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Wind tunnel simulation of short-range dispersion in an urban area

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Abstract: *The influence of surrounding buildings on the dispersion of gaseous release within a realistic urban environment was investigated in a boundary layer wind tunnel. An area of about 300 meters radius around the intersection of Marylebone Road and Gloucester Place in central London was simulated in the laboratory at a scale of 1:200. The experiments were conducted at a free stream velocity of 2.5 m/s for -51°, south-westerly wind, with reference to Marylebone Road.*

The development of plumes released at ground level and roof level was investigated. It is found that the reflected Gaussian model compares well with the upward vertical diffusion of the plume and under-predicts the concentration near the ground where the detailed arrangement of the buildings dominates the dispersion. It seems that the upper boundary of the plume was not affected by the release height; however, the ground level concentrations are considerably higher for the ground level releases than a roof level release within the distance of 3H, where H is the mean building height. Whether the plume released at ground level flows over or around the nearby buildings depends on the street dimension where the source was located. The concentration distribution in cross-sections of street canyons in realistic urban environment was also examined for ground level releases. It is believed that this study will improve the understanding of dispersion processes in urban environments and provide the necessary information to develop and validate practical mathematical model for urban air quality.

Keywords: *air quality, short-range dispersion, urban street canyon, wind tunnel simulation.*

1. Introduction

It is reported that by 2000 nearly half of the world's population was found in urban areas, and air quality in cities was deteriorating as the population, traffic, industrialisation and energy use increased. This problem is more severe in developing countries than the developed countries (Fenger, 1999). It is now recognised that traffic emissions are the most dominant and increasing source of urban air pollution world-wide (Colvile et al. 2001, Mayer, 1999). Many of the substances directly emitted by vehicles in the ambient air or indirectly produced through photochemical reactions pose a serious hazard to human health (Vardoulakis et al. 2003).

Nowadays, automatic monitoring network operate in many European cities providing air quality information on a regular basis. The number and the location of the monitoring stations within a city are limited by practical constraints, from which the data gathered are interpreted by assuming that pollutant concentration observed at a single or a few permanent stations are representative of the pollution level of the entire city. However, it is well accepted that short-term concentration might vary by a factor of 5 from one side of the street to the other within an urban street canyon (Wedding et al., 1977, Pavageau and

Schatzmann, 1999). In order to estimate the exposure of the urban inhabitant and to evaluate how representative the monitored urban air quality is, we need to understand how pollutants are dispersed in the urban canopy. It has been reported that such a dispersion process depends on the nature of the release, the property of the substance, the prevailing meteorological conditions and the influence of the surrounding terrain and buildings.

Our understanding of characteristics of flow and dispersion around individual obstacles has been progressed through studies by Robins and Castro (1977a, b), Wilson and Britter (1982), Eckerle and Awad (1991) and most recently by Mavroidis et al. (2003). There exist some literature on dispersion through uniform regular obstacle arrays, such as Davidson et al. (1995, 1996) and Macdonald et al. (1997, 1998). It is also noticed that literature on near-field dispersion studies in realistic urban environment is rare. Simulations of urban dispersion in real cities mainly come from the Meteorology Institute of the University of Hamburg. They have investigated dispersion in Oklahoma City (Leitl et al., 2003), Basel (Feddersen, 2005) and Hanover (Pascheke et al., 2003) in their wind tunnel. Snyder et al. (2003) also simulated the site of the destroyed World Trade Centre. There studies revealed complex flow and dispersion patterns and indicated that plumes were affected by the detailed building structures in the respective models. The near-field is the region close to the source where the highest concentration and greatest potential damage to human health occurs. It is reported that (Macdonald et al., 1998, Baechlin et al., 1991 and 1992), in this region, it is not just the overall roughness of the surface geometry that affects the dispersion; the details of the obstacles and their layout pattern are also important. The interaction between continuous plumes and surrounding buildings is the major factor affecting short-range pollutant dispersion in urban areas (Mavroidis, et al. 2003).

Davidson et al. (1995, 1996) investigated the dispersion of a point source released upwind a sparse array in both wind tunnel and field experiments, and indicated that the time-averaged concentration profiles were well approximated by a Gaussian distribution laterally and a reflected Gaussian vertically. Macdonald et al. (1997, 1998), who studied the effects of packing density and the width-to-height ratio for urban regular arrays, almost iterated the above point but emphasised that it is true only after a short distance from the source. They further indicated that within this short distance the concentration profiles in the obstacle array were quite variable. It is worth pointing out here that both research groups focused on idealised arrays of simple pattern.

The turbulence within urban arrays was observed by Davidson et al. (1996) to be of greater intensity and smaller scale than at corresponding locations outside obstacle arrays, which will undoubtedly enhance plume dispersion. On the other hand, for a ground level release, the flow was strongly influenced by the nearby building arrangement, and the dispersion thereby obstructed. Plate and Baechlin (1988) introduced a radius of homogenization, also termed the near-field, within which local street features are a dominant parameter and beyond which the buildings act more like a uniform roughness.

Theurer (1995) and Baechlin et al. (1992) found that for irregular arrays of building, the near-field profiles were dominated by the detail layout of the building and were usually not Gaussian shaped; in the far-field, where the behaviour of the plume was no longer affected by individual obstacles but influenced globally by an effective roughness length, a Gaussian plume model provided a good description of the plume behaviour.

The fundamental principle for a plume released in a turbulent flow is that the dispersion depends on the different scales of motion relative to the size of the plume. With reference to the width of the plume, smaller scale turbulent eddies cause mixing within and at the boundary of the plume, and larger or equivalent scale of motions cause the plume to meander. If the plume is large when compared to the overall size of the array then the obstacles will not alter the mean concentration, even though they will change the plume structure and concentration fluctuations. If however the plume is small relative to the array then there will be significant change to the mean dispersion (Davidson et al., 1995).

The objectives of this study were to examine the influence of surrounding buildings on the dispersion of neutrally buoyant plumes released within a realistic urban environment. This is part of a comprehensive project, DAPPLE, whose details can be found in Arnold et al. (2004), or at *www.dapple.org.uk*.

2. Experimental arrangement

2. 1 The Wind Tunnel and the model

The model and the wind tunnel used in this study are described in details elsewhere (Cheng and Robins 2005a), but they are briefly summarised as following. An area of about 300 m radius around the intersection of Marylebone Road and Gloucester Place in central London was simulated in the laboratory at a scale of 1:200. Each street block was represented by a sharp edged rectangular block with a flat roof, but for the concentration results described in this paper, roughness elements were placed on the roof of the model buildings in a similar pattern as in the upstream in an attempt to understand effects of roof features. The mean height of the model buildings is 110 mm, which corresponds to 22 m at full scale.

The experiments were conducted in the EnFlo wind tunnel, which is a low speed open circuit tunnel with a test section of 20 m length and 3.5x1.5 m cross section. It can operate in stable and unstable stratified conditions, but all the measurements described here were performed under neutral stability, without simulating the turbulence due to traffic flow. The model was mounted on a turntable, which is located at the tunnel centreline, 14 m downstream of the working section inlet.

This "low-resolution" model and its co-ordinate system are illustrated in Figure 1. The origin of the coordinate system is at the centre of the intersection. (x, y, z) are along Marylebone Road, Gloucester Place and vertical coordinates respectively, with z=0 being the top surface of the plastic sheet on which the model buildings were mounted.

2. 2 Flow conditions

The approach flow was simulated by the methods described by Irwin (1979, 1981), consisting of uniform inlet flow, vorticity generators and a substantial fetch of a homogeneously rough surface. The upstream roughness elements were 80 mm wide 20 mm high vertical plates, which were arranged in a staggered pattern between rows with both the lateral and longitudinal spacing of 240 mm. The roughness elements were normal to the flow direction.

All the measurements described here were carried out at a nominal free stream velocity of 2.5 m/s, and wind direction of -51° with reference to Marylebone Road in the model co-ordinate system. Based on building height and free stream velocity, the Reynolds number for the experiments described in this study was 18000, which considerably exceeded the critical value of 3400 for flow to be Reynolds number independent (Hoydysh et al., 1974).

2.3 Dispersion measurements

Two continuous sources, with one being 10 mm above the roof of Westminster City Council and another 10 mm above the ground at the road centre in Crawford Street, are used to investigate the development of the plume in urban environment. Both locations are marked with “WCC” and “A” in Figure 1 respectively. Concentration distributions across street canyons were also examined for release at A. The ground level concentration was measured at 10 mm above the surface in all cases. The emission, a mixture of air with a trace of propane (C_3H_8), was passive. The flow-rates of trace and carrier gas were separately controlled by two Hi-Tech thermal mass flow meters before entering a mixer. The source was released continuously downwards via a vertical open-ended pipe with an internal diameter of 6 mm at a flow rate no more than 3 l/min.

A fast flame ionisation detector (FFID), a combustion HFR400 with a frequency response at least 350 Hz, was used to detect the instantaneous concentration. Before measurements the FFID was calibrated with hydrocarbon gases of known concentrations. A series of vertical profiles were performed and the locations are also shown in Figure 1. The sampling frequency was 200 Hz and the averaging time for each measurement was 4-5 minutes.

All the concentration data presented in this study is the time averaged mean concentration; the non-dimensional concentration is defined as:

$$C_* = C\,U_r H^2 / Q_s \qquad (1)$$

where C is the measured volumetric concentration (ppm) divided by the strength of the source (ppm); U_r is the free stream velocity (m/s); H is the mean model height (m) and Q_s is the volumetric flow rate from the source (m^3/s).

