CONTRIBUTION OF ADVECTIVE AND TURBULENT MASS TRANSFERS TO THE VENTILATION OF URBAN CANOPY

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ABSTRACT

The study of dispersion through large idealised arrays of building-like obstacles is an important method of obtaining a better understanding of dispersion through a real urban environment. The vertical ventilation of the pollutants from the street level to the relatively unobstructed flow above the urban canopy is the main interest of our study. Simultaneous measurement of passive tracer concentration and vertical wind component with high temporal resolution allows us to directly derive the advective and turbulent vertical transport terms. Comparison of the concentration field within 18 different arrangements of idealised urban canopies (with changing packing densities, building layouts and height variations) is shown and the importance of a proper determination of the vertical turbulent fluxes at the edge of the plume and above the roof top level is emphasised.

KEYWORDS: WIND TUNNEL, ATMOSPHERIC DISPERSION, IDEALISED URBAN CANOPY

Introduction

Complex processes like the dispersion of car exhaust in street canyons or the dispersion of accidental releases of harmful substances in built-up areas are not yet fully understood. For a better insight of the driving phenomena it is helpful to study flow and dispersion of pollutants within an idealised urban setting first.

The study of dispersion through large idealised arrays of building-like obstacles is an important method of obtaining a better understanding of dispersion through a real urban environment. Field and laboratory studies of idealised obstacle arrays are necessarily simplifications of the real complex urban environment. They can reproduce some of the real urban characteristics as building packing density or building arrangement. These types of geometries, nonetheless, should display some of the characteristics of the more complex, real-world configurations, and show some generally valid rules. We examined flow and passive tracer dispersion within 18 different configurations of the idealised urban area layout during our experiment.

The objective of the presented paper is the analysis of the mean concentration field at the street level for different idealised urban canopy set-ups and showing the main mechanism of the pollutant transport within them. Such knowledge should play a significant role in design process of new urban structures or modification of already built-up areas to achieve better ventilation characteristics.

One of the first experiments dealing with an idealised urban canopy was conducted by MacDonald et al. (1997), who compared the mean concentration characteristics within the
idealised urban canopies with different packing densities. They did not find any significant differences between different packing densities and neither did Mavroidis (2000) in his work. Cheng et al. (2007) investigated the drag forces and momentum transport for two packing densities and aligned/staggered arrangement. They found significantly increased drag and momentum transport for the staggered arrays. Therefore, an enhanced vertical transport of passive contaminant could be expected. The vertical ventilation of the toxic gaseous pollutant from the street level to the relatively unobstructed flow above the urban canopy is the main interest of our study. Simultaneous measurement of passive tracer concentration and vertical wind component with high temporal resolution is very unique and allows us to directly derive the advective and turbulent vertical transport terms WC and \( w'c' \) from the equation of advection (see below). The magnitude of the terms depends on the character of flow in the given place and can vary significantly. There are not many papers concerning the concentration fluxes. Fackrell and Robins (1982) examined these fluxes in unobstructed atmospheric boundary layer flow and found that turbulent and advective transports are of the same magnitude. The magnitude of the turbulent transport of passive contaminant was found significant due to the suppressing of the mean flow within the plant canopy (Meyers, 1991).

**Definitions**

The advection equation for a scalar \( \psi \), such as concentration of passive contaminant, far from the source of the scalar is expressed mathematically as:

\[
\frac{\partial \psi}{\partial t} + \nabla \cdot (\psi \mathbf{u}) = 0,
\]

(1)

where \( \nabla \cdot \) is the divergence operator and \( \mathbf{u} \) is the velocity vector. Any variable within the turbulent field can be divided into the temporally constant mean value (depicted by overbar) and fluctuating part (depicted by prime), which time average mean value is zero. Therefore we can rewrite the temporal mean equation of advection as:

\[
\bar{\psi} = \psi + \psi' \Rightarrow \frac{\partial \bar{\psi}}{\partial t} + \nabla \cdot (\bar{\psi} \bar{\mathbf{u}} + \bar{\psi}' \bar{\mathbf{u}}') = 0
\]

(2)

The second term on the left hand side of the equation 2.2 of advection has two parts. The first term is product of the mean values of velocity and concentration and it describes the purely advective changes in the scalar field. The second part is mean value of the product of the fluctuating parts and it describes a turbulent contribution to the changes in the scalar field. The magnitude of both parts is dependent on the character of flow in the given place and can vary significantly.

