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A wind tunnel study of the effects of adjacent buildings on near-field pollutant dispersion from rooftop emissions in an urban environment

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ABSTRACT

This paper presents results from a wind tunnel study of near-field pollutant dispersion from rooftop emissions of two multiple building configurations. The configurations mainly consisted of an emitting building in the presence of an upstream and a downstream building. The various parameters that were varied include: stack height (h_s), stack location (X_s), spacing between upstream and emitting building (S1), spacing between downstream and emitting building (S2) and exhaust momentum ratio (M). Gas concentrations were measured at various building surfaces using a gas chromatograph. The wind tunnel dilutions were also compared to ASHRAE, 2007 and 2011 models. Results show that a taller upstream and a taller downstream building inhibit the plume from dispersing, thereby increasing the pollutant concentrations on the roof of the emitting building and leeward wall of the upstream building. In general, the spacing between the upstream and emitting buildings, besides the heights of each building were found to be critical parameters influencing the plume characteristics. ASHRAE, 2007 predictions were found to be overly conservative for the isolated building, while ASHRAE, 2011 estimates compared well with experimental data for a few cases. Safe placement of stack and intake on various building surfaces to avoid plume re-ingestion are suggested based on this study.

1. Introduction

Pollutants released from a rooftop stack can re-enter the building from which they are released or even enter a neighbouring building (Stathopoulos et al., 2008). In an urban environment, buildings are closely spaced as shown in Fig. 1, which depicts a view of downtown Toronto, Canada as seen from the CN tower. Unfortunately, the state-of-the-art is not fully developed to accurately assess the flow and concentration of pollutants through such a densely populated urban layout. Mavroidis and Griffiths, 2001 performed a flow visualization study (Fig. 2) for smoke dispersing through an array of obstacles, representing buildings. Their study showed that the plume geometry was affected as the spacing between the obstacles changed. However, no detailed study has been made to understand the pollutant flow in an urban environment. Most studies have focused on isolated building configurations that seldom exist in the built environment (e.g. Halitsky, 1963; Wilson, 1979 etc.). Near-field plume dispersion is greatly influenced by adjacent buildings as opposed to far-field problems where atmospheric turbulence is greater (Saathoff et al., 2009). There are many studies that have focussed on pollutant dispersion in street-canyons using wind tunnel and CFD simulations (e.g. Wedding et al., 1977; Chang and Meroney, 2000, 2001, 2003; Meroney, 2010), with few studies on the application of ASHRAE models on micro-scale pollutant dispersion problems (Stathopoulos et al., 2004, 2008). Recently, Hajra et al., 2011 carried out a detailed investigation of the effects of upstream buildings on near-field pollutant dispersion. The effect of downstream buildings of different geometries on effluent dispersion from rooftop emissions was performed by Hajra and Stathopoulos, 2012 more recently. The results from both these studies provided design guidelines for the safe placement of stack and intake on various building surfaces. The next step would be to include the effects of urban environment in terms of additional buildings placed in the vicinity of the emitting building which would affect the wind and pollutant flow. In order to accomplish this, the present study aims to extend the ongoing investigation to multiple building configurations consisting of a building placed upstream and another building placed downstream of an emitting building.

Efforts were made by Li and Meroney, 1983 to distinguish between near-field and far-field dispersion problems. They defined the “near-wake” region as $x/H < 5$, where x is the distance of the receptor from the source and H is the height of the building. Similarly, Wilson et al., 1998 defined near-field to be the distance

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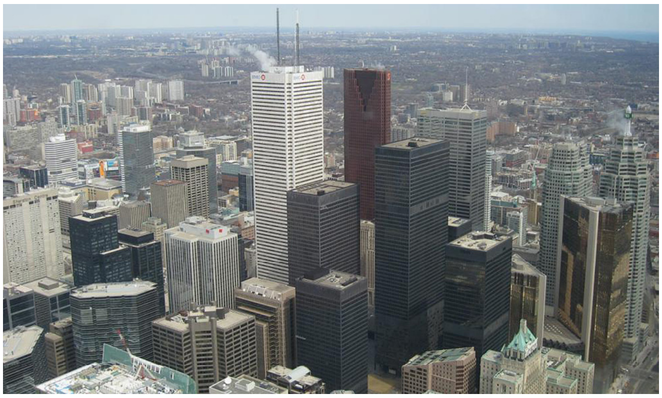

Fig. 1. View of downtown Toronto, Canada; picture taken from CN Tower.