3. Concentration results and discussion

3.1 Concentration distribution in nearby street canyons

Over the past two decades, significant progress has been made in measuring and modelling dispersion within urban street canyons. A recent review on air quality in street canyons was given by Vardoulakis et al. (2003). It is generally accepted that the geometry of a street canyon and wind direction are the determining factors of flow patterns. When the above-roof flow is perpendicular to the street canyon, based on the geometry, Oke (1987) identified three flow regimes: isolated roughness flow, wake interference flow and skimming flow. Among them, skimming flow, in which the bulk of the flow skims over the canyon, provides an effective sheltering effect at pedestrian level and minimum ventilation of the canyon, and is relatively ineffective in removing pollutant, heat and moisture (Hunter et al., 1992). A number of investigations have revealed the existence of vortex cells within a street canyon, most notably studies by Depaul and Sheih (1986), Nakamura, and Oke (1988), Hunter et al. (1992), Johnson and Hunter (1999), Jeong and Andrews (2002). Furthermore, Meroney et al. (1996) compared an isolated street canyon in open country and a street canyon in an urban environment, and discovered that the dynamic and dispersion characteristics of the flow in the two cases were quite different.

In the present work, near-field dispersion was investigated by taking a series of vertical profiles of concentration immediately downwind of continuous sources. The concentration measurements at street cross-sections were also carried out in a regular street canyon in Crawford Street and a deep street canyon in Durweston Street for ground level release at "A" (see Figure 1). According to the classification by Oke (1987) and the canyon geometry, the flow patterns for both streets are skimming flow. The locations of the vertical profiles and the source are illustrated in Figure 3 in details.

3.1.1 Regular street canyon; Crawford Street

To understand the interaction between the plume from a continuously releasing source and the surrounding buildings, numerous concentration contours across and along the street were performed in Crawford Street where the source was located. The dimensions of its cross-section are shown in Figure 4. Obviously, one side the buildings are 1.3 times taller than the other side, and the aspect ratio is close to 1, which is a regular step-down street canyon (Vardoulakis et al., 2003). A series of concentration contours in cross-sections away from the source and vertical planes along the street are illustrated in Figure 5 (a) to (e) and in Figure 6 (a) to (c) respectively. Here it is emphasized that the source was released at the centreline of the street at x=-356 mm and the wind direction was at an angle of -51° to the canyon axis. A few conclusions can be draw from these data. Firstly, at the cross section immediately downstream of the source, very high concentration was observed in the leeward vicinity of the street and almost zero concentration was measured in the windward of the street. Secondly, the concentration is always higher in the leeward half than that in the windward half for all cross-sections investigated, and therefore the concentration distribution is unbalanced across the street canyon. This is likely due to the vortex structure within the canyon. Thirdly, the plume centre (concentration maximum) is observed to be offset from the centreline towards the leeward side of the street, and its height increases with distance away from the source in all cross-sections examined, which is comparable with the presence of a helical vortex structure along the street as described by Johnson and Hunter (1999). Finally, substantial concentrations were always detected at heights above the roof level over the street canyon even at the closest cross-section, showing that a street canyon in a realistic urban environment, where the dominant features are high, irregular and heterogeneous structures, is better ventilated than that in a uniform regular urban roughness situation (Meroney et al. 1996). The asymmetry of the street canyon may have contributed towards the pollutant dispersion from the street cavity.

The horizontal and vertical profiles of concentration in the cross-section at x=-100 mm are shown in Figure 7(a) and (b) respectively. It is observed that the concentration increases monotonically across the street canyon from windward to leeward at all heights within the street canopy, which means one side of the street was more polluted than the other. This indicates that only one vortex cell exists within the street canyon. The difference in building height on both side of the street was perhaps not larger enough to permit the existence of a second vortex for such an asymmetrical canyon as described by Soulhac et al. (2002)

3.1.2 Deep street canyon; Durweston Street

According to the classification by Vardoulakis et al. (2003), Durweston Street with $H/W \approx 3.7$ and $L/H \approx 3.7$ is a deep and short street canyon, where L is the canyon length. The dimensions of the cross-section of the narrow street canyon are shown in Figure 8.

The concentration contours at two cross-section with y=-870 mm and y=-790 mm respectively are displayed in Figure 9 (a) and (b), where the "+" denotes the location of the data points. The vertical and horizontal profiles for both cross-sections are similar, and only those at y=-790 mm are presented in Figure 10 (a) and (b). From the concentration contours in Figure 9, it has been found that, in the lower part of the street canyon the concentration on the windward side is higher than that of the leeward, which is due to an anti-clockwise vortex; and in the upper part of the street canyon, the concentration at the leeward side is higher than that of the windward side, which again is likely as a result of clock wise vortex. From the horizontal profile of concentration shown in Figure 10 (a), it also revealed that the concentration increases with increasing x at height below z=40 mm, and decrease with increasing x across the street width at heights above. These characteristics of the concentration distribution in a street canyon are consistent with the classical picture of a counter-rotating vortex structure in a deep street canyon with aspect ratio larger than 2 (Lee and Park, 1994; Soulhac, et al. 2002), and contradict the prediction by Jeong and Andrews (2002) that three vortices exist in very narrow streets with H/W≥3. The boundary of these vortices is around z=40 mm for the cross-section at both locations. The maximum concentration region is located in the windward lower corner at the bottom of the street canyon. The parallel iso-concentration lines at the roof level of the street canyon suggests that the approaching flow skims the canyon and forces the vortex to remain confined within the canopy, as was reported by Pavageau and Schatzmann (1999). The concentration contours at the vertical plane along the centreline of Durweston Street are displayed in Figure 11. It is found that the concentration decreases with distance down the street, and significant concentration at height above roof level are only detected at locations y≤-951 mm. The vertical profile at y=-951mm is located on the plume path immediately downwind of the source; concentrations above roof level are likely to be due to advection over the buildings. This point will be discussed further in Section 3.3.

Combining results in Figure 9-11, it is found that the concentration values at heights above roof level are very close to zero for all vertical profiles taken in the rest of this street, which indicates that little pollutant was ventilated from the rooftop of this deep canyon. This also implies that pollutant emitted locally would be trapped within the very narrow street cavity and can only be transported along the street. During the experiments, it was noticed that the concentration values in the deep street canyon are quiet sensitive to small changes in the source and building locations in the models, a similar phenomena was also observed by Scaperdas (2000) who systematically studied an isolated intersection with a basic arrangement of four buildings in the same wind tunnel.

3.2 Plume vertical development with downstream distance

As described above, two source positions were investigated, with one at roof level and another at ground level in the road centre.

In the case of the roof level release, a series of vertical profiles was conducted downstream of the source, in which the distance between the source and the profile location increased from 0.05 m to 1.75 m. The full vertical profiles from ground level are used to fit a Gaussian model. Typical vertical profiles of mean concentration, together with the reflected Gaussian curve, are shown in Figure 12 (a)-(d). The reflected Gaussian profile is defined by;

$$\frac{C^*}{C_{\max}} = \exp\{-\frac{1}{2}(\frac{z-z_p}{\sigma_z})^2\} + \exp\{-\frac{1}{2}(\frac{z+z_p}{\sigma_z})^2\}$$

where C^* is non-dimensional concentration, σ_z the standard deviation of the vertical plume spreading, z_p the effective height of the plume centre, and C_{max} the maximum concentration (neglecting the reflection from the ground). The Gaussian parameters of σ_z, z_p and C_{max} can be estimated at each downwind location by fitting the experimental data to the above equation by the method of least squares; these are listed in Figures 12, where R is the direct distance between source and receptor location.

In general, upward diffusion of the plume is reasonably well described by the Gaussian model as this is a classical dispersion process and the presence of the buildings has no direct effect on the up boundary of the plume. Very close to the source the plume is fully Gaussian-like with its centre at about roof level. However, once significant material has been entrained into the street network, the concentration field below roof level tends to a well-mixed street with little variation with height and the Gaussian mode would underestimate the concentration there.

The behaviour of the plume from ground level source is somewhat different. Results of the analysis are shown in Figure 13 (the full vertical concentration profile closest to the source was 442 mm away from it as shown in Figure 18). The experimental data, taken at locations denoted by ⊗ in Figure 1, do not fitting well with the Gaussian model and one of the results was displayed in Figure 13(a). The Gaussian profile was also under-predict the concentration near the ground at the centre of Marylebone Road, which was shown in Figure 13(c). In all these locations, the vertical profiles at least the lower part of them may well be within the horseshoe vortex region of the preceding buildings. The rest of the vertical profiles are fitting well with the reflected Gaussian model.

The maximum concentration C_{max} in each vertical profile is plotted against the downwind distance from the source position in Figure 14. Similar to the empirical correlation derived from the maxima concentrations in the ground level, which was described in Cheng and Robins (2005a), these concentration data for both releases can be fitted to the form of power law and are independent of the building height H but with rather different fitting constants.

The development of the effective height of the plume centre (that is z_p) with downstream distance is exhibited in Figure 15 for both the ground level and roof level release, where z_s is the source height. The upper boundary of the plume is defined as of $z_{up}=3\sigma_z+ z_p$ and plotted in Figure 16 against downwind distance. Concentration contours in a vertical plane downwind of the source are plotted in Figure 17 and 18 for roof level and ground level releases respectively, where the building cross sections are also shown.

Combining Figure 15-18 and comparing the data for the ground level release and roof level release, it appears that the height of the release has no obvious influence on the vertical extent of plume except that the location of the maximum concentration is shifted accordingly, which implies that the canopy layer is well mixed.

