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Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons

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Abstract

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1. Introduction

Transport vehicles are by far the major emission source of nitrogen oxides and hydrocarbons in urban areas (Evers, 1994; Longhurst et al., 1994; Schatzmann, 1995). Vehicular exhausts dominate air pollution in cities because traffic there is usually dense and engines often run cold and at idle. Further worsening of the pollution may be expected in view of the continuous increase in city traffic; therefore it appears essential to seek ways to reduce or mitigate the effects of vehicular pollution. The aim of this study is to identify street canyon configurations which produce better ventilation.

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A limitation of direct field measurements of atmospheric phenomena is that all possible governing parameters are simultaneously operative; thus, it is not simple to determine which are governing, which are secondary or which are insignificant. In addition if nonlinear interactions occur their role may not be clear. Thus, independent influences of building geometry (building height, width, roof shape), street dimensions (breadth, width, intersection location), thermal stratification (solar insolation and orientation, building and street thermal capacitance), vehicular movement (size, number, frequency), plume buoyancy, vegetation or landscaping, and surface roughness are all interwined.

Wind tunnel simulations provide an opportunity to examine the linear and nonlinear effects of various parameters individually and/or in combination. Hoydysh and Chiu (1971), Hoydysh et al. (1974), Builtjes (1984), Kim et al. (1990) and Munchow (1991) considered two-dimensional street canyon arrangements. Hoydysh et al. (1974), Hussain and Lee (1980), Builtjes (1984), Hoydysh and Dabbert (1986) and Davidson et al. (1992) examined three-dimensional arrangements including intersections. Hoydysh et al. (1974) and Wedding et al. (1977) studied scale models of generic cities including varying block and street sizes and different height structures along the streets. Builtjes (1984) evaluated the effects of trees and landscaping along the streets on dispersion.

Kitabayashi et al. (1976), Leisen (1978), Leisen et al. (1982), Kitabayashi (1988) and Carpenter (1989) report measurements above carefully scaled models of actual street canyons. Kitabayashi et al. (1976) performed experiments with a scale model of a real street canyon in the center of Tokyo. Moving automobiles were simulated using model cars traveling along a street track. The floor temperature were adjusted to obtain stably stratified air flow conditions. Such studies were undertaken to check the validity of specific numerical and/or theoretical models.

In this work we chose to start with very simple geometric configurations which should exclude three dimensional effects. The experiments were performed in an open-circuit wind tunnel under neutral stratification conditions. The wind was directed perpendicular to the street canyons to preserve two-dimensionality.

Considerable effort was devoted to establish experimental procedures which give reliable results. Initially, emphasis was put on line source design since this is a key component of the experimental apparatus. We provide results from some tests which show that important errors may arise from inadequate line source design. Then we discuss the test case of an isolated street canyon in open country. The results are compared with those obtained with a street canyon amidst urban roughness.

2. Experimental set-up

2.1. The atmospheric boundary layer wind tunnel

The experiments were performed in the atmospheric boundary layer wind tunnel (BLASIUS) of the Meteorological Institute of Hamburg University shown in Fig. 1. The wind tunnel consisted of an inlet nozzle (16 : 1 contraction ratio), flow straighteners (honeycombs), vortex generators, a flow establishment section, a test section, anti-swirl devices (honeycombs and grids) and a squirrel-cage centrifugal fan. A DC motor with a thyristor type control system maintains test-section wind speeds ranging from 0 to 15 m/s. The effective working section is 1 m high, 1.5 m wide and 4 m long following a 7.5 m long development section just downstream of the boundary layer stimulation system. Four Irwin type vortex generators, Fig. 2, were spaced laterally and symmetrical to the tunnel centerline at intervals of half the height of the spires (Irwin, 1979, 1980).

Surface roughness for an open country situation was provided by blocks made of two 2×1 Lego™ elements[1], Fig. 3, placed on the floor in a regular array following a staggered pattern. The boundary layer generated is about 0.45 m thick. The vertical velocity distribution in the region where the boundary layer is fully developed may be described by a power law,

$$\frac{U(z)}{U(\delta)} = \left[\frac{z - d_0}{\delta - d_0}\right]^{\alpha}, \tag{2.1}$$

where d_0 is the displacement height, $U(z)$ the mean velocity at elevation z, and $U(\delta)$ is the mean velocity at the boundary layer height, δ. The displacement height is about 2 mm. For various external velocities taken in the free region of the flow, at a reference

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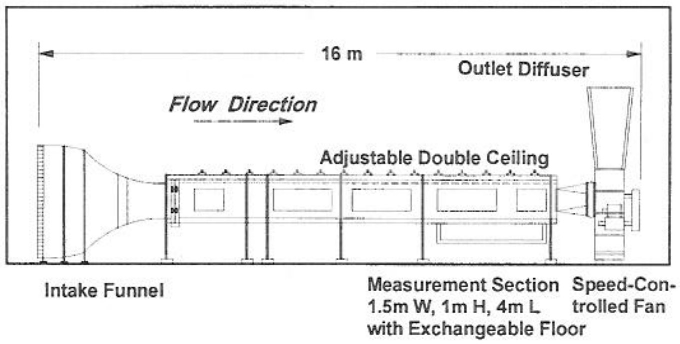
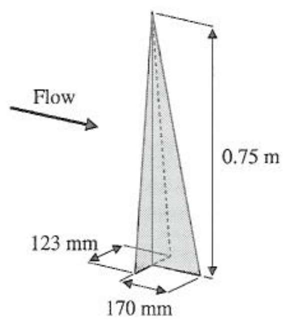


Fig. 1. BLASIUS boundary layer wind tunnel of Hamburg University (flow direction from left to right).



