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

J.M. Tomas a,*, M.J.B.M. Pourquie a, H.J.J. Jonker b

a Department Process & Energy, Lab. for Aero & Hydrodynamics, Delft University, Leegwaterstraat 21, 2628 CA Delft, The Netherlands

b Department Geoscience and Remote Sensing, Delft University, PO Box 5048, 2600 GA Delft, The Netherlands

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.

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.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

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
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, $Re_f = u_f / \nu_f$, 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 flow: $\frac{\nu_1}{\nu_f} = \frac{\nu_2}{\nu_f}$, where $\nu_1$ is the kinematic viscosity of the inflow, $\nu_f$ the kinematic viscosity of the TBL, and $\nu_2$ the kinematic viscosity of the wake. The 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: $\Delta U = U_{\text{obstacle}} - U_{\text{flat}}$, 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 Diacey (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 Diacey (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 Simulations (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.
2.1. Governing equations and numerical method

The filtered Navier–Stokes equations in the Boussinesq approximation are:

\[
\frac{\partial \tilde{u}_i}{\partial t} = 0, 
\]

\[
\frac{\partial \tilde{u}_i}{\partial t} - \frac{\partial}{\partial x_j} \left( \tilde{p} \tilde{u}_i + \tau_{ik} / 3 \right) + \frac{g}{\theta_0} \frac{\partial \tilde{b}_i}{\partial x_j} + \rho \frac{\partial^2 \tilde{u}_i}{\partial x_j^2} + \frac{\partial}{\partial x_j} (2 \tau_{sgs} S_{ij}), 
\]

\[
\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x_j} (\phi \tilde{u}_j) + \frac{\nu}{Pr} \frac{\partial^2 \phi}{\partial x_j^2} + \frac{\partial}{\partial x_j} \left( \tau_{sgs} \frac{\partial \phi}{\partial x_j} \right) + S, 
\]

where \(\tilde{\cdot}\) denotes filtered quantities, \(\tilde{p} / \rho_0 + \tau_{ik} / 3\) is the modified pressure, \(\tau_{ik}\) is the trace of subgrid-scale stress tensor, \(g\) is the gravitational acceleration, \(\nu\) is the fluid's kinematic viscosity. \(\tau_{sgs}\) is the subgrid-scale viscosity, \(Pr\) is the Prandtl number, \(Pr_{sgs}\) is the subgrid-scale Prandtl number, \(S_{ij}\) is the rate of strain tensor and \(S\) is a source term. Equation (3) describes the transport equation for all scalar quantities \(\phi\), which are the temperature \(\theta\) and pollutant concentration \(C\). From here on the \(\tilde{\cdot}\) symbol will be omitted for clarity. Furthermore, the \(\tilde{\cdot}\) symbol resembles time- and spanwise averaging.

The code developed for this study is based on DALES (Heus et al. (2010)). DALES has been validated and used extensively for atmospheric research in the Netherlands. It has been part of several intercomparison studies (Heus et al. (2010) and references therein). The main modifications are the addition of an immersed boundary method (Pourquie et al. (2009)), the implementation of inflow/outflow boundary conditions and the application of the eddy-viscosity subgrid model of Vreman (2004). This model has the advantage over the standard Smagorinsky-Lilly model (Smagorinsky (1963), Lilly (1962)) that no wall-damping is required to reduce the subgrid-scale energy near walls. The equations of motion are solved using second-order central differencing for the spatial derivatives and an explicit third-order Runge-Kutta method for time integration. For the scalar concentration field the second-order central \(\kappa\)-scheme is used to ensure positivity. The simulations are wall-resolved, so no use is made of wall-functions. \(Pr_{sgs}\) was set to 0.9, equal to the turbulent Prandtl number found in the major part of the TBL in DNS studies by Jonker et al. (2013). The subgrid-scale Schmidt number was set to 0.9 as well. The code has been applied before to simulate turbulent flow over a surface-mounted fence, showing excellent agreement with experimental data (Tomas et al. (2015)).