However, the ground level concentration against direct distance between source and measurement location is plotted in Figure 19 non-dimensionally. It is found that the ground level concentration is much higher for ground level release than roof level release within the region of *3H* radius. Beyond that, the difference between them becomes insignificant.

3.3 Flow over or around the buildings

To understand whether the pollutant passed over or around the nearby downstream buildings, a number of vertical profiles conducted at the streets along the roads surrounding building B23 (see Figure 1) were examined. One vertical profile was performed over the roof of B23 and another over the roof edge of B24. The first three vertical profiles immediately downwind of source "A" normalised by the building height of B23 are displayed in Figure 20. It is evident that immediately downwind of the source location, tracer was detected over the roof edge of B24, but significant concentration were measured at the location over B23. Comparing the vertical profile over B23 with the concentration contour at x-section of x=-200 mm in Crawford Street in Figure 9(b) and that at x-section of x=-870 mm in Durweston Street in Figure 5(a), little pollutant was detected above the roof level of Durweston Street, but significant concentration was observed at the roof level of Crawford Street. It is obviously evident that the pollutants detected above the roof of B23 come from Crawford Street and not from Durweston Street. Similarly, the concentration over the initial section of the deep street canyon, which is connected to Crawford Street, is likely due to the same reason.

Examining all the vertical profiles surrounding building B23, it is clear that a large amount of the pollutants were carried into Gloucester Place via Crawford Street, and a small fraction transported through the side street as well as over the buildings, eventually joining the main flow at the intersection between Gloucester Place and York Street downstream. It is likely that the strong turbulence intensity and canyon vortices in the canopy layer contribute to this vertical dispersion in the street canyon where the source was released. Combining these results with the concentration data in cross-section of the street canyons, whether the pollutants released at the ground will flow over the building or not depends on the height to width aspect ratio of the street canyon where the source was located. In a deep narrow street canyon, it is unlikely the pollutants emitted at the bottom of the canyon will flow over the building immediately downstream. However the heterogeneous nature of realistic urban environment has assisted pollutant ventilation in street canyons.

4. Conclusions

The development of plumes released at ground level and roof level in a realistic urban environment has been investigated. It is found that the reflected Gaussian model fits well with the upward vertical diffusion of the plume but under-predicts the concentration in the building wake and near the ground, where the dispersion is dictated by the detail arrangement of the local buildings. It seems that the upper boundary of the plume was not affected by the release height, however ground level concentrations are considerably higher for the ground level release than the roof level release within the distance of $3H$. Two street canyons have been carefully studied. It is revealed that, in a deep street canyon with an aspect ratio of 3.7, the pollutants were trapped inside the street cavity, and not ventilated from the roof top of street canyon; in a street canyon with an aspect ratio close to 1, substantial concentration was detected at the roof top of the canyon. Therefore, whether a plume released at ground level flows over or around the nearby building depends on the street dimension where the source is emitted. This study also confirmed the existence of two counter-rotating vortices in a deep street canyon and the presence of one vortex cell in a regular asymmetric canyon.

The measurements in the flow field have demonstrated that within the roughness sublayer, where the flow is strongly influenced by individual buildings, the flow field is independent of the upstream flow. Whether some roof features are considered or not in the wind tunnel simulation seems to have no obvious effects on the flow and consequence dispersion in that layer.

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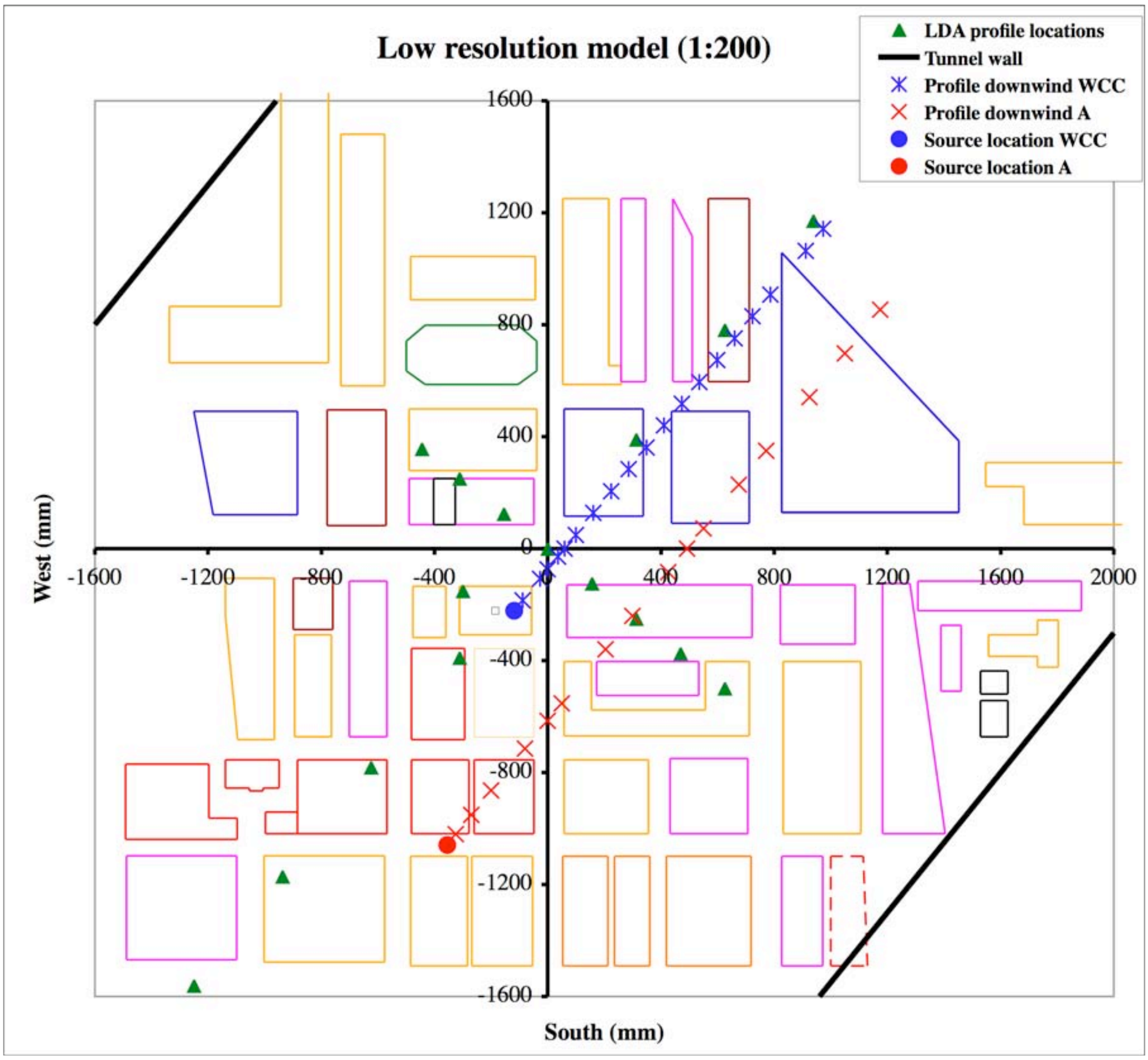

Figure 1. Plan view of the "low resolution" model (1:200) used in the wind tunnel simulation.

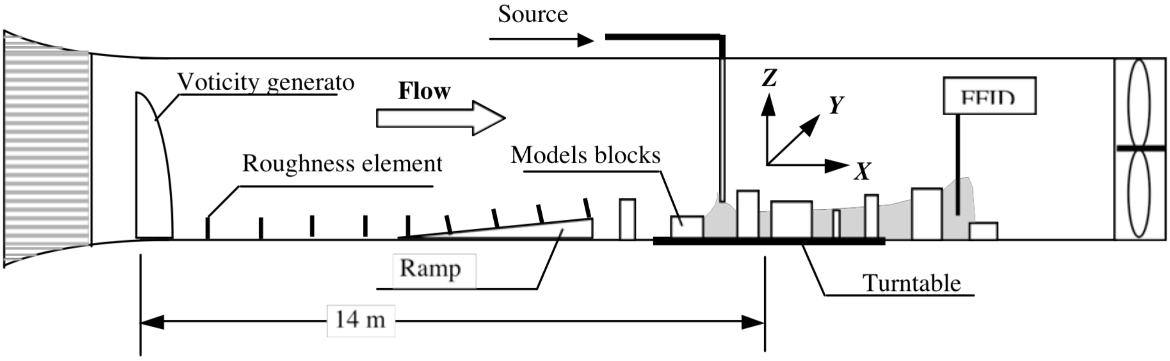

Figure 2. Schematic diagram of the arrangement in the wind tunnel.

Figure 3. Detailed profile locations in the region near the source.