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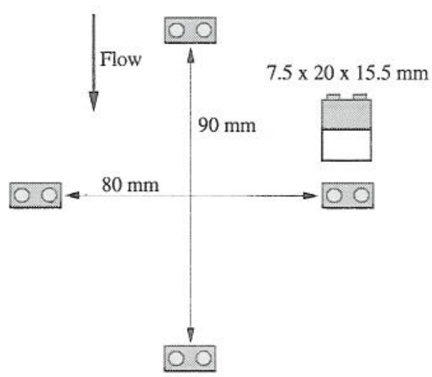

Fig. 3. Regular array of Lego™ elements following a staggered pattern.

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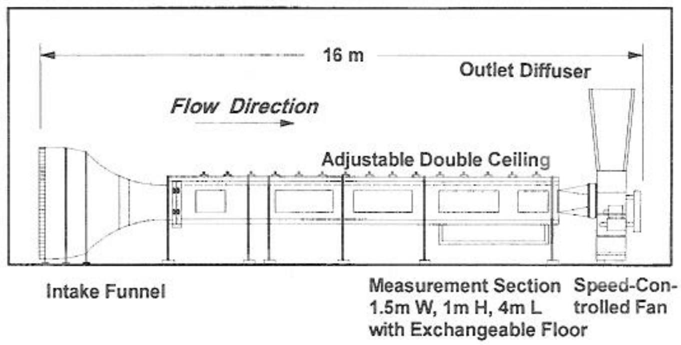

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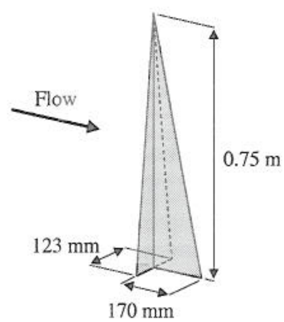

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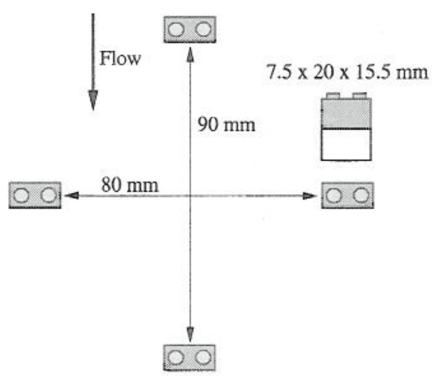

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height of 650 mm above the floor, the vertical wind profile exponent α was estimated to be 0.28.

Several studies have been carried out in the past on the turbulence properties of boundary layers created in this manner. There is a high degree of coincidence between wind tunnel and field measurements with regard to the vertical distribution of turbulence intensity as well as to spectra and correlations (Plate, 1982; Lohmeyer, 1984; Schatzmann et al., 1986). Donat (1989) performed spectral analysis and measured the vertical profiles of turbulence intensity for all three components of the velocity under equivalent tunnel flow conditions. The turbulent intensity profiles are independent of approach velocity when it is above 0.5 m/s. The vertical turbulent momentum flux is constant in the lower 10 cm of the boundary layer. In this layer, the ratio between friction and free stream velocities $U^*U(\delta)$ equals 0.065 and is independent of the Reynolds number, $Re^* = U(\delta)\delta/v$. The roughness length z_0, determined from a logarithmic profile up to 12 cm above the floor is about 1.5 mm. The roughness Reynolds number U^*z_0/v is larger than 2.5 as recommended by Snyder (1972). Comparing these tunnel characteristics with those found in nature we conclude that this arrangement corresponds to a simulation of the atmospheric surface layer at a scale of 1 : 500. Different ceiling positions were used to ensure negligible longitudinal pressure gradients (~ 0.25 Pa/m) for all configurations studied.

2.2. Measurement techniques

2.2.1. Velocity

The wind velocity was continuously recorded using both a Prandtl pitot-static tube and a conventional hot-film, Thermal Systems Inc. (TSI) Model 1210-20, connected to a constant temperature anemometer, TSI Model 1054-B, coupled to a monitor-supply unit, TSI Model 1051-2. Wind field measurments were limited to regions where no flow reversal occurred upwind or above the street canyon models. In contrast to stack emission studies where the reference height is specified at stack height, for street canyon situations no standard exists on the position at which the reference velocity should be measured. Here the reference height was chosen to be 650 mm above the floor in the free-stream region of the flow ($z_{ref} \approx 11$H). Actually the difference between the reference velocity, U_{ref} and $U(\delta)$ never exceeds 1% of $U(\delta)$.

