompass a sufficient area of central Paris, from the Arc de Triomphe, along Avenue des Champs Elysees to the Grand Palais, and an equivalent distance on either side. The model comprised almost a hundred blocks, each with a flat roof, a great simplification of the real topography but one judged to be fit for purpose, given that whatever was used in the wind tunnel work had to be reproduced in the numerical modelling. The 1:350 scale implied that the ratio of full scale and model wind speeds was $\sqrt{350}$ = 18.7, so that the standard 1ms^{-1} wind tunnel reference speed used in the bulk of MODITIC wind tunnel work was equivalent to 18.7ms^{-1}, or more usefully 9ms^{-1} at 10m height and 11.6ms^{-1} at the average building block height of 27m. and very large emission rates are required at this full-scale wind speed to ensure significant dense gas effects. Both the reference and emission velocities scale by 18.7 and the basic experimental conditions (Q = 50litre.min^{-1}, U_{ref} = 1ms^{-1}) were unrealistic when scaled. Additional experiments were carried out with reduced emission rates and lower tunnel speeds to provide data for more realistic full scale conditions - dense gas effects were much reduced but not absent in these cases. Experiments were conducted with both continuous and short duration emissions.

Three source locations and associated wind directions were identified: one in the Avenue des Champs Elysees (S1) and two in the narrow side streets on either side (S2, S3). A wind direction was associated with each: 300˚ for S1, 220˚ for S2 and 40˚ for S3. Three types of concentration measurements were made: in-street at z = 10mm, lateral profiles (cross-wind) above roof level, at z = 120mm, vertical profiles from street level. In contrast to the other scenarios, wide ranges of emission rates (1 to 50litre.min^{-1}), emission density ratios relative to air (1 to 1.52) and reference flow speeds (0.6 to 2.0 ms^{-1}) were examined. Dense gas effects were found to be very strong with the carbon dioxide plume almost entirely confined to the street network, with significant upwind and lateral spread apparent. In all the cases studied, the downwind carbon dioxide plume was much shallower than the equivalent air plume (Figure 1a), though upwind spread ceased at sufficiently low emission rates. The runs with air at different emission rates produced concentration results that scaled with emission rate, as expected of a passive plume (Figure 1b). Passive gas dispersion from S2 and S3 followed the empirical relation between maximum round level concentration and separation found in the DAPPLE work (Woods et al., 2009) but the confinement of the Av. Champs Elysees led to a slower decay rate for S1, a rate that reduced even further as density effects became more pronounced (i.e. with increasing source Richardson No.).

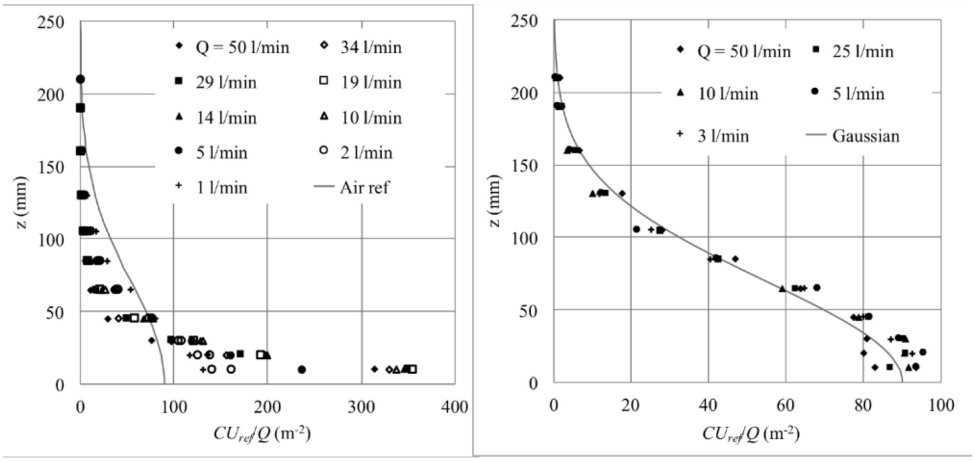

Figure 1. Vertical profiles of normalised mean concentration measured at 1000mm downwind (in Av. Champs Elysees) from source S1. 1a, left: Results for a range of emission rates compared with the results for an air plume; 1b, right: Results for air emissions fitted by a Gaussian profile. The reference speed was 1ms^{-1} in all cases.

CONCLUSIONS

A detailed and comprehensive data-base has been prepared from wind tunnel simulations of non-buoyant and dense gas dispersion in conditions of increasing geometrical complexity. Data were compiled as a set of text and Excel files, together with accompanying meta-data. The prime use of this data within the MODITIC project was to examine the performance of a range of forward and inverse dispersion models, though the results also provided insight into dense gas dispersion behaviour. Future research could most usefully: repeat the present work in stable and unstable boundary layers; study the relation between upwind and lateral spread near the source and the emission properties (geometry, Richardson number and velocity ratio); the adaptation of street network dispersion models to dense gas emissions through a Richardson number dependent entrainment velocity.

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