Cloud dispersion in complex flows

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1 INTRODUCTION

Recent experimental work, say in the last 50 or so years, with short duration emissions can be conveniently divided between field work in the USA at the US Army Dugway Proving Ground and in Oklahoma City, and wind tunnel simulations in Europe. Both have used urban or urban-like sites and open terrain. A full list of references to this work, summarised below, is to be found in [6].

Experiments at the Dugway site, an open area of low surface roughness, used passive emissions from a source at height 2.5m and were conducted over downwind fetches between about 200 and 1200 m under a wide range of atmospheric conditions, from very unstable to moderately stable stratification from Ensemble sizes varied from order 20 in the early work to order 200 in the later work, where off-centreline data was used to increase the ensemble size. Relevant work in Oklahoma City took place in 2000. Data from 10 fast-response tracer samplers were used to examine crosswind and along-wind spread, the decay of tracer concentrations, and the retention of tracer. Three to six puffs were released in each of ten experimental periods and dispersion studied over fetches up to about 1 km. A detailed wind tunnel study using a 1:300 scale model of the Oklahoma field site was also carried out, using emission durations between 0.3 and 2s and reference velocities in the range from 2.4 to 4.2ms^{-1}. The experiments investigated the validity of standard puff scaling parameters, using ensembles of order 200 to 400 to ensure good convergence of statistical properties.

The work described here begins with Robins and Fackrell [1], a wind tunnel study of the dispersion of short duration, ground level emissions in a deep turbulent boundary layer, modelling the atmospheric boundary layer. This focused of comparison with the analytical theory developed by Chatwin [2]. Next, we have the DAPPLE project that ran from 2002 to 2010 and treated short range dispersion in central London [3]. In addition to a series of 15-minute releases in the field, a set of wind tunnel experiments was carried out to examine cloud dispersion and the causes of variability. Some simple correlations were developed for cloud travel time, rise and fall time and advection speed, as functions of fetch in the near field. Further wind tunnel cloud dispersion studies were carried out in the DIPLOS project, where the underlying geometry was a regular array of cuboids. DNS simulations of these experiments have been reported in [4] and shown to agree well with the wind tunnel data. Most recently, wind tunnel studies of cloud dispersion in the presence of a surface mounted cube were reported in [5], the ADMLC project.

1.1 Objectives

In this paper, we address the short-range dispersion of pollutant clouds emitted from elevated sources, using wind tunnel data from the projects referred to above [1, 3, 4, 5]. The objective is to use the concentration measurements to describe the structure of the dispersing clouds and to develop simple scaling rules that reduce the data to universal forms and can therefore be used in a predictive manner. The methodology follows that described in [6].

First, a comment on the structure of dispersing clouds. Where the emission duration exceeds the time of flight ($T_s > T_{flt}$), the cloud has a plateau region and we might term this as being plume-like (but with end regions of course). Further downwind, where $T_{flt} \gg T_s$, the structure becomes puff-like as longitudinal spread has fully eroded the plateau region. How quickly this is established depends on the level of ambient turbulence and shear, and most importantly the emission duration. Between the two limiting regions, there is an intermediate regime, where the form should perhaps be simply referred to as a cloud.

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2 DISPERSION STUDIES

[1] demonstrated the key difference between the puff and plume regimes, characterised cloud structure and development and showed their alignment with Chatwin theory [2]. We now extend the empirical side of that work to complex flows in the presence of, first a single large cube and, second an array of obstacles.

2.1 Cloud dispersion around a cube

The work was carried out in a neutrally stable boundary layer, simulated by use of Irwin spires and a rough surface. The friction velocity and roughness length were $0.055U_{ref}$ and $0.001H$, respectively, where U_{ref}, the reference speed, was $2ms^{-1}$ and H, the boundary layer depth, 1m.

The cube, side $h = 0.24$m, was located with the centre of its base at the coordinate origin and, in the work described here, was orientated so that the oncoming flow as normal to the front face. Emissions were made from a source of height 0.06m, located 0.6m up of the cube centre. Large numbers of clouds were released in each case studied to ensure low standard errors in derived results, such as dosage; typically, the number of cloud emissions in an ensemble, N, was $N = 200$-399 for an emission time, $T_e = 0.05$s; 170-399 for 0.1s; 150-200 for 0.25s; 120-250 for 0.5s; 100-120 for 1.0s. These emission times allowed the full range of cloud behaviour to be observed.