2.2.2. Concentrations

Mixtures of ethane and air (1.4–6.5%) were used to simulate the dispersion of pollution in the model street canyon. A University of Hamburg design sampling system allows simultaneous collection of 20 individual gas samples in inflatable balloons over prespecified sampling periods. Each sample is analyzed afterwards using a flame-ionization type hydrocarbon analyzer Model 400A from Rosemount Analytical Inc. The concentration sampling system was calibrated against a laboratory prepared mixture of hydrocarbon gas. The between-sample variation was minimal, and the sample accuracy was determined to be $\pm 0.8\%$ of true concentration. The overall balloon sampling and concentration detection system error is about $\pm 5\%$ (Donat, 1989). The concentration measurements are presented in terms of the ratio $K = CU_{ref}HL/Q_s$, unless indicated otherwise, where C is the actual concentration [ppm], U_{ref} the free-stream wind approach velocity at a height of 0.65 m above the floor level [m/s], H the height of physical model of building [m], Q_s/L the line source strength [m^2/s], Q_s denotes ethane flow rate and L is the source length (0.90 m).

2.3. Street canyon physical modelling

2.3.1. Street canyon design

Wooden 60 mm × 60 mm bars were used to model two-dimensional multi-story flat-roofed buildings. We considered the two dimensional case which corresponds to a street canyon completely spanning the width of the tunnel and perpendicular to the wind direction. Blockage of the test section from the bars did not exceed 6%. The approach velocity was chosen large enough so that the Reynolds number, $U_H H/v$, exceeds the value of 3400 suggested by Hoydysh et al. (1974) to ensure that the flow pattern in the street canyon was independent of viscous effects[2].

The bars were equipped with flush mounted sampling ports located on a vertical plane on the tunnel axis, Fig. 4. In addition to the 14 sample ports on the vertical plane, five additional holes were provided along a horizontal line at the level of port #14 to evaluate the two-dimensionality of the tests. Sample ports #15 to #19 were placed at the positions y_i equal to -75, -50, -25, $+25$, and $+75$ mm relative to hole #14[3].

In the following discussion "open country" refers to an isolated street canyon amidst Lego roughness[4]. The "urban roughness" case is an approximation of the urban fabric and is obtained by replicating similar street canyons, parallel to the test canyon, upstream and downstream. Hoydysh et al. (1974) determined that an upwind fetch of 8 to 10 street canyons is required before street canyon flow and dispersion are independent of upwind fetch distance. Therefore, in this study the urban fetch consisted of 8 bars downstream and up to 20 bars upstream of the test canyon. To reduce secondary flows induced by street canyon vortex interaction with the side-wall wind-tunnel boundary layers end plates were added 150 mm from each wall.

The drag introduced by the street canyon roughness is a function of building and street dimensions. The resulting shear profile may be categorized depending on the nature of separation and attachment of streamline flow over the bars, i.e., skimming flow, wake interference, isolated roughness (following the nomenclature of

[2] The often quoted criteria of Golden (1961) which suggests setting flow conditions to exceed 11 000 is based on measurements he made at only one point on the roof of a smooth-walled cube placed in an uniform low-turbulence flow. Snyder (1992) suggests Reynolds numbers for tests on isolated cubical objects in turbulent boundary layers should exceed 4000. Neff and Meroney (1996) extended Snyder's measurements to a wider range of isolated building shapes, wind orientations, and measurement locations on the building and in the wake. They recommend that Re exceed 15000. For urban roughness the suggestion by Hoydysh et al. (1974) is appropriate.

[3] The x axis which defines the U component, is in the direction of the mean wind; the z axis is pointing upward; while the y axis is perpendicular to x and z in a right-hand coordinate system.

[4] The seemingly unrealistic "open country" configuration was chosen to focus on the nature of the flow and dispersion of an isolated building complex. Previous modelers (Leisen et al., 1982) examined similar configurations. Recently, a number of urban flow modelers have proposed numerical approaches based on the superposition of individual building elements where the flow perturbations are based on the measurement of flow about isolated building elements in wind tunnels. The measurements provided here will provide an opportunity to criticize such an approach.

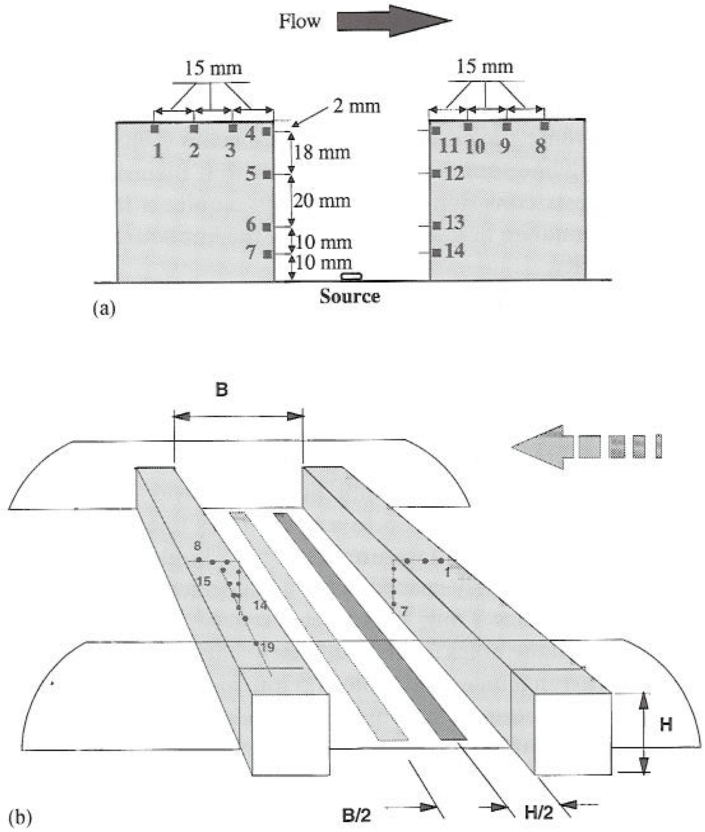

Fig. 4. Configuration of measurement tapping holes at the outline of the test street canyon.