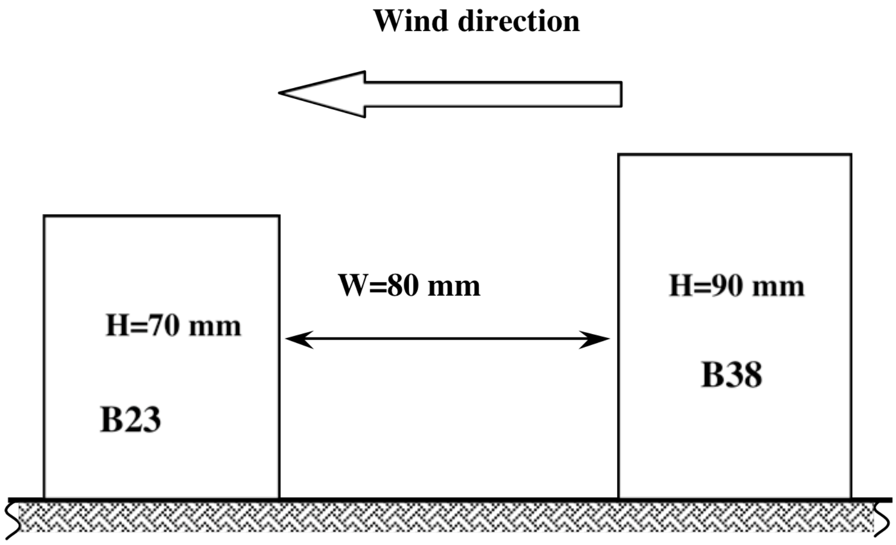

Figure 4. Street dimensions for regular street canyon (Crawford Street H/W≈1.0)

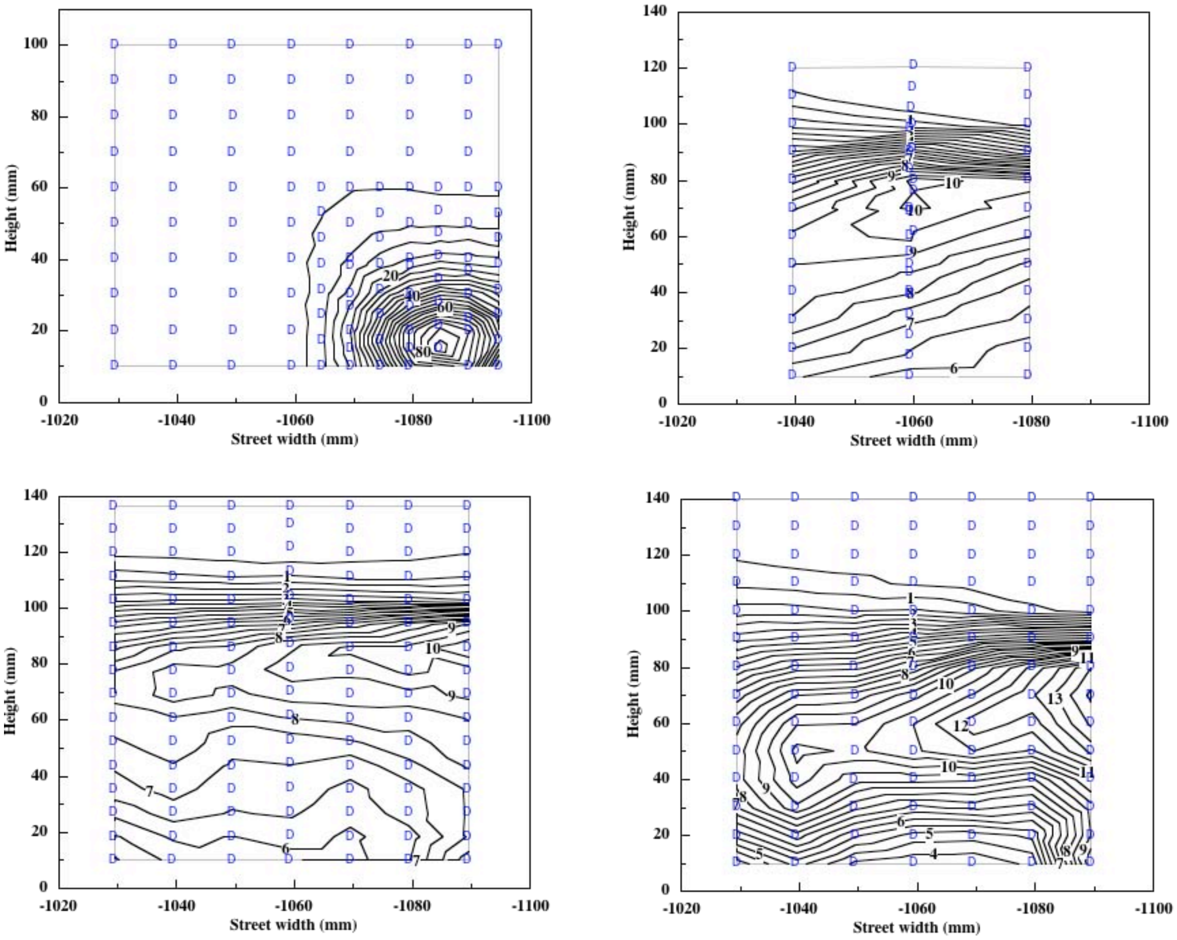

Figure 5. Concentration contours in cross-sections of Crawford Street (a) x=-320 mm; (b) x=-200 mm; (c) x=-150 mm; (d) x=-100 mm; (e) x=-50 mm.

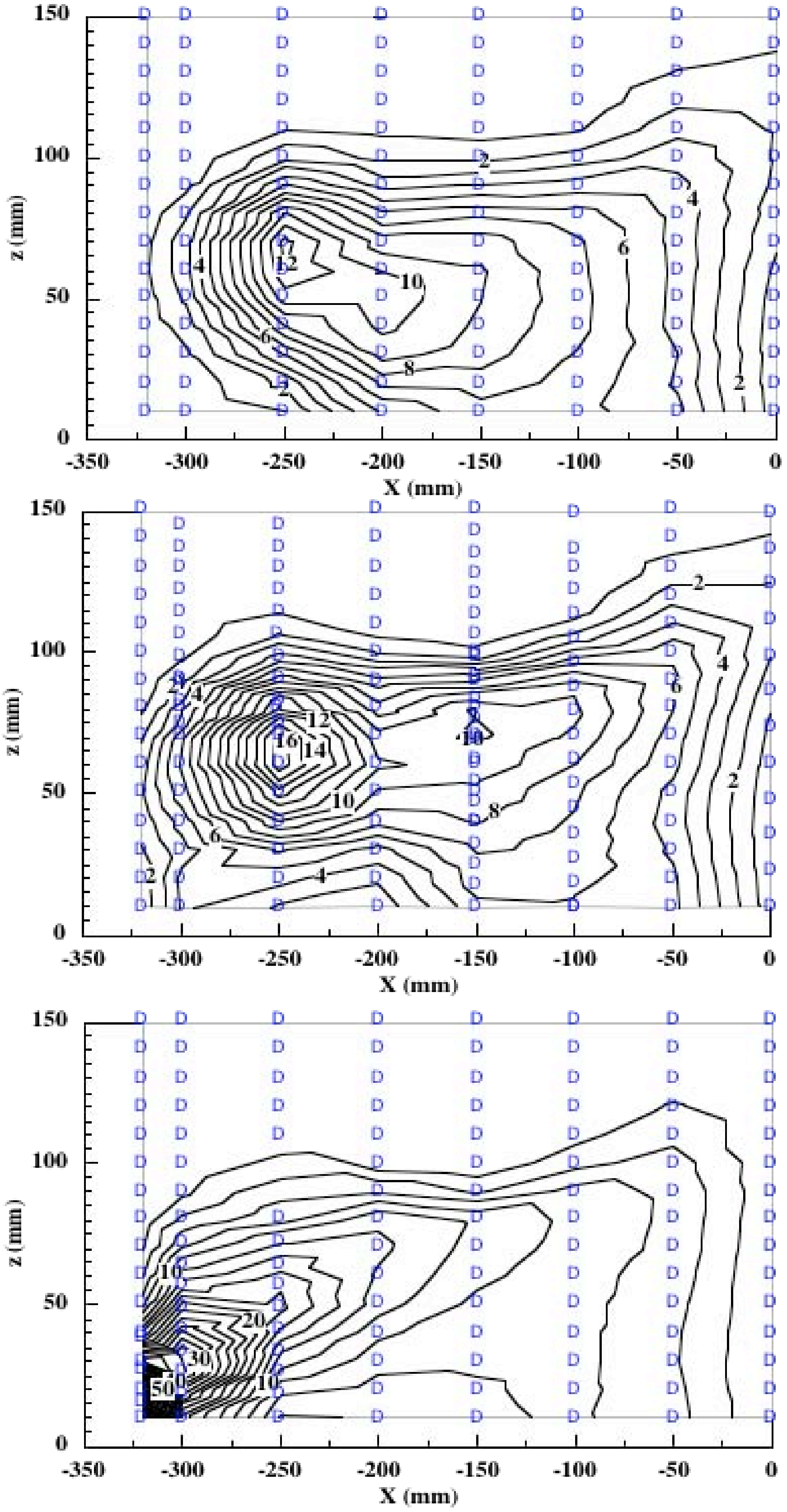

Figure 6. Concentration contours in vertical planes of Crawford Street. (a) y=-1039.5 mm; (b) y=-1059.5 mm; (c) y=-1079.5 mm.