Concentration measurements were made with either a Cambustion HFR400 or HFR500 Fast Flame Ionisation Detector (FFID) that had a spatial resolution of the order of 1 mm and a frequency response of about 200 Hz, the output being sampled at 400 Hz. Concentrations, C, and dosages, D, were made dimensionless as $C*$ and $D*$:

$$C^* = \frac{CU(h)h^2}{q} \qquad D^* = \frac{DU(h)h^2}{T_e q}$$

where h is the building height, q the tracer emission rate and T_e the emission duration.

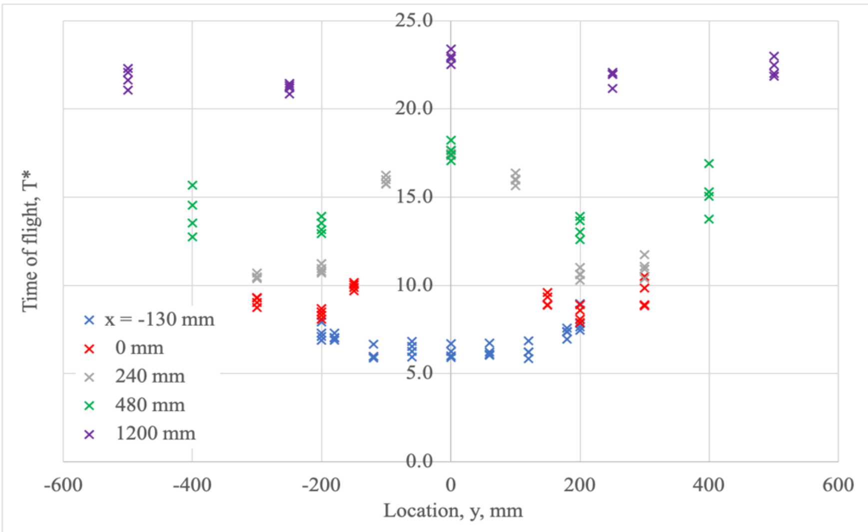

Figure 1. The dimensionless travel time, T, for the 2 ms^{-2} experiments.*

Fig. 1 demonstrates the distortion of the cloud as it passes around the cube and moves downwind. It shows mean time of flight results, determined from moments of the ensemble averaged concentration time series in clouds of emission durations: 0.1, 0.25, 05 and 1s. The profile at $x = 240$mm passes through the near wake of the cube and clearly shows the hold-up of the clouds in that region. This is equally pronounced at $x = 480$mm, but has largely disappeared at the furthest downwind profile, $x = 1200$mm. No distinction in emission duration has been made in plotting the results. $T*$, has been adjusted to remove effects of the initial time origin offset, t_o, and the duration of the emission, T_e.

$$T^* = \frac{U_{ref}\left(T_{flt} - t_o - T_e/2\right)}{H}$$

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A useful empirical formulation for the near wake residence time is that used in ADMS [14]. Time series from the near-wake region, shown in Fig. 2, confirm that this holds in the cases here. The figure shows results at two reference speeds and two emission durations – concentrations have been normalised and profiles overlapped according to time of flight.

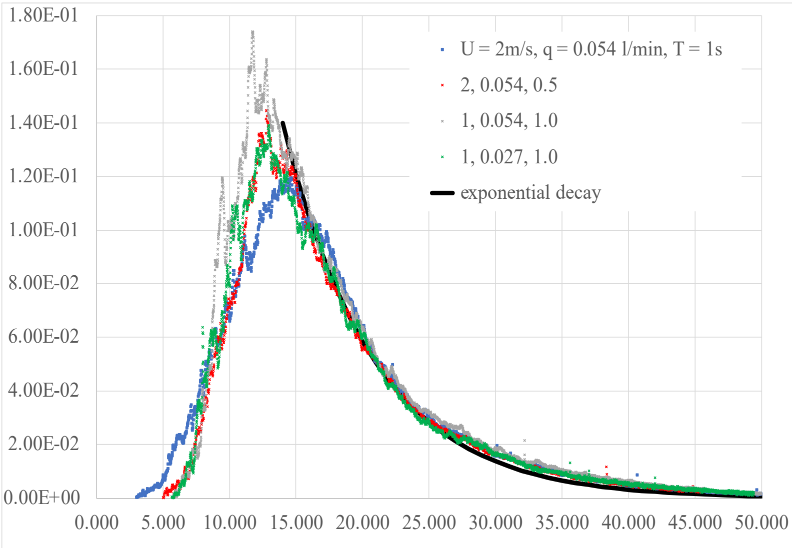

Figure 2. Normalised concentration time series from the near wake for a range of reference speeds, emission durations and emission rates. The thick, black line is the empirical exponential decay relationship from ADMS [7].