Table 1
Summary of 2-D street canyon velocity characteristics at the center of the tunnel with urban roughness present ($U_{ref} = 2$ m/s)

B/H	α	d_0 (mm)	u^*/u_{ref}	z_0 (mm)
1	0.20	57	0.050	0.25
2	0.25	50	0.075	1.00
3	0.28	50	0.080	1.50
4	0.28	50	0.100	3.00
8	0.28	40	0.100	3.00

Oke, 1988b; see also Hussain and Lee, 1980; Lee et al., 1980; and Hunter et al., 1992). Table 1 summarizes the characteristics of the tunnel wind velocity profiles, measured for different street canyon configurations where B is street canyon width, H is building height, and B/H varies from 1 to 8.

2.4. Line source

2.4.1. Line source design

Line sources are used to simulate exhausts from vehicles queuing along a street. Apart from the conference paper by Murphy and Davies (1988) no discussions have been found concerning line source design, implying that their design is a trivial issue. Our experience suggests consistent measurements require a laterally homogeneous release; hence, we summarize here a description of the line source and tests performed to confirm its reliability.

Vehicle exhaust is best represented by a source of low vertical momentum since most vehicle exhausts are directed horizontally. Vehicle exhaust can be assumed as neutrally buoyant gas flow, for even though the hot exhaust is initially buoyant, the accelerations induced by buoyancy forces will usually be small compared to automotive induced turbulence and street canyon circulations. Presuming uniform mixing of exhausts from slow moving traffic, uniform gas flow distribution along the line source is a good approximation to constant traffic flow. Moreover, a line of closely spaced point sources is a good approximation to a continuous line source.

Line sources described in the literature are of two kinds. Some were made from pipes or tubes in which regularly spaced holes were drilled. Kitabayashi et al. (1977) used tubes drilled with holes 2 mm in diameter spaced at an interval of 1 cm. The source was oriented with the holes facing the floor to eliminate vertical lofting. Builtjes (1984) used a similar arrangement with holes 1.5 mm in diameter spaced at intervals of 1.5 cm. At a distance of about 1 cm above the holes a thin flat plate was installed to deflect the vertical momentum laterally. It is possible based on our experience that in these designs the spacing between the holes was too wide, and the source was not laterally homogeneous in the near field.

Another popular line source system consists of plenum chambers which distribute the gases beneath drilled plates or sections of sintered porous metal plate such as used by Hoydysh and Griffiths (1974), Murphy and Davies (1988) and Münchow (1991). Various techniques were used to fill the plenum chamber with foams or other porous media to increase the pressure loss across the exit. Unfortunately, unless the porous materials are very homogeneous and the pressure drop across the materials is sufficiently large, it is not possible to produce laterally homogeneous flow. Local pressure variations above the exit section induced by local turbulence are often larger than the pressure drop produced across such porous materials.

In this study a plenum-type linear source design proposed by Münchow, Fig. 5, was studied first. The linear homogeneity of this source was found to be poor, and suspicions arose that the lateral gas discharge distribution varied between experiments. Thus, a number of design modifications were introduced with different porous materials inside the plenum. Unfortunately, with these modifications we could not achieve an even gas discharge.

The key characteristic influencing the gas flow from the source was found to be the pressure drop through the exhaust holes. The pressure drop across the holes determines the local flow rate more than any additional losses introduced by filling the cavity with porous materials. To achieve high discharge pressure drop each hole was

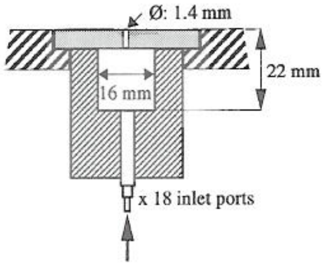

Fig. 5. Münchow (1991) line source design.

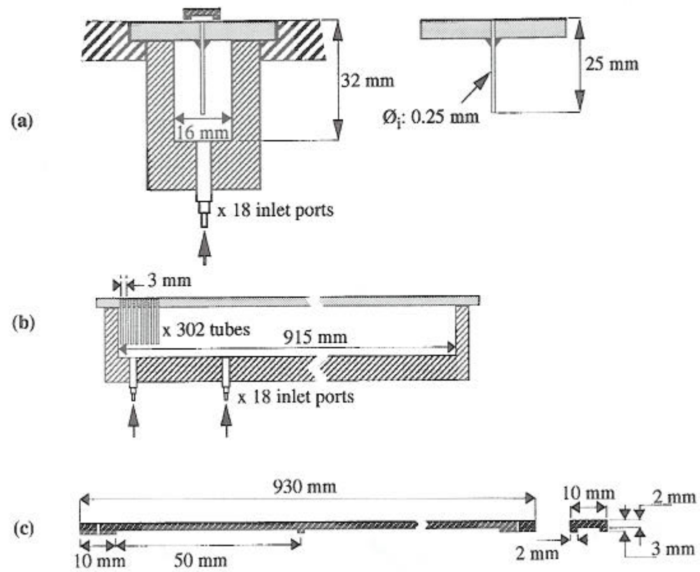

Fig. 6. Actual line source design. (a) Transverse cross section; (b) Longitudinal cross section; and (c) Capping brass bar.