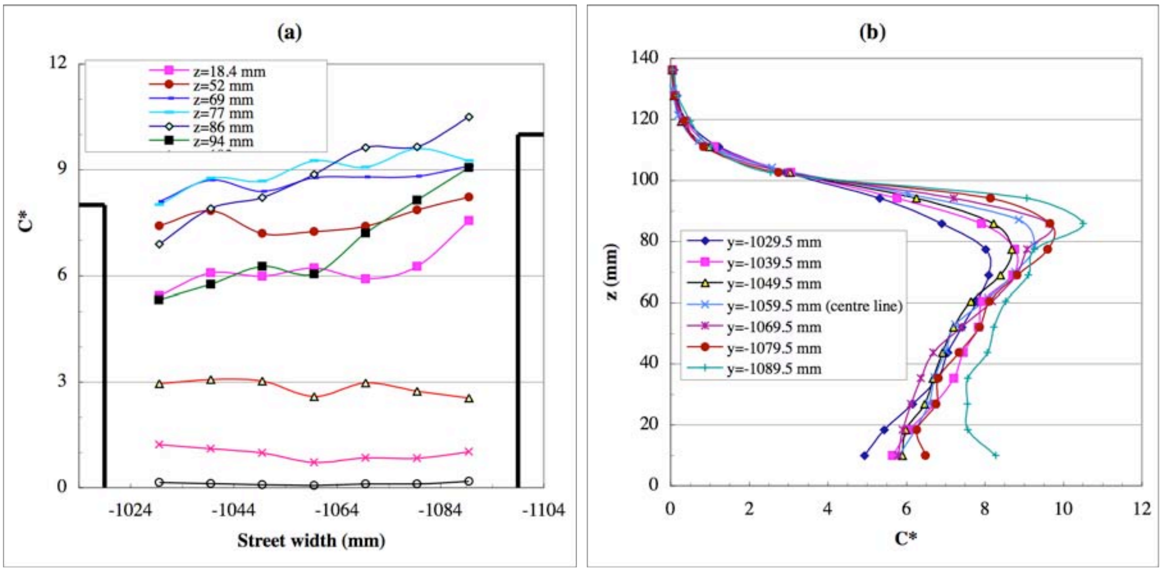

Figure 7. (a) horizontal profiles (b) vertical profiles of concentration in Crawford street.

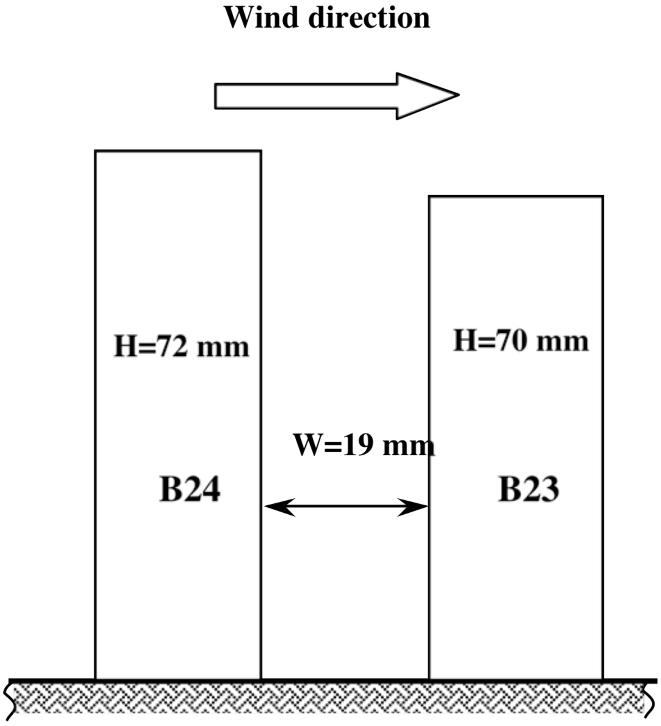

Figure 8. Street dimensions for deep street canyon (Durweston Street H/W=3.7).

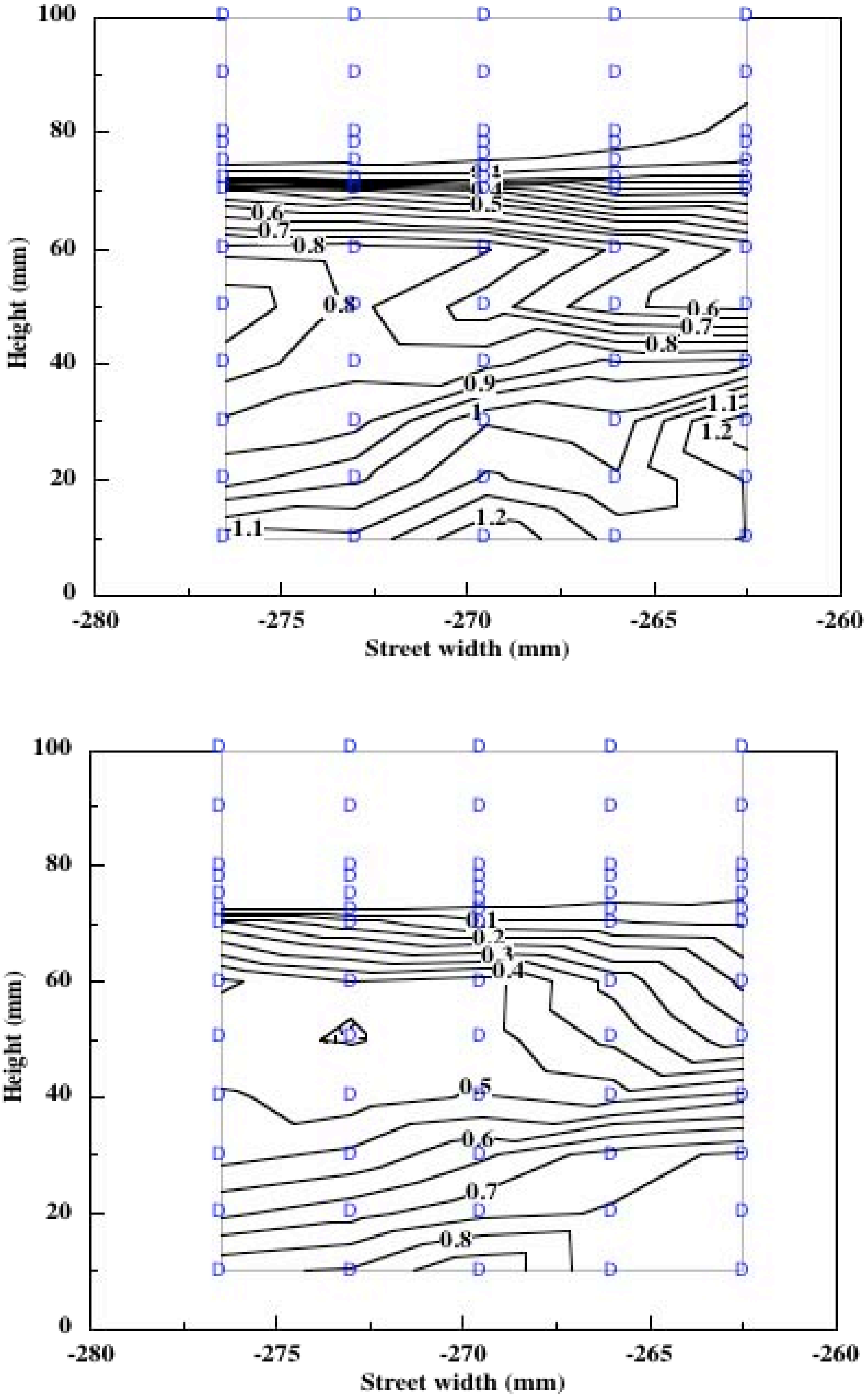

Figure 9. Concentration contours in cross-sections of Durweston Street (a) y=-870 mm; (b) y=-790 mm.

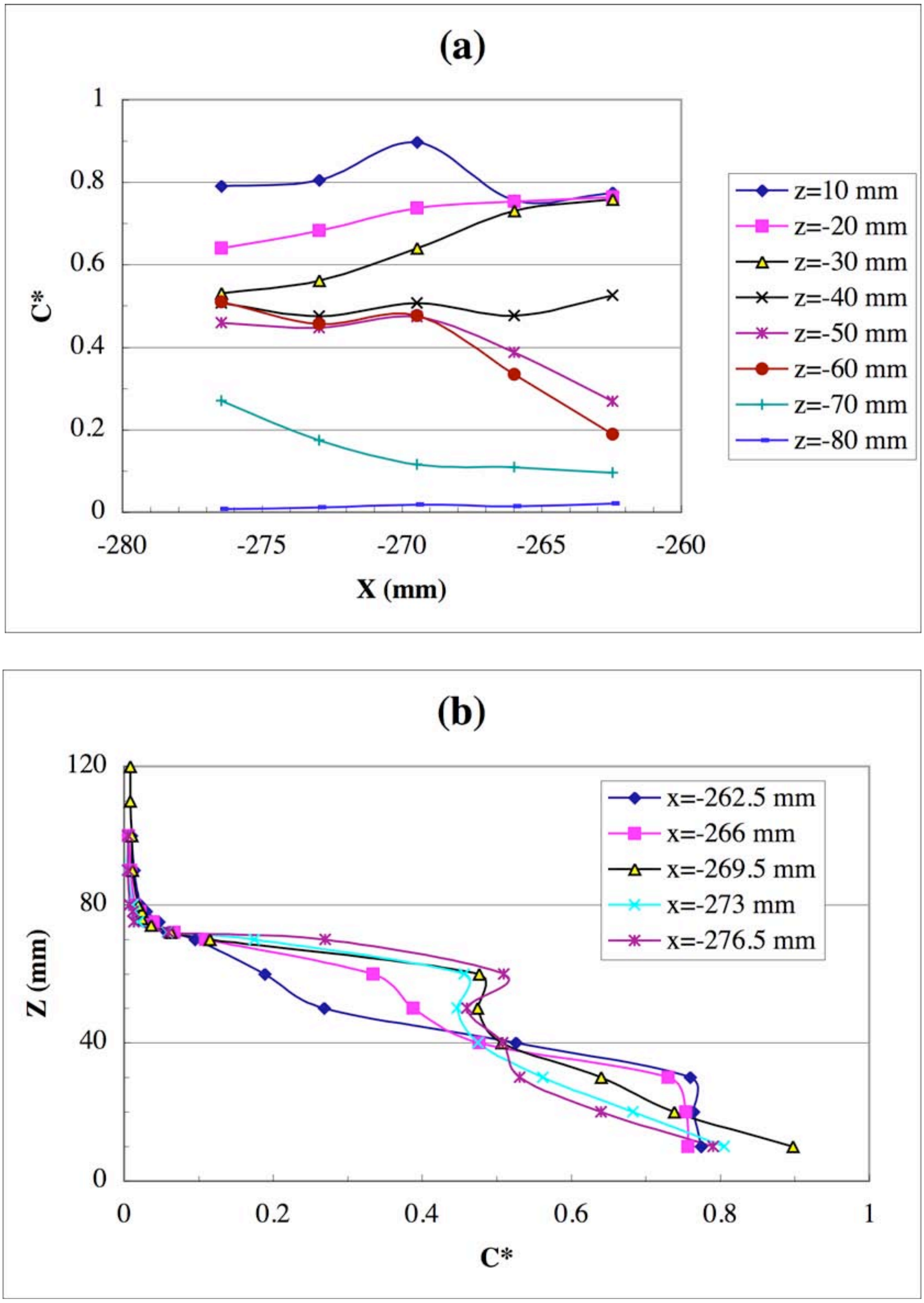

Figure 10. (a) Horizontal profiles; (b)Vertical profiles of concentration at cross section (y=-790 mm) in Durweston Street.

