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On the simulation of thick non-neutral boundary layers for urban studies in a wind tunnel

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ABSTRACT

Stable and convective boundary layers over a very rough surface have been studied in a thermally-stratified wind tunnel. Artificial thickening by means of spires was used to accelerate the formation of a sufficiently deep boundary layer, suitable for urban-like boundary layer flow and dispersion studies. For the stable boundary layer, the methodology presented in Hancock and Hayden (2018) for low-roughness offshore surface conditions has been successfully applied to cases with higher-roughness. Different levels of stratification and roughness produced modifications in the turbulence profiles of the lower half of the boundary layer, but little or no change in the region above. Data for a stronger stability case suggested that the employed spires may not be suitable to simulate such extreme condition, though further studies are needed. The results were in reasonably good agreement with field measurements. For the convective boundary layer, great attention was given to the flow uniformity inside the test section. The selection of a non-uniform inlet temperature profile was in this case found not as determinant as for the stable boundary layer to improve the longitudinal uniformity, while the application of a calibrated capping inversion considerably improved the lateral uniformity. The non-dimensional vertical profiles of turbulent quantities and heat fluxes, did not seem to be influenced by roughness.

1. Introduction

Atmospheric stratification is due to variations in temperature and humidity with height. A near-adiabatic profile of potential temperature is present in a neutrally stratified atmosphere, where vertical motions of fluid particles are neither amplified nor damped, while an unstable (or convective) stratification is characterised by an enhancement of vertical movements and stable flows are characterised by attenuated vertical motion. Stability affects the atmospheric boundary layer (ABL) depth and structure as well as velocity, temperature and turbulence profiles within it.

Non-neutral stratified conditions are frequently found in atmospheric flows. The data analysis by Argyle and Watson (2012) indicated that non-neutral conditions were present for 70% of the time in two UK offshore wind farm sites. In urban areas, a large predominance of non-neutral atmosphere was documented, for example, by Wood et al. (2010) over the city of London, UK, with convective cases happening three times more frequently than stable. Nevertheless, most of the experimental and numerical studies focus on neutral flows due to the difficulties in studying atmospheric stratification.

Some experimental studies involving stratified boundary layers (BLs) have been reported so far. The facilities used for this purpose range from water tanks (e.g., Willis and Deardorff, 1974, who simulated a convective boundary layer, CBL, by heating the water from the bottom), saline tanks (like the one in Hibberd and Sawford, 1994, in which the stratification was generated by differences in the salinity level instead of temperature) to wind tunnels. As pointed out by Fedorovich (2004), the first two techniques "omit or treat rather indirectly the effects of wind shears on the turbulence regime", effect that may acquire even more importance when dealing with very rough surfaces, such as urban environments. Thermally-stratified wind tunnels specifically designed for the simulation of stable (SBL) and convective (CBL) boundary layers have been built in the past decades. See Meroney (1998) for a review of the main requirements for CBL simulation.

One approach to simulating non-neutral flows in a wind tunnel relies on the development of the BL by means of floor cooling or heating, without any mechanical thickening device. Despite being conceptually simple, such a method requires a very long development region for thick BLs. For example, Arya and Plate (1969) managed to get a 70 cm thick SBL after 24 m of growing over a cooled aluminium plate, while Ogawa et al. (1985) obtained a depth of only about 20 cm after 12 m on a wind tunnel of similar length. Devices used to artificially thicken the BL include bidimensional blocks or fences, but methods like the ones

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described by Counihan (1969) and Irwin (1981) for neutral boundary layers (NBLs) give a better control of the BL thickness and turbulence characteristics. The first consists of a castellated barrier wall coupled with a set of quarter-elliptic vorticity generators, while the second makes use of triangular spires, easier to manufacture. Both are normally associated with roughness elements over the floor chosen to provide an aerodynamic rough surface with the desired flow characteristics. Despite being normal practice in NBL simulations, these methods have been rarely used for non-neutral BLs. Robins et al. (2001) employed Counihan's method for the generation of a thick SBL while Hancock et al. (2013), Hancock and Pascheke (2014), Hancock and Hayden (2016) and Hancock and Hayden (2018) used Irwin's spires to develop CBLs and SBLs suitable for low-roughness offshore BL conditions. In the latter two papers, in particular, a method to simulate artificially thickened SBLs was deployed, at least for weak to moderate stability levels and no overlying inversion.

The effect of roughness in a SBL was studied in the wind tunnel by Williams et al. (2017) and Ohya (2001), who compared his results with the smooth surface simulations by Ohya et al. (1997). Both concluded that turbulence characteristics remain substantially similar, with small differences attributed by the former to changes in local stratification. In their work different levels of stability were considered, ranging from weak to very stable. The transition between weak and strong stability conditions were found by Ohya et al. (1997) and Ohya (2001) to happen at a value of the bulk Richardson number equal to 0.25 for both smooth and rough surfaces, while Williams et al. (2017) reported two different values, both of them lower than Ohya's results (0.10 for the smooth surface and 0.15 for the rough one) with turbulence stress scaling with wall shear only before the transition.

As far as CBL simulations are concerned, Fedorovich et al. (1996) and Fedorovich and Kaiser (1998) carried out wind tunnel experiments, finding roughness and wind shear to be responsible of modifications in the regime of turbulence production, with an increment of the velocity variances closer to the surface respect to the shear-free case for values of the surface shear-to-buoyancy production ratio u_*/w_* greater than 0.3.