replaced by a length of hypodermic tube of 0.25 mm internal diameter and 25 mm long. The final design is depicted on Figs. 6(a)–6(c). The small tube diameter produced substantial pressure drop of the order of 450 Pa for a flow rate of 100 l/(h/m); thus rendering the gas flow insensitive to local pressure fluctuations in the model street canyon above the line source. The design flow rates required during the experiments resulted in discharge velocities from such small holes of the order of 1 m/s. This could potentially disturb the flow in the street canyon; hence, the discharge tube holes were covered with a metal strip canopy so that any initial vertical gas momentum was deflected laterally, Fig. 6(c).

2.4.2. Tests

Two series of tests were performed to check the lateral homogeneity of tracer gas discharge from the improved line source. During these tests only the Lego surface roughness was present upstream of the source. In the first test vertical profiles of concentrations were measured along the centerline axis of the tunnel. Downstream of the line source, the vertical dispersion of the plume follows quite closely a modified Gaussian distribution of the form

$$K = \exp\left[-A\left[\frac{z}{B}\right]^{n}\right], \tag{2.4}$$

where A and B are constants, Fig. 7. Except very close to the source where sample probe resolution was inadequate the slope α equals 1.2 which is the anticipated value for line source dispersion in boundary layers.

In the second test the gas concentrations were measured at floor level, at various distances downstream of the line source and spanning the width of the tunnel. The lateral variations of ground-level concentrations are shown in Fig. 8. Fig. 9 shows the downwind dispersion at ground level of the plumes released from the line source at different distances along the axis of the wind. The downwind decay of ground-level concentration displays a power-law slope of -1, which is the rate anticipated for a continuous ground-level line source release.

With the line source design shown in Fig. 6 the overall standard deviation of the crosswind plume concentration from the mean value does not exceed $\pm 2.5\%$, Fig. 8.

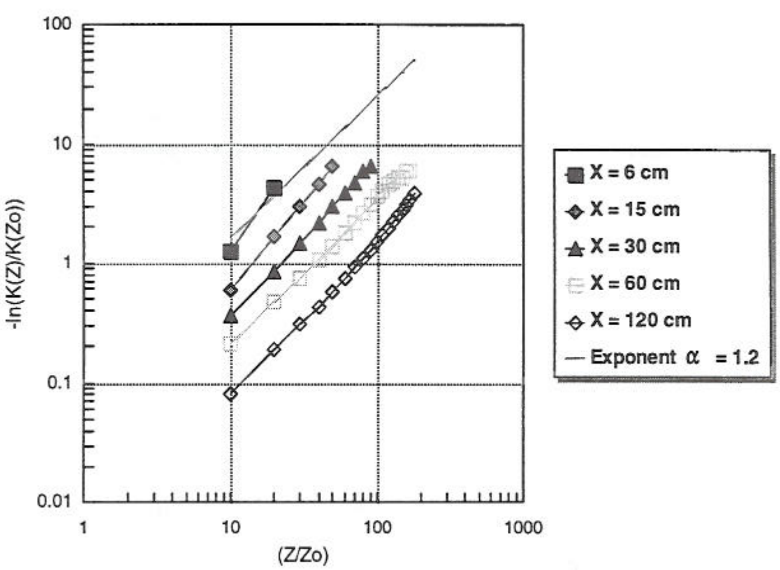

Fig. 7. Vertical concentration distributions downstream of the line source (open country roughness, $U_{ref} = 2$ m/s).

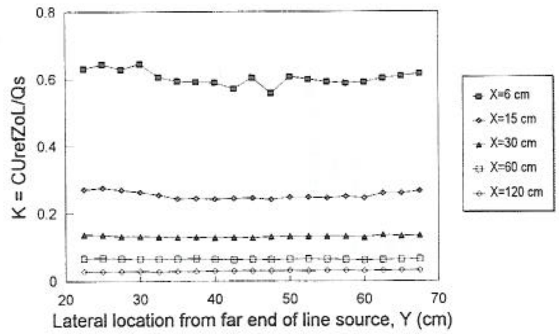

Fig. 8. Horizontal downstream dispersion of the gas plumes from the line source (open country roughness, $U_{ref} = 2$ m/s, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

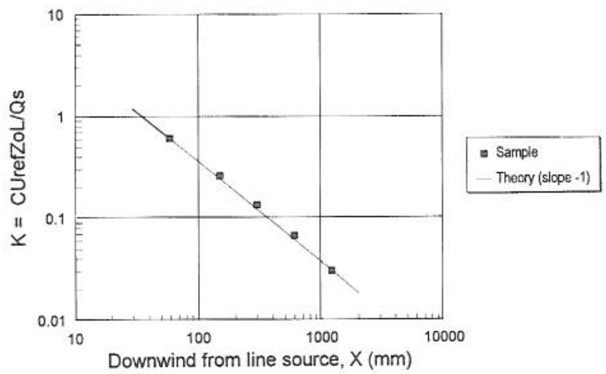

Fig. 9. The downstream floor dispersion characteristics of the plumes from the line source, along the axis of the tunnel (open country roughness, $U_{ref} = 2$ m/s, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

