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The influence of an obstacle on flow and pollutant dispersion in neutral and stable boundary layers

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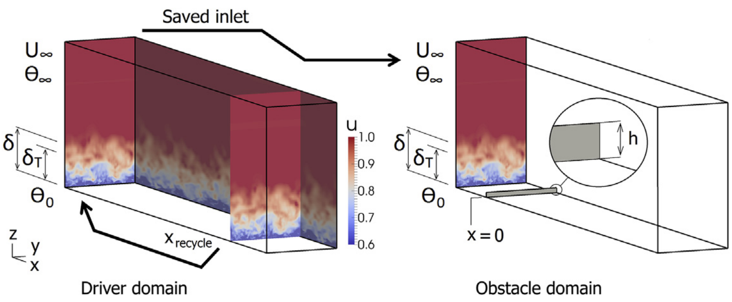
HIGHLIGHTS

- The combined effect of shear and buoyancy on dispersion behind a fence is examined.
- Stable turbulent boundary layers up to $Ri_{grad} = 0.2$ are generated by a recycle method.
- The fence affects concentrations up to at least 100 obstacle heights downstream.
- The decay of maximum velocity and temperature deficit is independent of stability.
- The decay in maximum concentration excess decreases appreciably with stability.

GRAPHICAL ABSTRACT



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ABSTRACT

Predicting pollutant dispersion in urban environments requires accurate treatment of obstacle geometry, inflow turbulence and temperature differences. This paper considers both the influence of thermal stratification and the presence of a single obstacle on pollutant dispersion in turbulent boundary layers (TBLs). Turbulent flow over a fence with line sources of pollutant in its vicinity is simulated by means of Large-Eddy Simulations. Separate 'driver' simulations are done to generate the inflow TBL for several levels of stratification. Using these inflow TBLs the flow development and pollutant dispersion behind the fence, up to 100 fence heights, h, is investigated. It is shown that the decay of velocity and temperature deficit is independent of stability, while the decay of Reynolds stress and concentration excess decreases with increasing stability. For neutral cases the influence of the obstacle is gone after approximately $75h$, while for stable cases near the ground the flow is still accelerated compared to the undisturbed case. The fence does cause a local reduction of stratification and thereby increased pollutant dispersion. However, neglecting the effect of buoyancy results in an underestimation of pollutant concentration by a factor 2.5 at $75h$ downstream of the emission source for the most stable case.

1. Introduction

Because of the global trend of urbanization the number of people living in urban areas compared to the number of people living in rural areas is increasing. This growth of urban

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environments also leads to an increase of pollutant emissions near populated areas. In order to quantify the health risks due to planned and existing emission sources there is an increasing demand for accurate predictions of urban air quality levels. Therefore, predicting the dispersion behaviour of pollutants in urban environments is of great interest. However, modelling the local flow field in urban areas is a challenging task because there are several factors that control it, e.g. the obstacle geometry, the character of the approaching turbulent boundary layer (TBL), as well as temperature differences. The review article by Barlow (2014) gives a clear overview of our current understanding of the urban boundary layer (UBL) showing that buoyancy effects in the roughness sub-layer are still poorly understood. Tominaga and Stathopoulos (2013) review the current modelling techniques for pollutant dispersion in the UBL; most pollutant dispersion studies do take into account obstacle geometry, but the correct treatment of inflow turbulence and thermal stratification is just as important for reliable results. Still, in order to simplify such flow and pollutant dispersion problems two practical approaches seem natural:

1. Neglect the presence of obstacles.
2. Neglect the effect of thermal stratification.

The first approach is plausible when the location of interest is at a large distance from obstacles. The latter approach can be justified by assuming that the flow becomes neutrally buoyant due to enhanced mixing by turbulence induced by the obstacle geometry. The objective of the current study is to investigate if and when these simplifications can be made. Use is made of Large-Eddy Simulations (LES) to simulate the flow and dispersion around a single prismatic obstacle. Realistic turbulent equilibrium inflow TBLs at friction Reynolds number, $Re_\tau = u_\tau \delta / \nu$, of 1950 are generated to investigate how these TBLs respond to the perturbation by the obstacle.