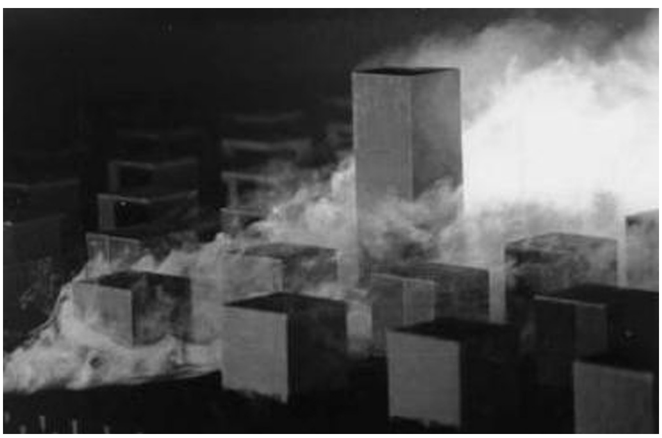

Fig. 2. Smoke dispersing through an array with an in-line configuration and a spacing of $S/H=1.5$, with a taller obstacle ($H=3$ W) located in the 3rd row of the array (from Mavroidis and Griffiths, 2001).

within the "recirculation region" from the source which is estimated from the dimensions of the building perpendicular to wind direction. The results of Wilson's study are still being used in the semi-Gaussian ASHRAE, 2007, 2011 models.

Other available dispersion models such as ADMS, SCREEN and AERMOD were not used for this study since they are incapable of simulating the turbulence caused by nearby buildings, and hence cannot accurately predict pollutant concentrations on building roofs (Stathopoulos et al., 2008). In fact, Riddle et al., 2004 suggested that "*such atmospheric dispersion packages are not able to assess the local effects of a complex of buildings on the flow field and turbulence, and whether gas will be drawn down amongst the buildings*". However, ASHRAE, 2007, 2011 have been used for the present study since they are capable of assessing dilutions on rooftop receptors, based on the recirculation zone formed in the building wake.

Section 2 of this paper describes the air and pollutant flow for different building configurations followed by a description of ASHRAE, 2007, 2011 models in Section 3. The experimental procedure and the various building configurations examined have been discussed in Sections 4 and 5 respectively. Results and discussion have been presented in Section 6. This is followed by design guidelines for safe placement of stack and intake on various building surfaces, as well as a summary of findings in Section 7. The conclusions of this study have been presented in Section 8, besides an appendix illustrating the application of ASHRAE, 2007, 2011 models.

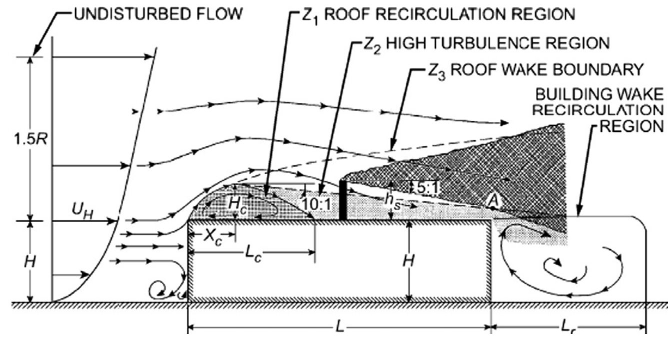

Fig. 3. Design procedure for required stack height to avoid contamination (from Wilson, 1979).

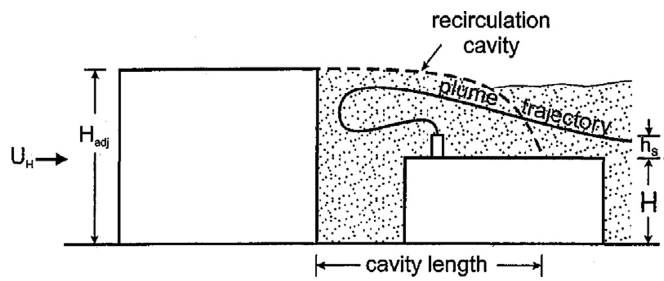

Fig. 4. Recirculation cavity for a taller upstream building (from Wilson et al., 1998).

2. Air and pollutant flow around buildings

Based on a series of experiments, Wilson, 1979 showed that the size of the recirculation region (shown as L_r in Fig. 3) formed in the wake of a building is estimated by using the building dimensions perpendicular to wind direction:

$$L_r = B_s^{0.67} B_L^{0.33} \tag{1}$$

where:

L_r is the zone of recirculating flow formed in the building wake (m),
B_s is the smaller building dimension perpendicular to wind direction (m),
B_L is the larger building dimension perpendicular to wind direction (m).

Wilson showed that turbulence due to the building occurs up to about 1.5 times 'R' from the roof of the building, where 'R' is the scaling length for roof flow patterns. The value of 'R' is obtained from Eq. (1), by replacing 'L_r' by 'R'. He suggested that the pollutants released from a rooftop stack form a triangle (in two dimensions) with the edges at 5:1 away from the plume centreline. Additionally, a recirculation length (L_c) also forms on the roof besides L_r in the wake for a longer building, as shown in Fig. 3. However, Wilson et al., 1998 was able to show that the plume trajectory changes in the presence of an upstream building, as shown in Fig. 4. They showed that the wake recirculation cavity of the upstream building brought the plume towards the leeward wall of the upstream building and the roof of the emitting building thereby increasing effluent concentrations on the emitting building. Similar observations were made by Stathopoulos et al., 2004 during field measurements at Concordia University. According to Wilson et al., 1998, the presence of a taller downstream building prevented the plume from dispersing along the roof of the emitting building with a small portion of the plume also escaping from the sides as "side-leakage" and over the roof of the