On the other hand, the maximum variability range relative to the average does not exceed 7.3%. This is an improvement over the sintered porous plate line source design of Murphy and Davies (1988) which showed deviations in lateral distribution ranging between $\pm 8\%$ and $\pm 45\%$ when wind tunnel reference velocity varied from 3 to 9 m/s. In the presence of a street canyon, the gas discharged from the line source becomes more evenly distributed laterally making the lateral inhomogeneity of the line source even smaller than $\pm 2.5\%$, or about the same accuracy as the concentration measuring system.

2.4.3. *Influence of source gas discharge*

It is known that the horizontal wind velocity at street level is typically of the order of 10% of the free stream velocity. For reference velocities achievable in our wind tunnel, this results in horizontal velocities at street level of a few cm/s. Simple calculations show that the gas discharge velocities from the line source of Fig. 6

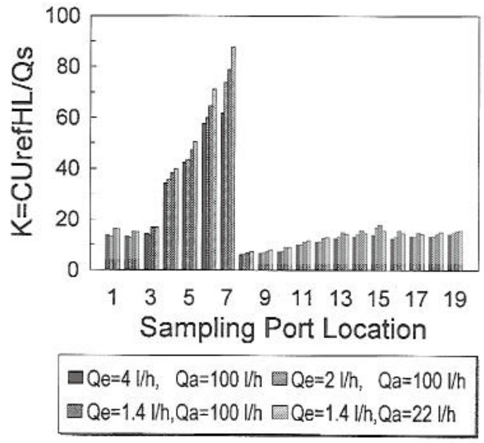

Fig. 10. The concentrations at different tracer gas discharge rates from the source ($B/H = 1$, $U_{ref} = 1$ m/s).

are of the same order of magnitude, so they may influence the recirculating flow patterns in the canyon.

Tests were performed to investigate the potential errors due to excessive source discharge. The total gas flow rate (a mixture of ethane, Q_e, and air, Q_a) from the source was varied by a factor of 4 as summarized in Fig. 10. The effect of source strength on concentration measurements and street canyon flow behavior were less than 15%, well within the specified accuracy of the balloon measurement system.

3. The test case of street canyons

To evaluate dispersion in a model urban street canyon, we ran two series of tests. The case of an isolated street canyon in open country was examined first. The same street canyon geometry was subsequently studied in an urban environment, i.e., with additional canyons of similar geometry upstream and downstream of the test section.

3.1. Experimental detail

In each case various street canyon aspect ratios were tested under different wind conditions. Each measurement was repeated twice, to verify that an equilibrium in the canyon flow and the gas dispersion existed.

Slight misalignment of a few degrees in the bar(s) and the source with one another and/or the tunnel axis produced asymmetric lateral deviations in the concentrations measured downstream. To avoid such systematic errors, both the bars and the line source were carefully aligned to be parallel to each other and perpendicular to the flow. Furthermore, to avoid interaction of street canyon vortices with the sidewall boundary layers which might distort two-dimensionality, end plates were erected at

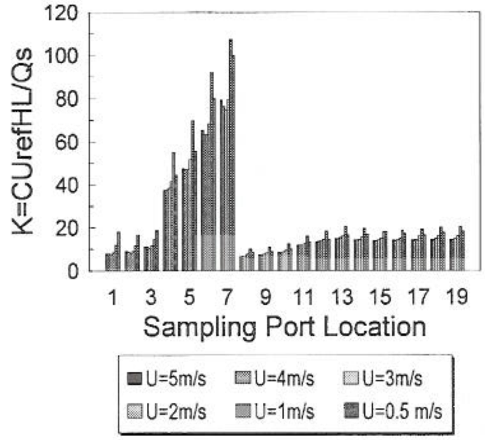

Fig. 11. The effect of different wind velocities on pollutant concentrations in a street canyon (open country roughness, $B/H = 1$, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

both ends of the line source parallel to the direction of flow. These plates were constructed from 2×1 Lego bricks and extended to a height of 10 brick layers (100 mm), 8 times the height H of the wooden bars downstream (500 mm) and $1H$ upstream (60 mm).

3.2. Open country case

3.2.1. Street canyon flow and the effect of wind speed

The effect of varying wind speeds on the concentration of pollutants within the canyon will first be discussed for the reference case $B/H = 1$, Fig. 11. The general characteristics of the typical concentration profiles measured are discussed below.

- Visualization using smoke and a vertical light sheet revealed that clean air is drawn into the canyon by an intermittent eddy circulating down into the canyon[5]. This eddy circulates upwind at street level. A roof top eddy which begins at the upwind upstream building roof corner convects canyon gases onto the roof.
- Significant pollution concentrations are measured on the roof of the upstream building, indicating that gas from the canyon is transported into the roof bubble before eventually being carried away by the oncoming flow. On the leeward side of the upstream building concentrations decrease from a maximum at the base of the building to lower values along the roof line (port #7 to port #4). On the windward face of the downstream building, the concentration increases from the roof to the

[5] The canyon region almost appears to inhale and exhale. The flow forms a canyon vortex, the vortex occasionally washed out of the canyon, the free-stream flow penetrates the canyon, and another vortex forms.

street (ports #11 down to #8). At positions #9 and #8 an equilibrium was apparently reached. This was consistent in all measurements, despite the fact that these positions differed vertically by 10 mm.