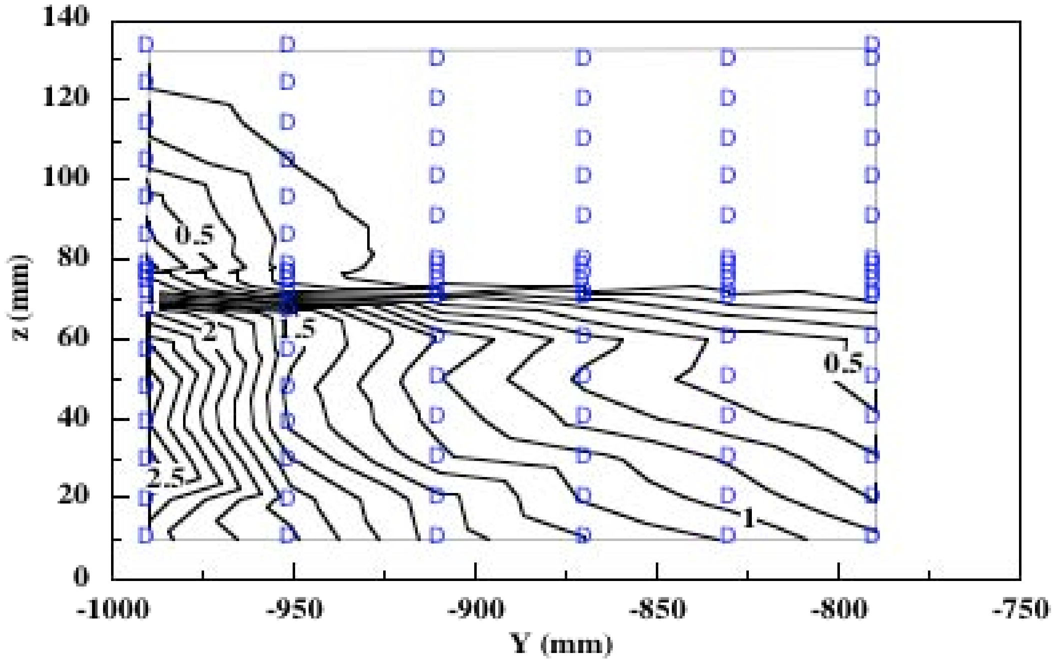

Figure 11. Concentration contour in the vertical plane along the street centreline in Durweston Street.

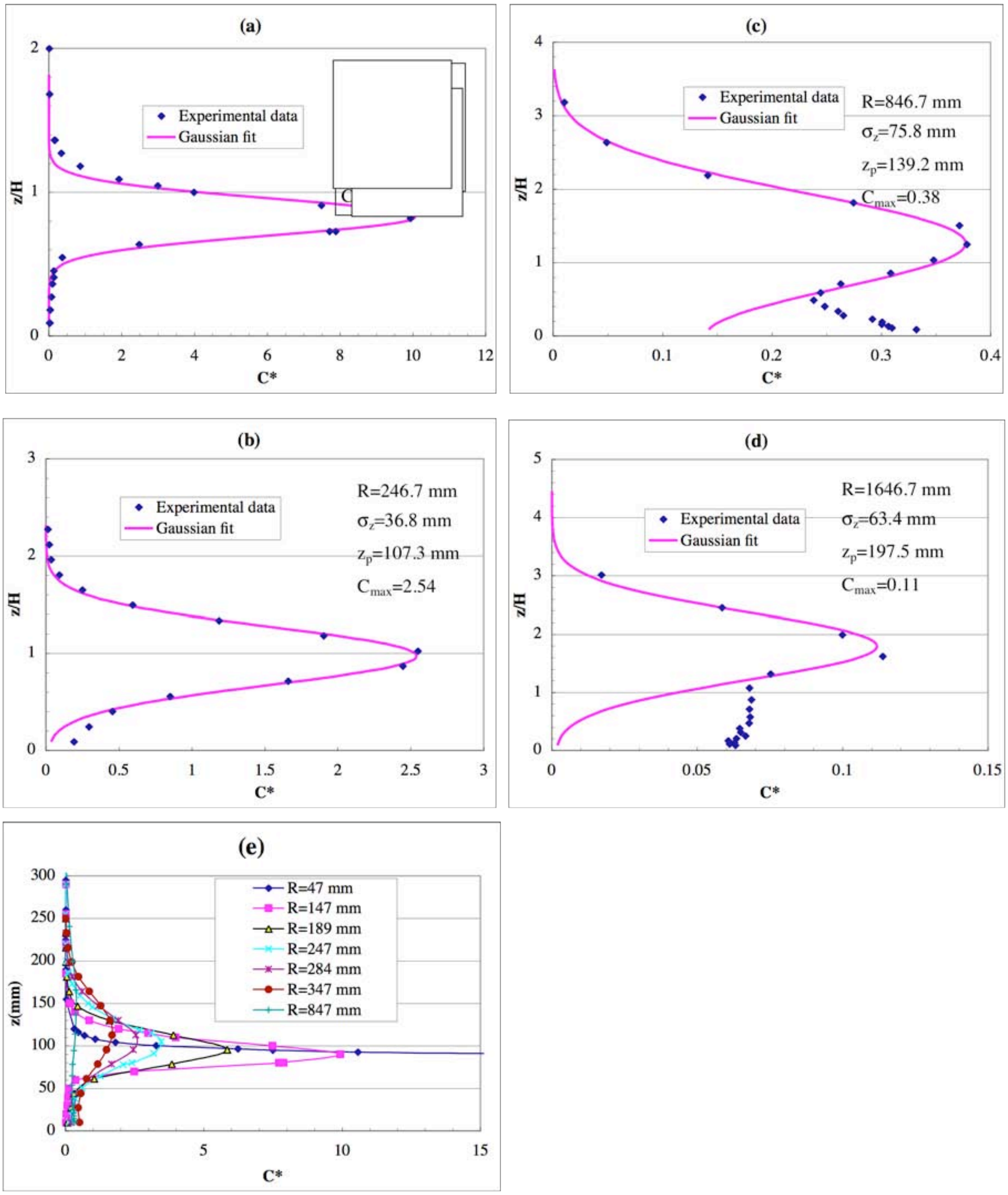

Figure 12. Vertical profiles of mean concentration together with the reflected Gaussian model at different downwind distance from the source for the roof level release. (a) 146.7 mm; (b) 246.7 mm; (c) 846.7 mm; (d) 1646.7 mm; (e) a number of vertical profiles.