2.2. Generation of turbulent inflow

The instantaneous velocity at the inlet plane of the driver simulations is generated using a recycling method similar to the method proposed by Lund et al. (1998). Both the mean velocity profile and the velocity fluctuations at a recycle plane (8.24\(\delta\) distant from the inlet) are rescaled according to the law of the wall for the inner region and the velocity defect law for the outer region. The input parameters of the method are the free stream velocity, \(U_{\infty}\), and the inlet TBL height, \(\delta\). There are two differences compared to the original method by Lund et al. (1998). Firstly, to avoid instabilities, above 1.2\(\delta\) the fluctuations are dampened using the smooth Heaviside function as described by Bohr (2005), which results in zero rescaling of the fluctuations above 1.3\(\delta\). Secondly, a mass flux correction is applied because the rescaling procedure and the associated interpolation can cause the mass flux at the inlet to slightly change between time steps. This results in pressure pulses through the domain (Sillero et al. (2013)). Although the mass flux variations in our simulations were very small (maximum of order 0.01%), we did see effects in the pressure statistics. Therefore, when the mean variables were fully converged this very small mass flux correction was applied each time step.

The inlet temperature field is generated in a similar vein as the velocity field by using the method developed by Kong et al. (2000). However, in contrast to their simulations the buoyancy force was taken into account in the driver simulations in order to generate stably stratified TBLs. The level of thermal stratification is set by fixing the ground temperature, \(\theta_0\), the free stream temperature, \(\theta_{\infty}\) and the thermal boundary layer height, \(\delta_T\). For stable TBLs this is a delicate procedure because re-laminarization can occur while the mean variables have not yet converged, which causes instabilities. Our results were generated by first assuming the temperature to be passive until the mean variables were converged. Next, the buoyancy force was taken into account while the level of stratification was increased slowly. Finally, to prevent the development of a strong inversion the local gradient Richardson number,

\[
R_{i,grad} = \frac{g \frac{\partial \theta}{\partial z}}{2 S_{ij} S_{ij}},
\]

is kept below the critical value \(R_{i,grad}^{crit} = 0.25\) inside the boundary.
layer. This is achieved by setting \(\delta_f\) slightly smaller than \(\delta\) at the inlet: \(\delta_f\) was fixed at 0.95\(\delta\) at the inlet.

3. Flow configuration, mesh and boundary conditions

3.1. Characteristics of the flow

To approximate the flow over an obstacle in the atmosphere the following criteria were used to specify the properties of the flow:

- **The Reynolds number**: Experimental studies have shown that the flow over a fence becomes independent of the Reynolds number if \(Re = U_{inf} h/\nu\) is above 4000 to 5000 (Huppertz and Fernholz (2002), Castro (1979)). The results presented here are based on a minimum Reynolds number of 5000.

- **Obstacle height in inner scaling**: Because the Reynolds number is finite a viscous sublayer forms near walls for which the characteristic velocity scale is \(U_\infty = (r \partial u/\partial z)_{wall}\) and the characteristic length scale is \(r/\nu\) (for smooth walls). The thickness of the viscous sublayer was approximately kept constant for all levels of stability. In addition, the top of the obstacle was in the logarithmic region of the velocity profile in case of neutral stratification.

- **Obstacle height in outer scaling**: The atmospheric boundary layer height is in the order of one kilometer in neutral conditions. For stably stratified cases it can be in the order of 100 m. However, in the current study we are only interested in the development in the region close to the ground. Therefore, the TBL height at the inlet of the simulations was kept constant at 10h, which, as will be shown in Section 5, proved to be high enough for the wake not to reach the top of the boundary layer at 100h downstream.

After exploration of boundary layer data we found that these criteria are met when \(Re_{\infty} = u_{\infty} \delta_f/\nu \geq 1900\) at the location of the fence. Therefore, at the inlet of all simulations \(Re_{\infty}\) was kept constant at approximately 1950. In addition to the neutral case three stably stratified TBLs were considered, for which the bulk Richardson number,

\[
Ri = \frac{(\rho \theta_0 \theta_{\infty} - \theta_0 \theta_{\infty}) \delta}{U_{\infty}^2},
\]

was 0.049, 0.098 and 0.147, respectively.