- The characteristics described above do not change significantly with different wind approach velocities. Any influence appears to be marginal, indicating that, at least for an aspect ratio of $B/H = 1$, the flow inside the canyon remains largely unchanged. It may be concluded that the canyon dispersion behavior was Reynolds number-independent[6].

3.2.2. Different street canyon configurations

The influence of different street canyon aspect ratios was studied for two different line source locations:

- The line source was placed at a fixed distance $x_s = H/2$ downstream of the leeward wall of the upstream bar, and its position was left unchanged while the downstream block was moved to represent street widths $B = 1H$, $2H$, $3H$, $4H$, $8H$ and ∞ downstream, or
- The line source was placed midway between the downstream and upstream blocks, while the street widths varied, again, as $B = 1H$, $2H$, $3H$, $4H$ and $8H$.

These tests were performed for a wind approach velocity of $U_{ref} = 2$ m/s. The results are presented in Figs. 12 and 13. The concentrations measured reveal that

- Substantial concentrations are always measured on the roof of the upstream building. This indicates that some pollutant gases are convected or mixed into the roof separation bubble, before being vented away into the main flow.
- High tracer concentrations are observed at the leeward face of the upwind building. The concentrations increase from top to bottom, with the highest measurement at the intersection between the wall and the street.
- In all cases the horizontal distribution of tracer gas from the line source are homogeneous horizontally, both up- and down-stream of the source (sample ports #8 and #15 to #19).
- In terms of the non-dimensional coefficient, $K = CU_{ref}HL/Q_s$, little variation is observed by increasing the approach velocity from 2 to 5 m/s while the canyon aspect ratio remained constant.
- Varying the canyon geometry has small effect on the concentrations on the roof of the upwind building when the source is placed at $x_s = H/2$. This was expected due to

[6] Concentrations were non-dimensionalized using a reference wind velocity. Any errors made in determining the value of this velocity directly influenced the observed concentration coefficient, K. This is an important consideration, especially at lower wind velocities, because then the errors of the hot wire anemometry technique used to define the reference velocity become larger. To determine the likely effect of such systematic errors in the actual street canyon behaviour at low wind speeds, the experimental data were analyzed using a number of different methods to estimate the reference wind speed (e.g. wind speed was estimated from fan motor rotation rate, a pitot-static probe, and two separate hot-film calibration algorithms). The effect of the likely errors were insignificant at velocities above 2 m/s, but the variations possible at the lowest wind velocity of 0.5 m/s easily explained any deviation of dimensionless concentration from the trends observed at higher velocities.

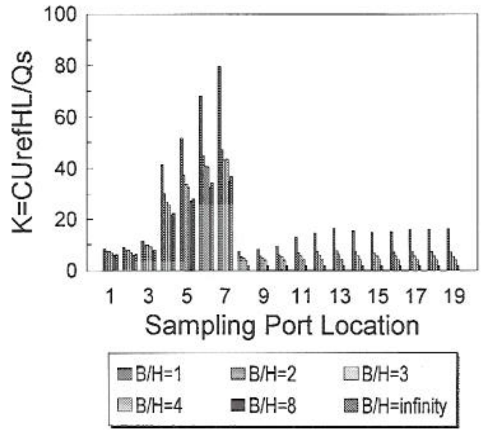

Fig. 12. Concentrations in the canyon for different canyon aspect ratios (open country roughness, $X_s = H/2$, $U_{ref} = 2$ m/s, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

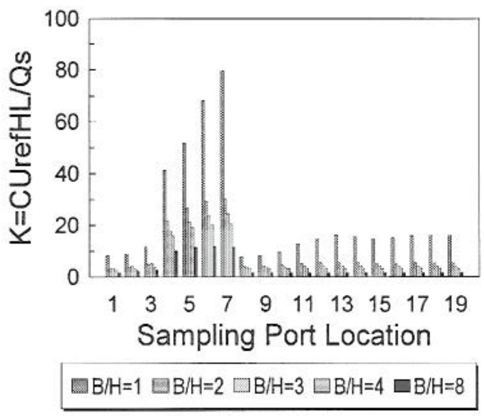

Fig. 13. Concentrations in the canyon for different canyon aspect ratios (open country roughness, $X_s = B/2$, $U_{ref} = 2$ m/s, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

the relative proximity of the source and the insensitivity of the upstream roof separation bubble to the flow characteristics downstream. Concentrations at the rest of the sample ports decrease as the canyon widens.

The above observations are appropriate when the line source is close to the upstream building ($x_s = H/2$). Similar considerations, however, apply when the line source is halfway between the two bars.

- The roof concentrations are more heavily affected by widening the canyon than the other positions, because the source moves further away from the upstream roof than when $x_s = H/2$.

