Dispersion of Passive and Dense Plumes over a Step-Change in Wall Roughness

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1 INTRODUCTION

Most of the literature on atmospheric dispersion, to date, considers boundary layers with homogenous surface roughness morphologies. However, in many scenarios in nature this is not the case. For example, wind flow over farmland encountering an urban area or ocean winds blowing over a coastline. This discontinuity - or step-change - in surface roughness will generate an internal boundary layer (IBL) within the existing boundary layer as the flow adjusts to the new surface conditions. The IBL (from a smoother to a rougher case) is characterised by a region of more turbulent 'adjusted flow' close to the wall within the existing boundary layer that grows in height with downstream distance [1]. Given that IBLs are so ubiquitous, it is of interest to assess whether they have a significant impact on the dispersion phenomenon.

Currently, there is very little experimental work considering the effect of IBLs on dispersion in boundary layers. Recently, [2] and [3] have performed numerical studies using LES to model dispersion of a passive scalar released within an array of cuboids (which simulate an urban environment) immersed in an boundary layer . Thus, the work herein aims to study the effect of an IBL on the dispersion of both passive and dense gas plumes released both upstream and downstream to the newly-developed IBL.

2 METHODOLOGY

This experiment was performed in the EnFlo Tunnel at the University of Surrey, a suck-down atmospheric wind tunnel. The IBL was generated using the method detailed by [1]; a step-change in roughness length, with an upstream section of relatively smaller roughness length to a downstream section of higher roughness length. Passively buoyant (air) and dense (CO_2) plumes are released from a ground level point source in three different locations: 1m upstream from, 1m downstream from and at the step change location. An additional reference case was considered with no step change, so that the smaller roughness elements (i.e. the smaller roughness length here) extended the entire length of the tunnel. Time-resolved concentration measurements were taken via a single Cambustion HFR400 Fast Flame Ionisation Detector mounted on a 3-axis traverse (Figure 1). For brevity, only the case with the plume released upstream of the step change will be considered in this paper.

Concentration profiles were taken at seven streamwise locations, one vertical and two lateral (one within roughness sublayer, one within the log-law region), to observe the plume lateral and vertical growth rate as well as the behaviour of concentration within the plume, both in terms of its mean and higher-order properties. The experiment was carried out with three different sources: a 100mm diameter point source releasing air and CO_2 at a flowrate of 10L/min and a third case the same source diameter, with CO_2 but a higher flowrate (20L/min to increase the source's buoyancy flux). Given the large diameter of the source (100mm) it can be assumed that momentum effects are negligible in all cases.

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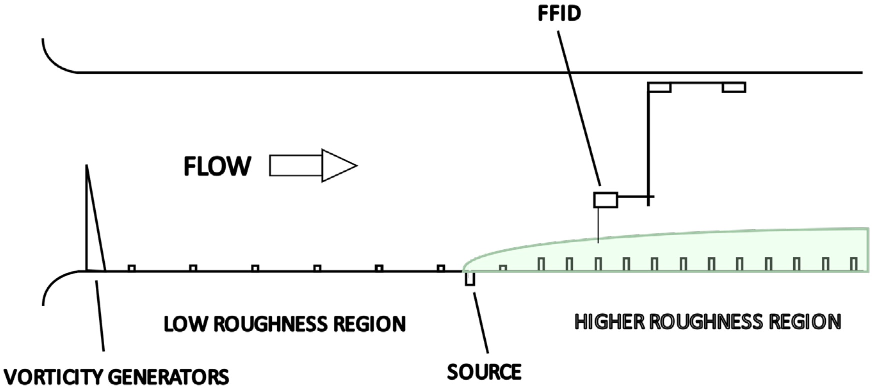

Figure 1: Diagram of EnFlo Tunnel test section showing the experimental setup.

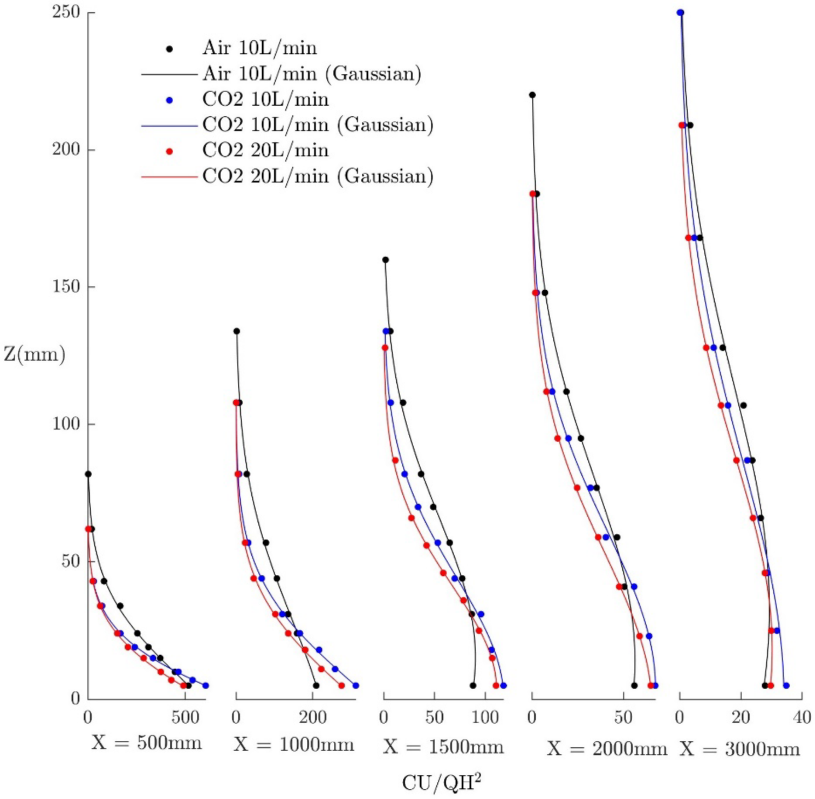

Figure 2: Vertical Profiles of non-dimensional mean concentrations at y = 0. Dots indicate a measurement point and lines show a best-fit single-peaked Gaussian curve. In this case, the step change is located approximately 1m downstream of the source which is defined at the origin.