3.2. Domain and grid

The domains for all simulations are 1.57\(h = 15.7h\) wide and 3\(h\) high in order to capture also the largest eddies in the TBL. The length of the domain is 10\(h\), 11.25\(h\), or 11.36 for the driver, flat and obstacle simulations, respectively. The flow is well resolved, since the average subgrid stress, \(\overline{2\nu_s \delta_u \delta_v}\), did not exceed 6\% of the total Reynolds stress. Table 1 summarizes the domains and the number of grid points that were used for each case, including the local mesh size and maximum expansion ratio of the grid.

3.3. Pollutant line sources

Five independent constant-flux line sources of passive scalar, indicated by concentrations \(C_1, C_2, C_3, C_4\) and \(C_5\), are located at locations \(x = -5h, -1h, 1h, 10h, \) and 20\(h\). All sources are located at \(z = 0.2h\). The source terms are distributed over the surrounding cells using a Gaussian distribution with a standard deviation of 0.25\(h\).

3.4. Boundary conditions

In spanwise direction periodicity was assumed for all variables. Velocity and temperature data were imposed at the inlet as described in paragraph 2.2. At the outlet a convective outflow boundary condition was applied for all variables. Furthermore, on the ground and fence walls no slip conditions were applied, while at the top boundary a free slip condition was used with a constant outflow velocity of \(w = U_{\infty} \partial \delta_f / \partial x\), where \(\partial \delta_f / \partial x\) is the mean streamwise growth of the displacement thickness. This was done to establish a zero-pressure gradient in the driver simulations. In the flat and obstacle simulations the same outflow velocity was applied as in the driver simulations. For the scalars \(\theta\) and \(C\) zero-flux boundaries were assumed, except for \(\theta\) at the ground, for which isothermal conditions were applied. Applying isoflux thermal conditions would be another possibility. For TBLs nearly identical results are reported for \(z^+ > 20\) (Kong et al. 2000). If this also holds for the flow behind an obstacle is a question requiring future investigation.

3.5. Statistics

After the driver simulations reached a steady state the results were averaged over 1000\(T\), where \(T = \delta/\nu U_{\infty}\). For the driver and flat simulations sampling was done at intervals of 0.2\(T\), while a constant time step of 0.02\(T\) was used. The obstacle simulations used a time step of 0.0032\(T\) and a sampling interval of 0.032\(T\). The duration of these simulations was 150\(T\) of which the first 50\(T\) was not used for averaging to make sure that start-up effects were gone.

4. Discussion of the inflow boundary layers

Four TBLs were generated; one neutral case and three stably stratified cases. In Table 2 the properties of each TBL are given for the inflow of the domain, because this is the plane that was saved in time and used as inlet for the flat and obstacle simulations. \(\delta_1\) is the displacement thickness, \(\delta_2\) is the momentum thickness and \(H\) is the shape factor.

Table 1: Dimensional and grid for simulated cases; \(\Delta x^*, \Delta y^*\) and \(\Delta z^*\) are based on \(u_\infty\) at the inlet.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Dim.</th>
<th>(L_i)</th>
<th>(N_i)</th>
<th>Max. (\Delta x^*)</th>
<th>Min. (\Delta y^*)</th>
<th>Max.(\Delta z^*)</th>
<th>Max. expansions ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>x</td>
<td>100</td>
<td>256</td>
<td>77</td>
<td>77</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>1.57h</td>
<td>160</td>
<td>19</td>
<td>19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>3h</td>
<td>80</td>
<td>196</td>
<td>3.9</td>
<td>1.07</td>
<td>-</td>
</tr>
<tr>
<td>Flat</td>
<td>x</td>
<td>112.5h (11.25(h))</td>
<td>288</td>
<td>77</td>
<td>77</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>15.7h (1.57h)</td>
<td>160</td>
<td>19</td>
<td>19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>30h (3(h))</td>
<td>80</td>
<td>196</td>
<td>3.9</td>
<td>1.07</td>
<td>-</td>
</tr>
<tr>
<td>Obstacle</td>
<td>x</td>
<td>113h (11.36)</td>
<td>656</td>
<td>90</td>
<td>6.2</td>
<td>1.05</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>15.7h (1.57h)</td>
<td>160</td>
<td>19</td>
<td>19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>30h (3(h))</td>
<td>128</td>
<td>196</td>
<td>3.2</td>
<td>1.07</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: Properties of the inflow TBLs created in driver simulations; thermal BL height \(\delta_0\), displacement thickness \(\delta_1\), momentum thickness \(\delta_2\), shape factor \(H\) and Obukhov length \(L\).