The present work aims to investigate techniques for the development of thick high-roughness SBLs and CBLs suitable for studying flow and dispersion in urban areas. For this purpose the method presented by Hancock and Hayden (2018) for SBLs has been applied with success to a higher roughness case. Artificially thickened CBLs have also been investigated. In this case great efforts were put on the enhancement of longitudinal and lateral uniformity of the temperature and velocity fields. In particular, the use of different inlet temperature gradients as well as an overlying inversion have been tested for this purpose.

2. Methodology

2.1. Experimental setup

Flow measurements were performed in the suck-down open-return EnFlo meteorological wind tunnel with a test section 20 m long, 3.5 m wide and 1.5 m high. The x-axis was in the streamwise direction, measured from the working-section inlet; the y-axis was in the spanwise direction, measured from the wind tunnel centre line; the z-axis represented the vertical, starting from the floor. The wind tunnel flow speed could range from 0.3 to 2.5 m/s as measured by a sonic anemometer placed at $x = 5$ m, $y = 1$ m, $z = 1$ m (which provided a reference velocity U_{REF}).

The wind tunnel was specifically designed to generate thermally stratified flows: a series of 15 vertically piled electrical heaters at the inlet section allowed the generation of a vertical temperature gradient, which combined with the heating/cooling floor system created the different types of atmospheric stability. For stable stratification the central 3 m of the floor along most of the working section in the streamwise direction were cooled by means of recirculating water at the

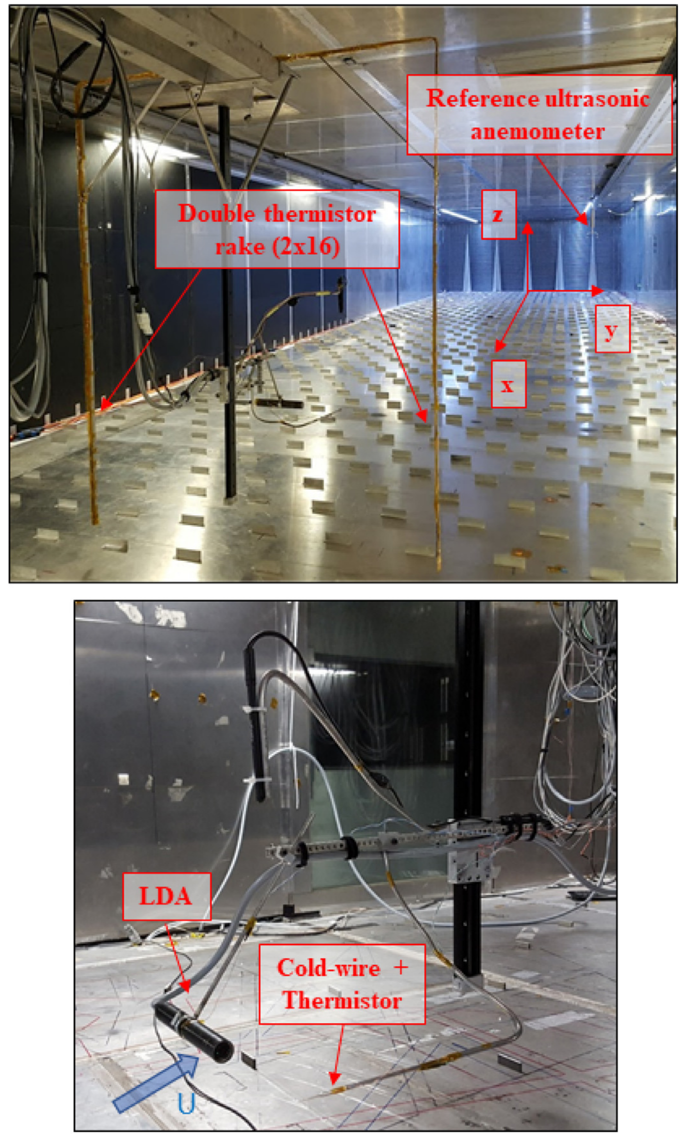

Fig. 1. Wind tunnel and measuring setup.

desired temperature. When CBLs had to be simulated, electrical heater mats were added on the wind tunnel floor (on top of additional insulating panels). Their maximum power was 2.0 kW/m^2, with dimensions 1295 × 333 × 5 mm; different arrangements were considered in order to improve the lateral uniformity (further explanation will be given in the following sections). Panel temperatures were controlled in a closed-loop system. The air leaving the wind tunnel was cooled by means of recirculating water in order to keep the laboratory temperature as constant as possible. The latter presented a vertical variation up to 1 °C between floor and ceiling. Such a gradient was mitigated using a series of fans that helped air mixing, improving the temperature homogeneity at the inlet.

As the main purpose of the work is the development of stratified BLs suitable for urban studies (for which the micro-scale was of interest), a wind-tunnel scale of 1:200 was considered for all the cases. In order to obtain sufficiently thick BLs, Irwin-like spires (Irwin, 1981) after the inlet section and rectangular-shaped roughness elements on the floor were employed to artificially develop the flow. For the CBL simulation five spires 1260 mm high, 170 mm wide at the base and spaced laterally 630 mm were used (shown in Fig. 1). They had been extensively employed in previous works for generating urban neutrally stratified BLs about 1 m thick (δ), together with surface roughness elements 80 mm