The ventilation of the toxic gaseous pollutant is the main interest of our study. If we look at the situation from the point of view of the street inhabitants and looking for the most suitable solution of a high pollutant concentration, the most preferable way of the ventilation of those pollutants is vertical. Vertical ventilation will transport pollutants to the relatively free stream above the urban canopy and there the pollutants concentration will be quickly reduced. Therefore we focused on the vertical component of the equation of passive contaminant advection:

\[
\frac{\partial c}{\partial t} + \frac{\partial}{\partial z} (WC + w'c') = 0,
\]

(3)

where \( W \) and \( w' \) is the mean and fluctuation part of vertical wind component, respectively; and \( C \) and \( c' \) is the mean and fluctuation part of concentration of passive contaminant. The first and second terms in the brackets are called the advective and turbulent vertical flux of the passive pollutant, respectively.
Experimental methods

The experiment was carried out in the Boundary Layer Wind Tunnel at Wind Engineering Center of Tokyo Polytechnic University, Atsugi, Japan. The 14 m long facility provides test section with 1.2m in width and 1m in height. Spires and roughness elements were used to develop model of the suburban atmospheric boundary layer in the scale 1:400. Logarithmic and power law profiles were applied to the measured vertical mean wind profile with following parameters (in full scale): roughness length $z_0=1m$, displacement length $d_0=3.2m$, and power law exponent $\alpha=0.25$. These parameters correspond to those observed in atmospheric boundary layer above moderately rough terrain (Snyder, 1981). Also high order statistical moments were measured and compared to full scale data. Vertical profile of turbulence intensity compared to the empirical formula proposed by Snyder (1981) and dimensionless power spectra compared with empirical formula proposed by Kaimal et al. (1972). For more detail about boundary layer characteristics see Bezpalcova, 2007.

The researcher team of Wind Engineering Center of Tokyo Polytechnic University has developed a method for simultaneous measurement of velocity and concentration by the means of thermo-anemometry and flame ionisation detection (Yoshie et al., 2007). This set-up allows deriving turbulent fluxes related to the momentum and concentration at the same time. The flow measurement was conducted using a thermo-anemometer with split-fibre probe and constant temperature adjustment module. The ground-level point source of the tracer gas ethylene ($C_2H_4$) was located in the wake of the cube at coordinates $x=-5.43H$, $y=0$, and $z=0$ (depicted by red dot in Fig.2). The location was chosen to be right behind an obstacle with height 1H in its wake. It was the same for all set-ups. Density of ethylene is 1.18 kg m$^{-3}$ in standard atmospheric conditions and it can be considered as a passive tracer because its density is very close to standard air density (1.2 kg m$^{-3}$). The molecular diffusivity is negligible compared to the turbulent diffusivity.

Eighteen different obstacle set-ups were examined to evaluate the dispersion properties as a function of the obstacle array characteristics as packing density, layout arrangement, and building height variation. Overview of the set-ups is given in Table1.

The set-ups creation was inspired by work of Cheng and Castro (2002) in which authors examined aerodynamic properties of various idealised urban settings. Our basic uniform height set-ups (labelled C) are created by the cubes with the side length of 70 mm (1H). The layout of these set-ups has aspect ratio (ratio between the street width and the building height) equals to 1.5, 1, and 0.71, which corresponds with the packing density of 16%, 25%, and 34% respectively. The A set-ups contain aligned obstacles, while the S set-ups contain staggered obstacles, respectively.

The D and E set-ups follow the layout arrangement of uniform height set-ups, only the individual buildings have different height. We use 5 different obstacle heights and create units with a random normal distribution of the elements as shown in Fig.1. We choose 3 rows of the obstacles covering the whole width of the wind tunnel as a unit and this unit was repeated to cover the whole test section. Two different non-uniform height distribution cases for each packing density and arrangement were investigated. Set-ups beginning with letter D follow the normal distribution with mean value 1H (70 mm) and standard deviation $\sigma_D=0.17H$. E set-ups follow exactly the same distribution as in the case of D set-ups, the mean value was the same, but $\sigma_E=0.33H$.

The temporal mean concentration is shown in the dimensionless form $c^*=CUH^2/Q$, which is used to compensate the influence of the mean wind speed $U$ (the stronger wind the smaller concentration) and source flux $Q$ (the higher source emission the higher concentration), and provide comparable results.
The experimental conditions were carefully checked by series of measurements. The independence of dimensionless properties on the source emission rate $Q$ and Building Reynolds number $Re_B = U_H H / \nu$ were found for experiments with $Q > 50 \text{cc/min}$ and $Re_B > 12000$ (i.e. $U_H > 6 \text{ m/s}$), respectively. The characteristic experimental conditions were: $Q \approx 300 \text{ cc/min}$ (i.e. 18 l per hour) and $Re_B \approx 16000 \text{ cc/min}$ (i.e. $U_H \approx 8 \text{ m/s}$).

![Figure 1: Urban canopy model for the case C_25_A (left picture); split fibre probe and fast flame ionisation detector (middle picture); and building height distribution (right picture).](image)

Table 1: Experimental conditions.