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Case</th>
<th>(Re_{\infty})</th>
<th>Ri</th>
<th>(\delta_0/\delta_{\infty})</th>
<th>(\delta_1/\delta_{\infty})</th>
<th>(\delta_2/\delta_{\infty})</th>
<th>(H)</th>
<th>(L/\delta_{\infty})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>BL0</td>
<td>1916</td>
<td>0</td>
<td>0.163</td>
<td>0.120</td>
<td>1.35</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BL1</td>
<td>1952</td>
<td>0.049</td>
<td>0.95</td>
<td>0.208</td>
<td>0.140</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BL2</td>
<td>1952</td>
<td>0.049</td>
<td>0.95</td>
<td>0.254</td>
<td>0.155</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BL3</td>
<td>1908</td>
<td>0.147</td>
<td>0.95</td>
<td>0.290</td>
<td>0.160</td>
<td>1.82</td>
<td>0.20</td>
</tr>
</tbody>
</table>
adequate: at $z/\delta_0 = 0.15$ at least 18 spanwise integral length scales fit the domain width and the streamwise two-point velocity correlations have decreased to zero before half of the domain length is reached. The spanwise energy spectra decrease five orders of magnitude, which indicates that a large part of the turbulence is resolved.

The mean profiles of BL0 are in good agreement with the results from DNS of a zero pressure-gradient TBL at $Re_c = 1990$ by Sillero et al. (2013), as can be seen in Fig. 2, where the mean velocity profiles at the inlet are shown in both outer and inner scaling. Fig. 3 shows the r.m.s. of the velocity fluctuations for BL0 also in outer and inner scaling. $u_\text{rms}$ shows a slight underprediction in the outer region. In addition, near the ground $u_\text{rms}$ is slightly overpredicted, while $v_\text{rms}$ and $w_\text{rms}$ are slightly underpredicted; a symptom of coarseness of the mesh. The mean velocity profiles for the stable TBLs show good agreement with the log-linear velocity profiles following from Monin-Obukhov similarity theory (Monin and Obukhov (1954));

$$\frac{\bar{u}}{U_\infty} = \frac{1}{\kappa} \left[ \ln \frac{z^+}{\alpha} + \frac{z^+}{L} \right] + 5.0,$$

where $\kappa$ is the Von Kármán constant, $L = -u_\text{rms}^2/\kappa g \bar{w} \bar{T}$ is the Obukhov length and $\alpha$ is a constant approximately equal to 5. In Fig. 2b it can be seen that the temperature gradient has the largest effect in the outer region of the boundary layer, because in non-neutral cases the large eddies scale with $L$ instead of $\delta$. The inner region appears to be unaffected by the stratification; for $z^+ < 20$ no effect is visible in the temperature profile. The most stable case ($Ri = 0.147$) shows the largest deviation from the Monin-Obukhov similarity profile; the flow starts to accelerate above $z^+ = 10$. Fig. 4 shows the mean temperature profiles at the inlet of the driver simulations for the stable cases (BL1, BL2 and BL3) in both outer and inner scaling, while Fig. 5 shows the corresponding profiles for the r.m.s. of the temperature fluctuations. The mean temperature profiles show the same behaviour as the mean velocity profiles; the logarithmic profile transforms into a near-linear profile with increasing Richardson number. Furthermore, the temperature fluctuations in the logarithmic region increase compared to the peak value in the buffer layer (at $z^+ = 25$). In inner scaling the peak itself also increases slightly. Finally, Fig. 6 shows the gradient Richardson number, $Ri_{\text{grad}}$ (Equation (4)), for the stable TBLs. Near the ground $Ri_{\text{grad}}$ increases with height until it reaches an approximately constant value in the outer region. Near the top of the boundary layer $Ri_{\text{grad}}$ increases again until the top of the boundary layer is reached, where it is not defined. In all driver simulations $Ri_{\text{grad}}$ stays below the critical gradient Richardson number, $Ri_{\text{crit}} = 0.25$, inside the boundary layer, except for BL3, which reached $Ri_{\text{grad}} = 0.25$ at $z/\delta = 0.95$. BL3 remained turbulent, but further increasing $\Delta\theta$ did result in intermittent turbulent flow.