The dataset enables the relationship developed in [6] between dimensionless plume concentrations and cloud doses to be demonstrated for a much more complex flow, namely that:

$$D = C.T_e$$

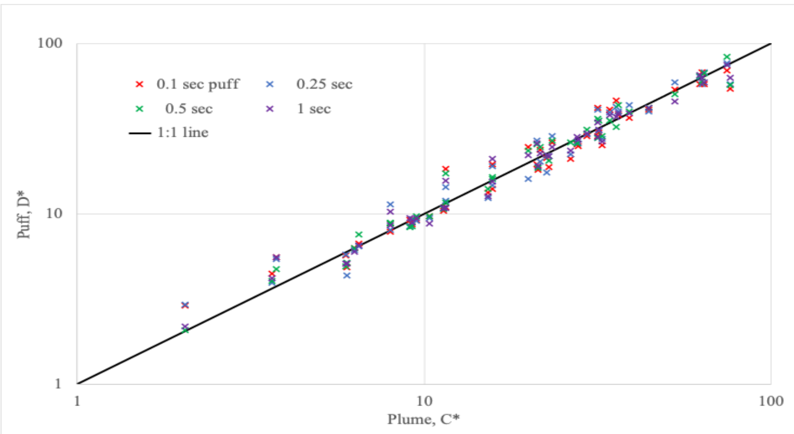

Figure 3. Scatter plot of dimensionless cloud dosage and plume concentrations.

2.2 Cloud dispersion in obstacle arrays

Finally, we show a further demonstration for a complex flow, this from the DIPLOS study [4], Fig. 4, using a large, regular array of cuboids. The source was at ground level at $x = y = 0$, diameter = h, the block height; the cloud release duration was T_e = 0.3s. Mean dosage profiles were formed from 47, 47, 49 individual runs, implying a standard error in the means of about 10%. The averaging time for the mean plume concentration was 150s, implying a standard error of about 5% in the central part of the plume.

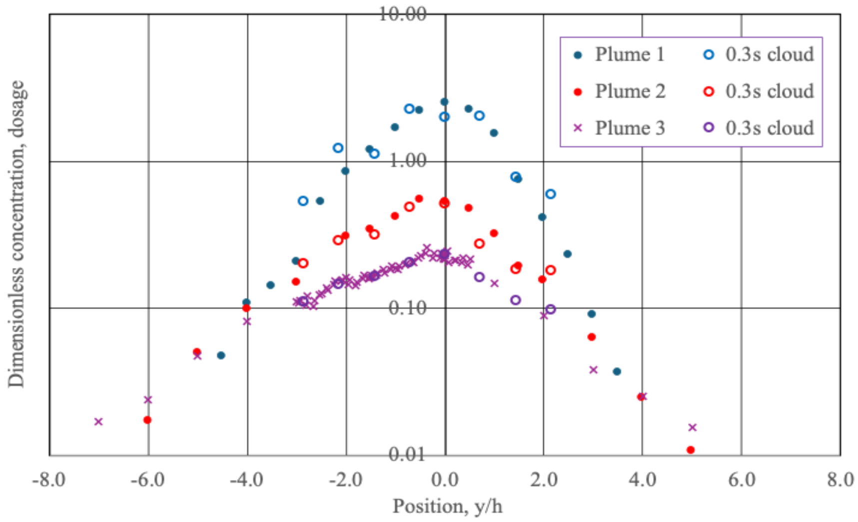

Figure 4. Lateral profiles of dimensionless mean concentration and dosage at x/h = 1, 7, 15, z/h = 0.5 in the DIPLOS array; h = block element height.

3 CONCLUSIONS

This work continued the theme of [6], demonstrating the correspondence between dimensionless cloud dosage and plume concentration in complex flows. The result provides a simple means of estimating dosage from a passing cloud from prediction of plume dispersion.

The work also demonstrated the distortion of pollutant clouds as they interact with obstacles. Here, the imposition of an additional time scale from the near wake has been highlighted.

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