<table>
<thead>
<tr>
<th>Packing density</th>
<th>16%</th>
<th>16%</th>
<th>25%</th>
<th>25%</th>
<th>34%</th>
<th>34%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrangement</td>
<td>Aligned</td>
<td>Staggered</td>
<td>Aligned</td>
<td>Staggered</td>
<td>Aligned</td>
<td>Staggered</td>
</tr>
<tr>
<td>Height deviation</td>
<td>uniform height $\sigma = 0$</td>
<td>C_16_A</td>
<td>C_16_S</td>
<td>C_25_A</td>
<td>C_25_S</td>
<td>C_34_A</td>
</tr>
<tr>
<td></td>
<td>$\sigma = 0.17H$</td>
<td>D_16_A</td>
<td>D_16_S</td>
<td>D_25_A</td>
<td>D_25_S</td>
<td>D_34_A</td>
</tr>
<tr>
<td></td>
<td>$\sigma = 0.33H$</td>
<td>E_16_A</td>
<td>E_16_S</td>
<td>E_25_A</td>
<td>E_25_S</td>
<td>E_34_A</td>
</tr>
</tbody>
</table>

**Mean Concentration**

The mean concentration distribution of the passive tracer gas at the height of 0.29H for different obstacle set-ups is shown in Fig.2. The number on each building depicted the normalised height. The E set-ups with the most variable building heights were chosen for comparison. The upper row of plots in Fig.2 shows the aligned set-ups while the lower row show the staggered set-ups. The first, middle, and last column show set-ups with packing density 34%, 25%, and 16%, respectively. The zone with highest concentration (red colour) occupies approximately the same area for every set-up, but it shows different shape for aligned and staggered set-ups. It has shape of triangle with a long side at the street canyon, where the source is located, and shape of diamond in the case of aligned and staggered set-up, respectively. This is due to wide lateral spread of passive pollutant in the aligned set-ups, which is caused by suppressed mean wind flow in such set-ups. The plume is asymmetric in all cases because of the random layout of the individual buildings. The highest buildings with height 1.57H cause severe disturbance of the flow field and the plume is driven to the areas with lower building heights than average. These areas can be found on the right hand side of the source and therefore the plume is forced to go to the right. This phenomenon is more significant and visible for the denser set-ups.

The comparison with previous experiments (e.g. by MacDonald et al., 1997 and Mavroidis, 2000) is difficult because of the significant difference in the release conditions. In the other studies the tracer gas was emitted in front of the building array to the boundary layer free stream. Therefore a wide lateral spreading of the tracer close to the source was not observed. The difference in the plume shape for aligned/staggered set-ups was clearly shown
in Fig.2 due to much better spatial resolution of the measurement points than the previous experiments had.

![Figure 2: Mean dimensionless concentration distribution at height z=0.29H for E set-ups.](image)

**Vertical transport**

Horizontal and vertical advections are two main mechanisms of passive contaminant transport. Less dense and aligned set-ups allow higher wind speeds at the street level compared to denser and staggered set-ups. However, nearly the same concentration at lower elevations in all cases is caused by the enhanced vertical transport of passive tracer. The vertical wind speed component and the concentration of passive tracer gas were measured simultaneously at one place to obtain the normalised vertical advective and turbulent fluxes \( w_c^*/U_\text{Hthin} \) and \( w^*c^*/U_\text{Hthin} \), respectively. The momentum, turbulent and advective fluxes as well as normalized contribution of the turbulent flux to the total flux (from 0 to 1) in the leeward street canyon position are shown in Fig.3. The magnitude of the advective vertical flux is predominant within the roughness sublayer, the turbulent transport becomes important in the inertial layer above urban canopy as is shown last column of plots in Fig.3.

The space adjacent to the leeward and windward façades plays a crucial role in the vertical transport of the passive pollutants from the ground level. The mean vertical velocity is negative in the windward regions and positive in the leeward regions following the well-know street canyon vortex layout (Oke, 1987). Therefore, the sign of the advective vertical transport is given. Data in Fig.3 show that the turbulent vertical flux has magnitude much smaller than advective vertical flux within the urban canopy. They reach the same magnitude at the rooftop level and the turbulent transport prevails in the higher levels, where the mean value of vertical velocity and also the advective vertical flux become zero. The magnitude of both advective and turbulent transports is much higher in the case of higher packing densities (bold lines).
However, the influence of the packing density is less significant than the influence of the canopy arrangement. The highest values of both fluxes within the vertical profiles were found approximately in the middle of the obstacle height at all locations, followed by the rapid decrease in the case of advective flux. The turbulent fluxes showed significant values also above canopy, sometimes displayed secondary local maximum at height around 1.5 - 2H, and played significant role in the ventilation process.

Figure 3: Vertical profiles of Reynolds stress, turbulent flux, advective flux, and contribution of turbulent flux to the total flux at leeward position for C, D, and E set-ups in first, second, and third column, respectively.

Conclusion

The dispersion of the passive pollutant through an idealised urban canopy is greatly influenced by the initial spread from the source. This phenomenon is mainly driven by the layout of the obstacles, but not by packing density. The comparison of the advective and
turbulent fluxes within 18 different arrangements of idealised urban canopies has shown prevailing advective transport close to the building walls and significant contribution of the turbulent transport at the edge of the plume and at the roof top areas. The strongest downward and upward advective transport of the passive contaminant was found at windward and leeward positions, respectively.

Enhanced turbulent and advective vertical transport of passive tracer were found within the denser set-ups and set-ups with more variable building heights. On the other hand, these set-ups suppressed the horizontal ventilation. Since the ground level concentration do not vary significantly, according to our experiment these two phenomena are of the same magnitude.

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