5. Discussion of the flat and obstacle simulations

Next, we considered the flow over a fence together with pollutant emissions from line sources by using the previously generated TBLs as inflow condition. The flat cases were simulated as well. Table 3 lists the characteristics of the flat and obstacle simulations and the corresponding inflow boundary layer that was used. Firstly, we will discuss the flow up to the recirculation zone, after which we will consider the flow development further downstream. Then, we try to answer the main research question by investigating the dispersion of pollutants. Finally, we will study the decay of maximum deficit/excess of velocity, temperature, Reynolds stress and concentration to quantify up to what distance the obstacle is of influence.

5.1. Near wake

Fig. 7 shows the mean flow patterns in the vicinity of the fence for $Ri = 0.000$ and $Ri = 0.147$. There is an upstream recirculation zone with length of $h$ that reaches up to 2/3 of the fence height. The reattachment length of the downstream recirculation zone, $L_R$, depends only slightly on $Ri$. For $Ri = 0.000$, $Ri = 0.047$, $Ri = 0.098$ and $Ri = 0.147$ $L_R$ is 10.6h, 10.6h, 10.4h and 10.1h, respectively. It is mainly the height of the recirculation zone that is affected by stratification. The maximum height of separating streamline is 1.70h, 1.65h, 1.60h and 1.45h, respectively.

5.2. Wake development

Fig. 8 shows the development of $\tau$, $\theta$ and $Ri_{\text{grad}}$ for the cases with and without the fence present. The results are given at downstream locations of 10h, 30h, 50h and 100h downstream of the fence. The variables are presented in outer scaling using the TBL height at the inlet to scale the vertical dimension.

At $x/h = 10$ the profiles of $\tau$ for the obstacle cases show a region of reduced velocity (a deficit) near the ground and a region of increased velocity (an excess) above $z = 0.2 \delta_0 = 2h$ compared to the flat cases. Going downstream both the deficit region and the excess region move upwards, while their maximum value decreases. Furthermore, for the stable cases the flow downstream of the fence starts to develop a velocity excess near the ground. This velocity

Fig. 2. Mean streamwise velocity for BL0, BL1, BL2 and BL3. For reference results from DNS at $Re_c = 1990$ (neutral) from Sillero et al. (2013) are shown (BL0 almost collapses with DNS data). (a) Outer scaling. (b) Inner scaling; coloured lines correspond to Monin-Obukhov theory.
excess is larger for higher levels of stratification. We attribute the near-ground excess in $\Pi$ to enhanced mixing due to turbulence added by the presence of the fence, which results in a momentum flux from the outer flow to the flow near the ground. For the stable cases the effect becomes more apparent because in those cases there is still an excess in Reynolds stress (see Fig. 9) at the point where the mean velocity has recovered to its undisturbed value. Just downstream of the fence the profiles for $T$ are almost uniform up to $z = 0.2\delta_0$, because the near wake has fully mixed the flow. Further downstream the profiles become similar to the $\Pi$ profiles with a temperature deficit in the outer region and a temperature excess developing near the ground, which is larger for higher levels of stratification. This temperature excess is caused by the same effect that causes the near-ground acceleration.