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3 PRELIMINARY RESULTS

In figure 2, vertical profiles of mean concentration at five streamwise locations are shown. To note that the step-change is located at *X=995*mm. Mean concentration has been nondimensionalized as:

$$\frac{CU}{QH^2}, \tag{1}$$

where C is tracer concentration, U is freestream velocity (1.5ms^{-1}), Q is tracer flowrate and H is boundary layer depth (1m). A single -eaked Gaussian curve has been fitted to each vertical profile. Plume vertical spread, centreline location and maximum concentration can be extracted from this as the coefficients of the fitted Gaussian curves. While this curve generally appears to be a good fit for most profiles, at X = 1000mm it does not appear that the centreline of the plume is at Z = 0, suggesting that the plume does not strictly follow a pure Gaussian profile in vertical spread immediately behind the step-change. This is likely due to the initial growth of the IBL behind the step change changing flow properties only in the region closest to the surface, or a wall reflection from the ground-level source.

When comparing plumes of different densities, they follow expected behaviour both before and after the step change, with the denser plumes exhibiting a lower vertical spread. Despite having the same density, the lower buoyancy flux in the case of the higher-flowrate dense gas case has a significant impact, with this again showing a lower vertical spreading than the lower-flowrate case.

It is notable that the plume appears to show relatively little vertical growth in the region immediately behind the step change (X = 1000 – 1500mm), when compared to the regions immediately before and after this.

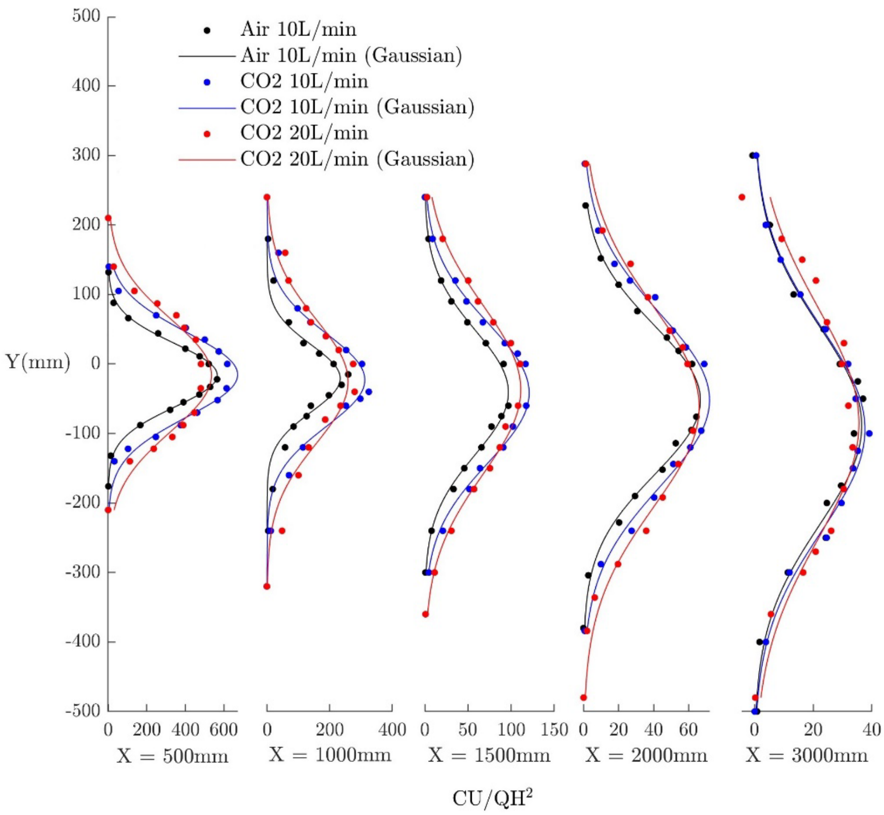

Figure 3: Lateral profiles of non-dimensional mean concentration at Z = 5mm (below the roughness height). As in figure 2, dots denote measured data and lines are a fitted Gaussian curve.

As with the vertical profiles shown in figure 2, Gaussian profiles have been fitted to lateral profiles of mean concentrations and show a good fit of the data. As expected, both downstream and upstream of the step

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change, the dense (CO_2) plumes show a greater lateral spreading, with the higher flowrate (i.e. the 20L/min plume) clearly having a significant impact, showing greater lateral extent when compared to the lower flowrate case.

The centreline of the vertical profiles appears to shift in the *Y*-negative direction with increasing streamwise distance. Laterally, this setup was symmetrical with all elements perpendicular to the flow, meaning that any lateral deviation is likely due to flow quality within the tunnel itself, local three-dimensional roughness effects, and vastly unrelated to the presence of the step-change.

From the width of the fitted Gaussian profiles, the plume appears to show a large increase in growth rate immediately behind the step change, in contrast to the lower vertical growth rate seen in figure 2. Ding [1] found that immediately behind the step change, a region of flow with a negative vertical velocity component existed. It is possible that this region acts as to 'squash' the plume downwards, decreasing its vertical growth rate, while increasing its lateral growth rate. Sessa et al. [2] noted similar behaviour, with lower vertical growth and greater lateral growth observed in this region.

Further work on this topic will examine the other two step change locations investigated and examine the fluctuating component of concentration.

References

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