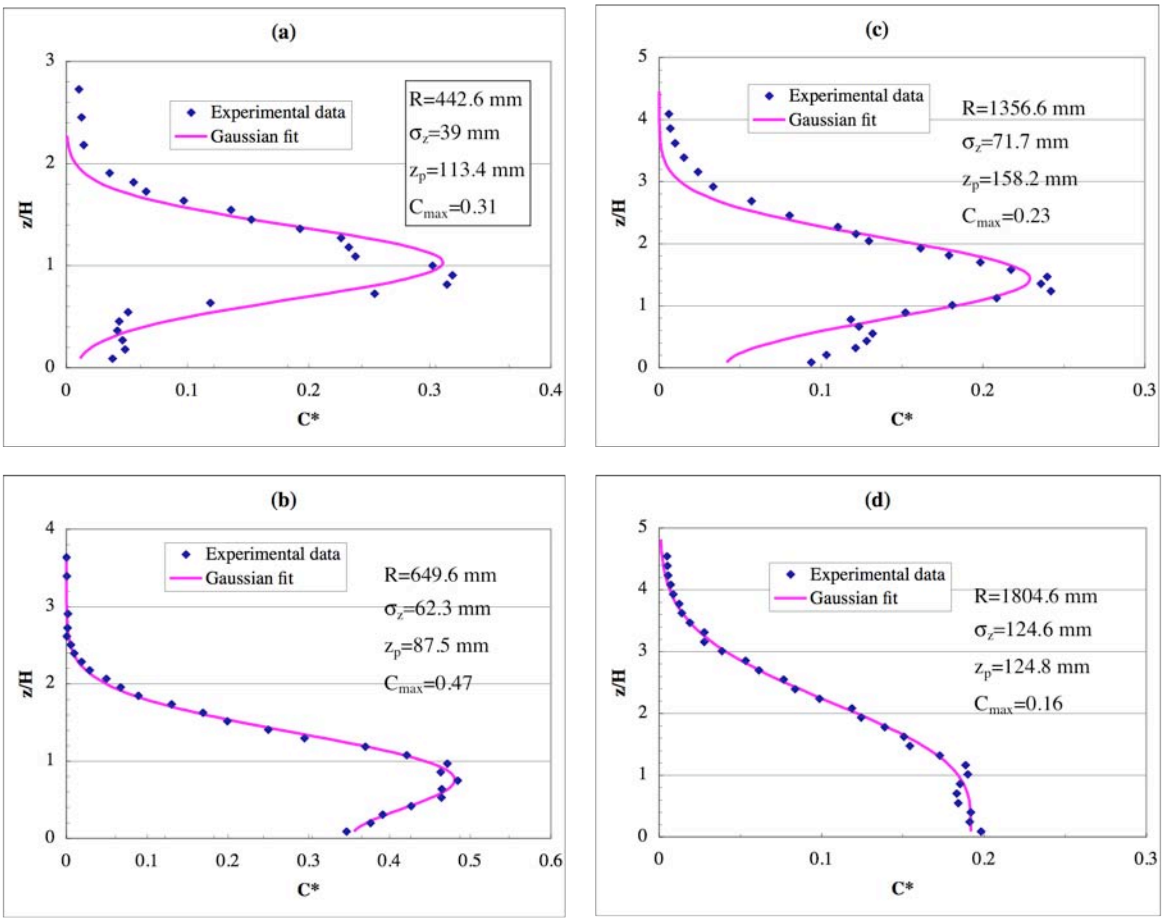

Figure 13. Vertical profiles of mean concentration together with the reflected Gaussian model at different downwind distance from the source for ground level release.

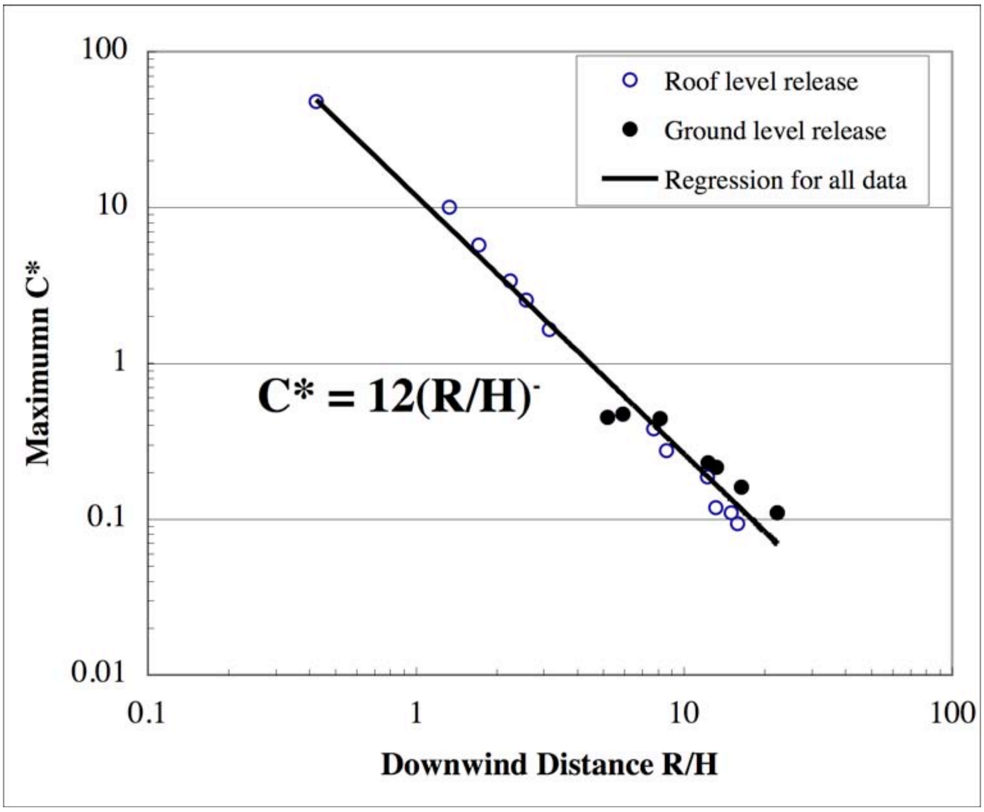

Figure 14. Decay of the maximum concentration with downwind distance.

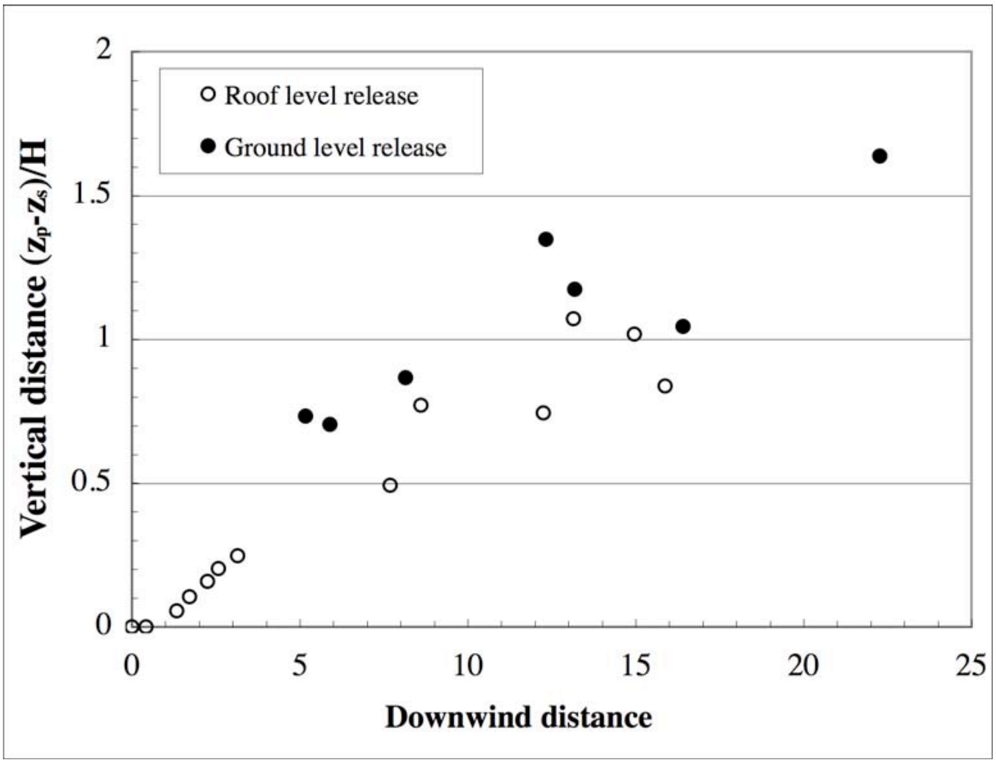

Figure 15 Development of plume centre height with downwind distance.

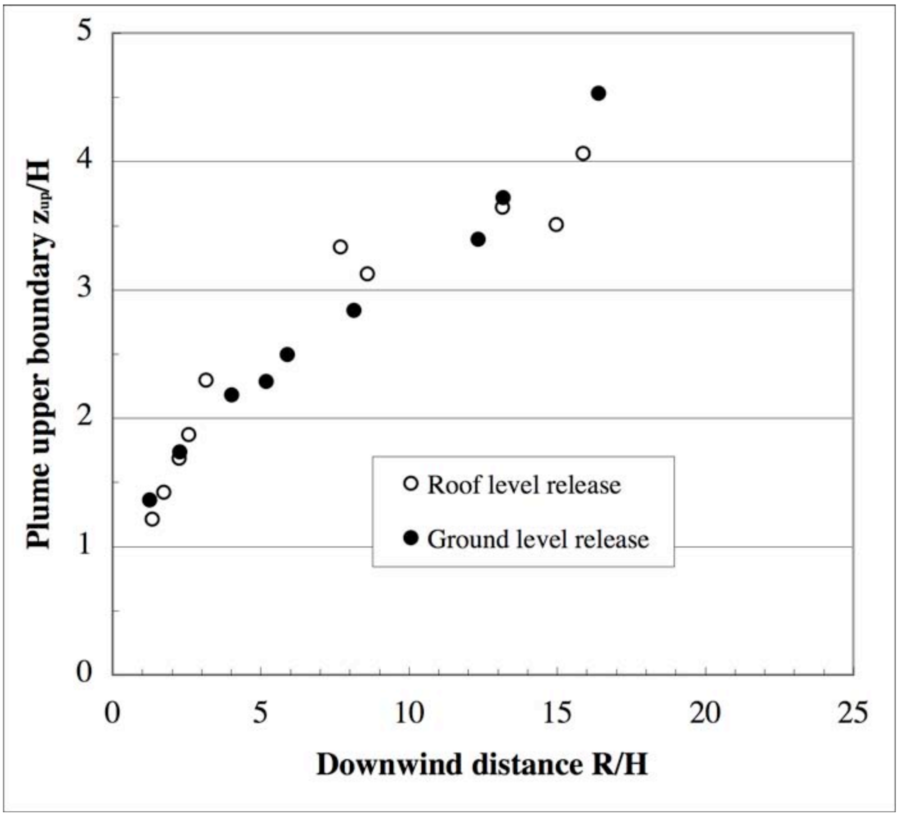

Figure 16. Development of upwards vertical boundary of the plume with downwind distance.