Although the profiles of $R_{\text{grad}}$ for the obstacle simulations are rather distorted (due to limited averaging time) the effects of both the presence of the obstacle and stratification are visible. Because at $x = 10h$ up to $z = 0.2\delta_0$ the flow is fully mixed $R_{\text{grad}} = 0$. However, above that region $R_{\text{grad}}$ has increased almost by a factor two with respect to the flat case due to the increased vertical gradient in $T$ between $z = 0.2\delta_0$ and $z = 0.4\delta_0$. Going downstream the deficit in $R_{\text{grad}}$ moves upwards during which it spreads and decreases in

---

Fig. 3. Mean r.m.s. of velocity components for BL0 (continuous lines). For reference results from DNS at $Re = 1990$ (neutral) from Sillero et al. (2013) are shown (dashed lines). (a) Outer scaling. (b) Inner scaling.

Fig. 4. Mean temperature for BL1, BL2 and BL3. (a) Outer scaling. (b) Inner scaling.

Fig. 5. Mean r.m.s. of temperature for BL1, BL2 and BL3. (a) Outer scaling. (b) Inner scaling.
magnitude. Increasing the stratification causes the deficit in $Ri_{grad}$ to move upwards slower and spread slower.

Fig. 9 shows the profiles of $\sqrt{\overline{u^2} w^2}$ and $\theta_{rms}$. For the fence cases at $x = 10h$ the r.m.s. of the three velocity components (not shown) as well as $\sqrt{\overline{u^2} w^2}$ have their maximum around $z = 0.15\delta_0$ while the flat cases are nearly constant. Going downstream the excess moves upwards into the outer flow. Higher levels of stratification show slower spreading in vertical direction in accordance with a slower decay of the maximum. The development of $\theta_{rms}$ shows a different behaviour. Very close to the ground there is an increase in $\theta_{rms}$, while there is a decrease from there up to $z = 0.2\delta_0$ because the near wake is fully mixed. Above $z = 0.2\delta_0$ $\theta_{rms}$ has increased again. Further downstream the excess in the outer flow moves upwards, while the excess region near the ground remains equal in magnitude and location. Going downstream the deficit region around $z = 0.1\delta_0$ changes into an excess for the most stable case.

### 5.3. Pollutant dispersion

Next, we consider the effect of both the presence of the obstacle and thermal stratification on the dispersion of pollutants. This will answer the question if and when these two factors can be neglected in order to use simplified models to predict air quality. The five independent spanwise line sources of passive scalar, indicated by concentrations $C_1$, $C_2$, $C_3$, $C_4$ and $C_5$, are located at locations $x_0 = -5h$, $-1h$, $1h$, $10h$, and $20h$, respectively. All sources are located at $z = 0.2h$ to mimic the exhaust gases from traffic. We will diagnose the concentration at ground level because that is approximately what the population is exposed to. Moreover, for the cases studied here the ground concentrations are the maximum concentrations for the region downstream of reattachment.

Fig. 10 shows the influence of $Ri$ on the measured concentration at ground level at locations 10h, 30h, 50h and 75h downstream of each source location, $x_0$. Results are given for obstacle cases as well as the flat cases. The concentration has been scaled with the concentration measured in the neutral case. As expected, the concentration profiles for the flat cases collapse. For the fence simulations the profiles are also in good agreement with each other even though the source location relative to the position of the fence differs per source. Overall, ground concentrations increase with higher levels of stratification. The effect is less for the obstacle simulations because of enhanced mixing due to increased turbulence. Still, for the case at $Ri = 0.147$ concentrations are 2.5 times higher than the neutral case at 75h downstream of the emission source, which indicates that stratification effects cannot be neglected.