• Moreover, as B/H increases smaller dimensionless concentrations occur at all locations.
• Consideration of Figs. 12 and 13 suggests that the flow inside the canyon cannot be in the form of a permanently recirculating eddy. If a permanent eddy existed then concentrations would be indifferent to where the eddy was fed with tracer gas. Instead, the figures corroborate the hypothesis of intermittent streaming of pollutant from the source to the side walls of the canyon. Under such conditions, the geometry between the source and the walls becomes critical, influencing directly the routing of gas plume from the source to the sample ports. Thus, moving the upstream sample ports #4 to #7 farther from the source results in a drop in the concentrations measured.

3.3. Urban roughness case

Experiments were also performed on the dispersion within extended urban roughness associated with additional up- and down-stream bars. For this part of the study the line source was positioned in the middle of the street ($x_s = B/2$). The results are summarized in Fig. 14 for $U_{ref} = 2$ m/s. The overall characteristics discussed for the open country case were identified also in canyons amidst large urban roughness, but some significant differences were observed.
• At both wind velocities studied (2 and 5 m/s) the pollution concentration on the roof of the upstream building is almost zero. This suggests that the roof recirculation bubble into which pollution may be drawn from inside the canyon has totally disappeared. Elsewhere in the canyon the pollution increased, in absolute terms, compare Figs. 13 with 14. This suggests that intermittent ventilation of a canyon in the middle of the city by the already well-developed internal boundary layer is inhibited more than if the canyon had been surrounded by open country.
• To clarify the above description we provide sketches in Figs. 15(a) and 15(b) for the case $B/H = 1$. These drawings summarize observations during a visualization study

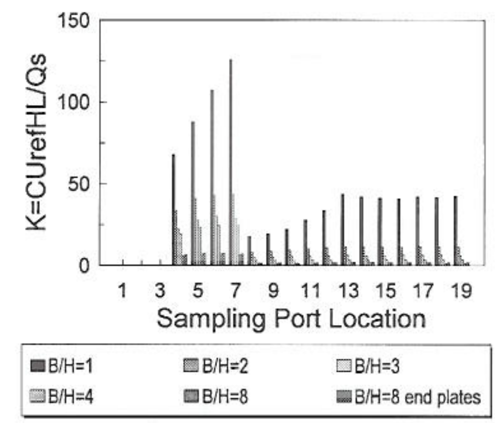

Fig. 14. Concentrations in the canyon for different canyon aspect ratios (urban roughness, $X_s = H/2$, $U_{ref} = 2$ m/s, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

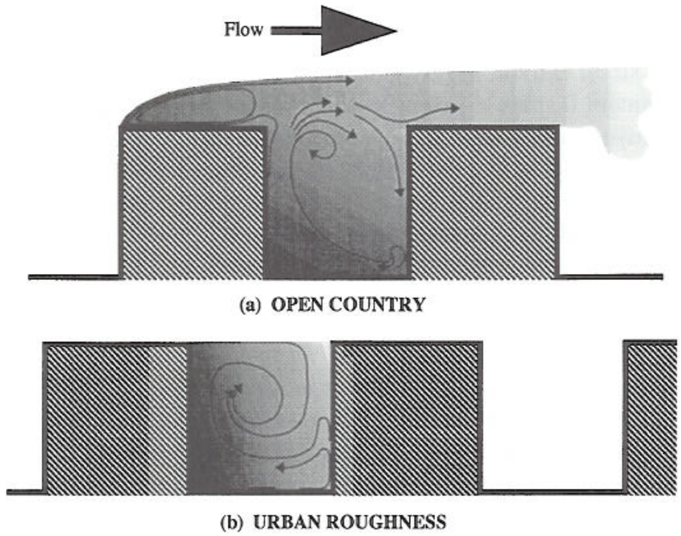

Fig. 15. Difference in the flow structure within the canyon between open country and urban roughness.

made on the circulation inside the canyon under varying operating conditions. Flow visualization was performed using an illuminating laser sheet and a non-buoyant mixture of air and oil smoke injected at street level along the street canyon. The beam of a 200 mW laser was spread by a semi-cylindrical lens to a light sheet of a constant thickness of the order of 2 mm. Photographs were taken using exposure times of about 5 s.

- The flow inside the canyon in open country is much more nonstationary than in the urban canyon case. A recirculating eddy forms only intermittently in the former, whereas it is clearly much more stable amidst urban roughness.

In the open country case, the first building alters the flow locally quite dramatically, promoting separation from the ground. On the other hand, in the urban roughness case the surrounding buildings raise the displacement height to the urban canopy level, almost to the roof of the buildings. The shear zone thus formed at the ceiling of the canyon induces a permanent eddy recirculating inside the canyon. As a result, vertical mixing across this shear layer is suppressed and pollution is trapped inside for longer times, until upstream turbulence in the main flow may cause sufficient disturbance to break down the recirculating eddy.

4. Conclusions

From the experimental work described above a number of conclusions may be drawn:

- The use of a stable and laterally homogeneous line source is one of the key requirements for simulation of vehicular pollution in an urban model study. The important design parameter is found to be the pressure difference across the discharge holes.

- An isolated street canyon in the middle of open country roughness and another in urban environment display different flow characteristics. In the canyon amidst open country the canyon vortex is unstable and is discharged regularly upwards. Inside the urban canyon a stable rotating vortex develops, street ventilation is suppressed, and pollution is trapped inside the canyon. There is a total absence of an upstream roof bubble; hence, no pollution is measured on the roof.

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