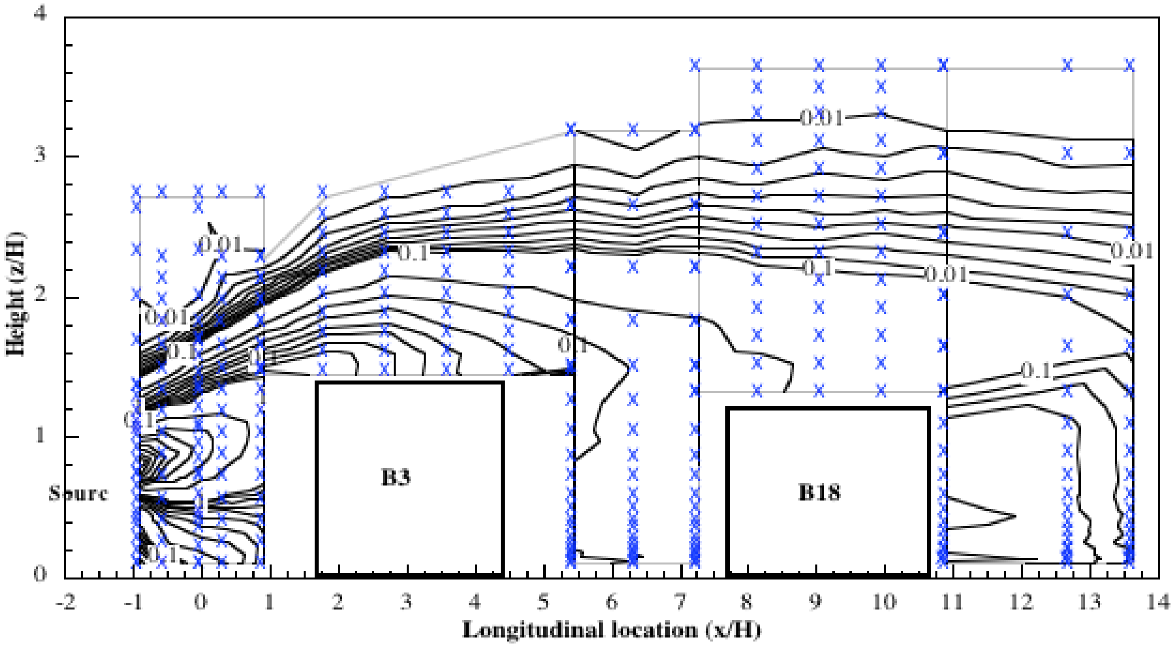

Figure 17. Vertical development of plume dispersion with downstream distance for roof level release.

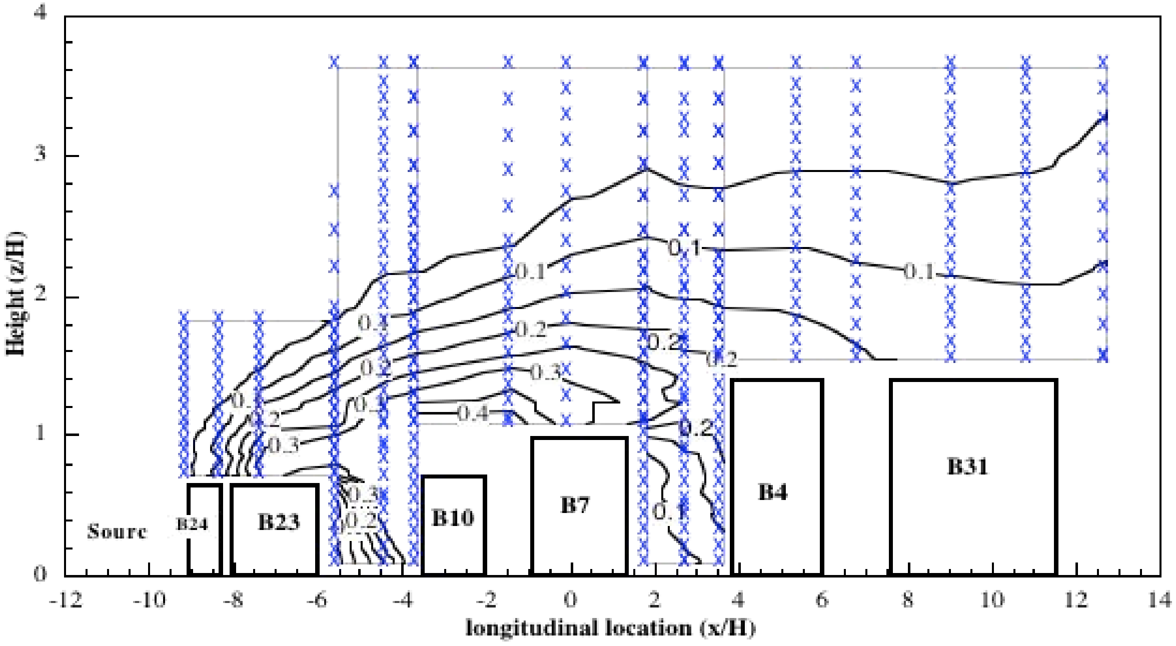

Figure 18. Vertical development of plume disperse with downstream distance for ground level release.

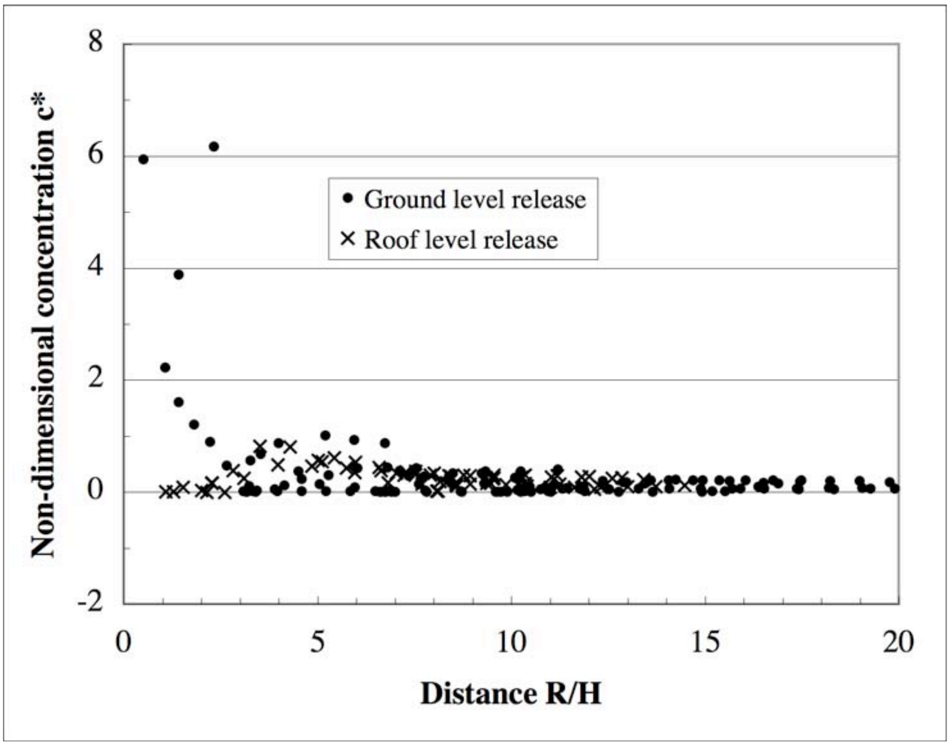

Figure 19. Ground level concentration comparison between roof and ground level release.

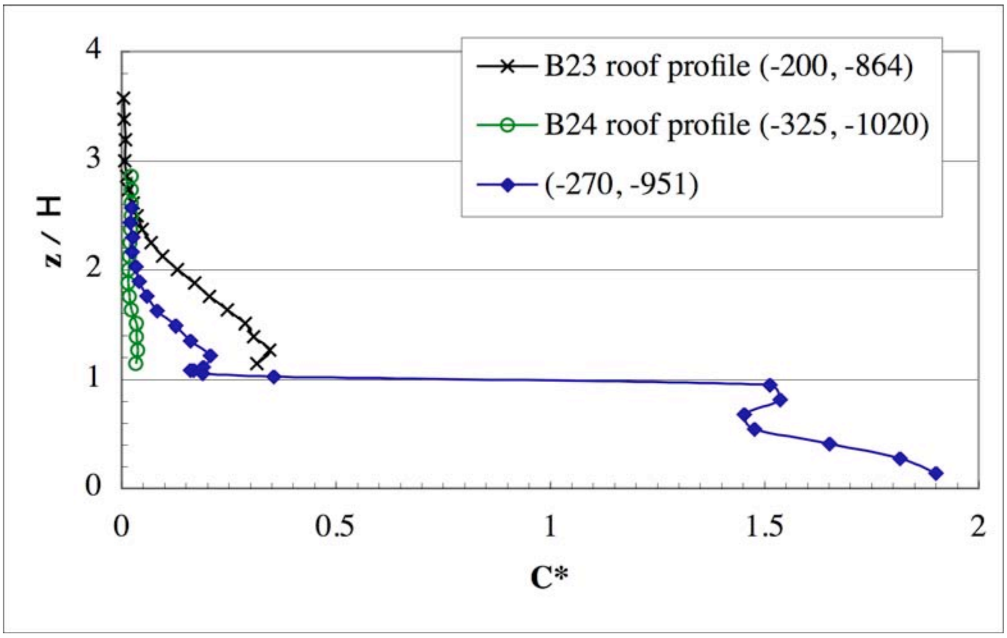

Figure 20. Vertical profiles of concentration downwind source location "A" for the ground level release.