The effect of the obstacle on the ground concentration is shown in Fig. 11, where the ratio of ground level concentration for the obstacle case over the flat case, $(C_{obs}/C_{flat})_{ground}$, is given along the downstream direction for source 1 (located at $x/h = -5$) and source 4 (located at $x/h = 10$). The result for source 2 is similar to Fig. 11a while sources 3 and 5 give results similar to Fig. 11b. In all cases the

### Table 3

A summary of the main simulations.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Case</th>
<th>Inflow</th>
<th>$Re_\tau$</th>
<th>$Ri$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>LESS00</td>
<td>BL0</td>
<td>1916</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LESS10</td>
<td>BL1</td>
<td>1952</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>LESS20</td>
<td>BL3</td>
<td>1908</td>
<td>0.147</td>
</tr>
<tr>
<td>Obstacle</td>
<td>LESS01</td>
<td>BL0</td>
<td>1916</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LESS11</td>
<td>BL1</td>
<td>1952</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>LESS12</td>
<td>BL2</td>
<td>1952</td>
<td>0.098</td>
</tr>
<tr>
<td></td>
<td>LESS21</td>
<td>BL3</td>
<td>1908</td>
<td>0.147</td>
</tr>
</tbody>
</table>

---

Fig. 6. Gradient Richardson number, $Ri_{grad}$.

Fig. 7. Mean streamlines for (a) LESS01 ($Ri = 0$) and (b) LESS21 ($Ri = 0.147$). The fence is located at $x=0$. 
presence of the fence causes ground concentrations initially to decrease compared to the flat situation. The influence of the fence is largest for the most stratified case, for which $C_{vis}^{ob}$ has decreased to 28% of the flat case in the region downstream of reattachment. For the neutral case this is 50%. At $x/h = 100$ this ratio has increased to 35% (stable) and 65% (neutral). The largest reduction in ground concentration is measured for source 4. This can be explained by the fact that source 4 is located just before the point of reattachment. At this location the shear layer emanating from the top of the fence impinges on the surface which has a strong mixing effect. The least reduction is measured for sources 1 and 5, which are located at the largest distance from the recirculation zone of the fence.

5.4. Decay of maximum deficits

According to Schofield and Logan (1990) in the outer flow the decay of maximum deficit in mean velocity relative to its value at the reattachment location should scale with the length scales $x_r - x_0$ and $\delta$, where $x - x_0$ is the distance from the reattachment location, $x_0$. Using data from several experiments they showed that the decay has a logarithmic dependence on the recovery distance, $x - x_0$, of the form:

$$\Delta \bar{u} = -0.50 \log_{10} \frac{x - x_R}{\delta} + 0.49,$$

where $\Delta \bar{u}$ is the maximum velocity deficit and subscript $R$ indicates the value at the reattachment location. If we determine $\Delta \bar{u}$ at each downstream location and scale our results accordingly the data does not match the profile of Equation (7). However, as mentioned in paragraph 5.2, there is a velocity excess just above the obstacle, which is not present in the experimental results on which the empirical fit of Equation (7) is based. If we consider the mean velocity deficit relative to the velocity excess at the fence location, the data does collapse, as can be seen in Fig. 12a. The experimental results from four experiments by Counihan et al. (1974) and Castro (1979) are plotted as well. All the experimental results are based on a two-dimensional square obstacle in a rough-wall TBL where $h/\delta$ ranged from 5.9 to 14.5. Remarkably, the decay appears to be independent of the stratification.

In Fig. 12b it is shown that the decay of the maximum deficit in mean temperature, $\Delta \bar{q}$, shows reasonable agreement with the profile of Equation (7) (for $\Delta \bar{u}$); $\Delta \bar{q}$ decays similarly as $\Delta \bar{u}$ even though the profiles at the reattachment location are different as
explained in paragraph 5.2. Just as for $\Delta \Pi$, stratification does not have an effect on the decay of $\Delta \Pi$. This cannot be said for the decay of maximum excess in mean Reynolds stress, $\Delta \overline{u'w'}$, which is shown in Fig. 13a. From about $14 \delta = L_D$ downstream of the reattachment point the decay shows $((x - x_R)/\delta)^{-1}$ dependence for the neutral case. For the most stable case this has changed to an exponent...
of $-1/2$. Similar effects are visible for the decay of maximum excess in mean concentration, $\Delta C$, shown in Fig. 13b, where results are given for source 3. The same conclusion can be drawn for the other line sources. This $Ri$ dependence is in accordance with the observation that in the stratified cases the reduction in ground concentrations lasts further downstream than in the neutral case (Fig. 11).