1.1. Case of interest

The obstacle studied here is a two-dimensional fence characterized by a small w/h ratio and an infinite l/h ratio, where w is the obstacle width, h the obstacle height and l the obstacle length. Spanwise line sources of passive tracers are located in its vicinity. This set-up resembles in idealized form the case of an undisturbed (low roughness) TBL approaching a noise barrier located next to a highway. The simple geometry of a noise barrier is of interest because it is the first obstacle that will influence the dispersion of pollutant emitted by traffic along a highway. Besides that, it is one of the most elementary ways to perturb a boundary layer, which could give insight in how perturbations of the TBL develop. Due to its two-dimensional geometry the flow is statistically homogeneous in the spanwise direction, which allows for periodic boundary conditions to be used.

Several wind tunnel studies have been reported on neutral turbulent flow over two-dimensional obstacles. Counihan et al. (1974) measured the flow behind a riblet in a TBL that was six times higher than the obstacle. They considered the difference with the undisturbed flow: $\Delta\overline{u} = \overline{u}_{obstacle} - \overline{u}_{flat}$, which can be negative (deficit) or positive (excess). In addition, they proposed a model for the velocity and turbulence deficit based on self-similarity of the wake. Castro (1979) compared this model to his experimental results, which showed reasonable agreement for the velocity and turbulence deficit up to 30 obstacle heights downstream. However, the model is incapable of predicting the flow further downstream. Schofield and Logan (1990) collected data from multiple experiments on high Reynolds number shear flows distorted by an obstacle smaller than the TBL height. They confirm the conclusion of Castro (1979) that the inner region adjusts quicker to the distortion by the obstacle than the outer region.

Experimental data on flow over surface-mounted obstacles in stably stratified flows are sparse. Kothari et al. (1986) performed wind tunnel measurements on three-dimensional surface obstacles in a TBL with weak thermal stratification. Their results show a temperature excess up to 60h downstream of the obstacle, while the velocity deficit disappears after $7.5h - 10h$. In addition, they developed a model for the temperature wake behind three-dimensional obstacles in weakly stratified TBLs. Ogawa and Diosey (1980) did wind tunnel experiments on a two-dimensional fence in stable and convective TBLs. The measurements were only done up to 13.5h downstream of the fence, because the interest was in the recirculation length.

Several numerical simulations of flow past a two-dimensional obstacle under neutral conditions have been reported. Orellano and Wengle (2000) performed LES and DNS of a fence in perpendicular approaching flow. Kaltenbach and Janke (2000) and di Mare and Jones (2003) investigated the fence geometry for several wind angles with LES. Abdalla et al. (2009) compared the flow over a riblet ($w/h = 1$) and the flow over a forward-facing step by means of LES. All of these numerical investigations considered approaching boundary layers with a height smaller than the obstacle, which does not resemble atmospheric conditions. Furthermore, the effects of thermal stratification are not accounted for. Only Trifonopoulos and Bergeles (1992) reported results for a two-dimensional obstacle under stable conditions using a model based on the Reynolds-averaged Navier–Stokes (RANS) equations. They showed reasonable agreement with experimental results from Ogawa and Diosey (1980). However, results were only given up to 10h downstream of the obstacle.

Taking into account this paucity in available data the scope of the current study is:

1. A single two-dimensional fence subject to an approaching equilibrium TBL much larger than the fence.
2. A domain that extends up to 100h downstream of the fence to investigate both the near wake and the wake development inside the TBL.
3. Three levels of stable stratification together with the neutral case.
4. Spanwise line sources of passive tracers in the vicinity of the fence.

The paper is set up as follows: In Section 2 the numerical methods are explained, after which in Section 3 the details on the flow configuration, computational mesh and boundary conditions are given. The results for the inflow TBLs are discussed in Section 4. Subsequently, the results for the obstacle and flat cases are discussed in Section 5. Finally, conclusions are given in Section 6.

2. Numerical method

The cases were simulated by means of Large-Eddy Simulation (LES). Firstly, TBLs were generated in separate 'driver' simulations using a recycling method. The inlet plane was saved for each time step and subsequently used as inlet condition in the corresponding pollutant line source simulations with and without the obstacle present. We will refer to those simulations by 'obstacle' and 'flat', respectively. Fig. 1 visualizes the procedure.