6. Conclusions

We have shown that by using a recycling method accurate turbulent inflow TBLs for stable stratification up to $Ri_{\text{grad}} = 0.2$ can be generated. This enabled a detailed investigation of the response of neutral and stably stratified flows to the presence of an obstacle. The validity of two simplifications has been studied; either neglect the presence of the obstacle, or neglect thermal stratification effects. We conclude that for neutral cases the effect of a two-dimensional obstacle can be neglected after approximately 75$h$ if $\tau$ is considered. However, for stable cases the $\tau$ and $\theta$ profiles have not recovered to their undisturbed shape, even after 100$h$; $\tau$ and $\theta$ are increased near the ground proportional to the level of stratification. Moreover, for all Richardson numbers turbulence levels are significantly increased for longer distances, which results in lower

---

**Fig. 11.** Effect of obstacle on ground concentrations downstream. (a) Source 1. (b) Source 4.

---

**Fig. 12.** Decay of maximum deficit in (a) mean velocity and (b) mean temperature downstream of reattachment. $\Delta \tau$ is corrected with maximum $\Delta \tau$ at fence location. Experimental data from Counihan et al. (1974) and Castro (1979) are shown.

---

**Fig. 13.** Decay of (a) maximum deficit in mean Reynolds stress and (b) maximum excess in mean concentration (Source 3).
Regarding the second simplification, i.e. to neglect thermal stratification, we can conclude that stratification is indeed reduced locally due to enhanced mixing by the obstacle. However, making the assumption that the flow in the wake of the obstacle is neutrally buoyant results in an understimation of concentrations by a factor 2.5 at 75h downstream of the emission source for the case at $Ri = 0.147$. We therefore conclude that both suggested simplifications are unjustified when considering a single obstacle in an undisturbed flow. Whether the same conclusion holds for multiple obstacles requires further investigation.

Furthermore, we have shown that the maximum deficit in mean velocity relative to the maximum deficit at the point of reattachment shows the same decay for all levels of stratification. If scaled with the development length $(x - x_0)/\delta$ the results collapse with data from several experiments under neutral conditions, showing a logarithmic dependence. The decay of maximum deficit in mean temperature shows similar behaviour. However, the decay of the maximum deficit in mean Reynolds stress does show a dependence on the stratification. For neutral conditions, after one TBL height behind the reattachment location the decay starts to show a $-1$ power-law dependence on $(x - x_0)/\delta$, while for the most stratified case the exponent reduces to $-1/2$. This means that in stratified cases the presence of an obstacle can be visible up to much larger distances than in the neutral case. If we extrapolate the measured decay of Reynolds stress excess the neutral case will reach 1% of the value at the reattachment location at $(x - x_0)/\delta = 47$. This is $(x - x_0)/\delta = 1850$ for the case at $Ri = 0.147$. Moreover, the decay of maximum excess in mean concentration shows a similar dependence on $Ri$ as the turbulent stresses. For three-dimensional obstacles qualitatively similar behaviour can be expected, but the obstacle effect will disappear more rapidly with decreasing $I/\delta$ ratio. The effect of multiple obstacles will be subject of future investigations.

Modelling pollutant dispersion near obstacles with a Gaussian plume-like model most likely fails. Computational fluid dynamics (CFD) models based on RANS equations predict complex flow fields reasonably for neutral conditions. However, around complex geometries buoyancy can have a large influence on both the flow field and the surface energy balance (Schrijvers et al. (2014)). Unfortunately, RANS models handle buoyancy effects poorly. Therefore, results from such simplified models should be compared with experimental data and/or LES/DNS results in order to assess their validity.

Acknowledgements

This study was done within the STW project DisTurbE (project no. 11989) using the computational resources of SURFsara with the funding of the Netherlands Organization for Scientific Research (NWO), project no. SG-015.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.05.016.

References