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DISPERSION IN IDEALIZED URBAN STREET CANYONS

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INTRODUCTION

Urban street canyon geometry and pollution source configuration play important roles in determining the level of peak levels of air pollution due to transportation sources. Urban air pollution specialists anticipate that street canyon depth and width, intersection locations, canyon orientation to the dominant wind directions and local building geometries will determine most of the peak pollution incidents which determine air pollution control strategies. Most relevant urban air pollution models are based on limited measurements made at field and laboratory scales. Uncertainty still exists concerning the level of complexity which must be contained in numerical models to reproduce critical aspects of canyon motions, especially at lower wind speeds. Past laboratory measurements may have been biased by inaccuracies introduced by the line source designs used in the experiments. This paper reports the results of visualization, wind field, and dispersion measurements made in a meteorological wind tunnel using an improved line-source configuration. Results suggest that mean concentrations vary inversely with wind speed. Observations also confirm hat the flow within the canyon is highly intermittent, and the street level vortex periodically lifts out of the canyon and then reforms.

In complicated roughness areas like large cities pollutant dispersion is often poor and can deteriorate further when unfavorable meteorological conditions exist (weak winds, cloudy skies, low inversion capping layer). Fortunately, building and street patterns exist for which ventilation of street canyons (a road and its flanking buildings) is significantly improved (Oke, 1988). For example wind tunnel studies have found that entrapment of pollution may be alleviated by distributing higher rise structures along a street which generates corner vortices that mix pollution upward (Hoydysh and Griffiths ,1974; Wedding et al, 1977; Rafailidis, 1995).

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. Meroney et al. (1995) 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.

EXPERIMENTAL SET-UP

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. 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.

Surface roughness for an open country situation was provided by blocks made of two stacked Lego™ elements, 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, displacement height is about 2 mm, and the vertical wind profile exponent α was estimated to 0.28. 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, $Re^* = U(\delta)\delta/\nu$. 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 (Jensen number) U^*z_0/ν is larger than 2.5 as recommended by Snyder (1972). Comparing these tunnel characteristics with those found in the 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.

Measurement techniques

Velocity. The wind velocity was continuously recorded using both a Prandtl pitot-static tube and a hot-film anemometer. 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).

Concentrations. A neutrally buoyant gas mixture of ethane and air was 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 ± 0.8 % of true concentration. The overall balloon sampling and concentration detection system error is about ± 5 %. The concentration measurements are presented in terms of the ratio $K = CU_{ref}HL/Q_e$ unless indicated otherwise, where

C	: actual concentration [ppm]
U_{ref}	: free-stream wind approach velocity at a height of 0.65 m above the floor level [m/s]
H	: height of physical model of building [m]
Q_e/L	: line source strength [m^2/s]
	Q_e denotes ethane flow rate and L is the source length (0.90 m)

Street canyon design.

Wooden 60 mm x 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, $U_H H/ \nu$, 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.

The bars were equipped with flush mounted sampling ports located on a vertical plane on the tunnel axis, Figure (1). 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.

In the following discussion "open country" refers to an isolated street canyon amidst Lego roughness. 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.

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 (Oke, 1988b). The tunnel wind velocity profiles measured for different street canyon configurations as B/H increased from 1 to 8 became fuller in shape. Power law coefficient, α, increased from 0.20 to 0.25 as the flow changed from skimming to wake interference, then remained at 0.28 for isolated roughness conditions. Displacement height varied from 57 to 40 mm as B/H increased. Surface drag coefficient, u^*/u_{ref}, varied from 0.05 to 0.10 and surface roughness, z_o, ranged from 0.25 to 3.00 mm as B/H increased.

Line source

Line sources are used to simulate exhausts from vehicles queuing along a street. Our experience suggests consistent measurements require a laterally homogeneous release; hence, Meroney et al. (1995) describe the line source and tests performed to confirm its reliability. The final design is depicted in Figure (2). The small tube diameter produced substantial pressure drop of the order of 450 Pa for a flow rate of 100 liter/hr/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, but any initial vertical gas momentum was deflected laterally using a capping plate.

With the line source design shown in Figure (2) the overall standard deviation of the downstream plume concentration from the mean value does not exceed ± 2.5 %. On the other hand, the maximum variability range relative to the average does not exceed 7.3 %. 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 ±2.5%.

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.

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.

Open country case

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, Figure (3). 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. This eddy circulates upwind at street level. A roof top eddy which begins at the upwind upstream building roof corner sucks canyon gases onto the roof

- Significant pollution concentrations are measured on the roof of the upstream building, indicating that gas from the canyon is *sucked* inside 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 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.

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 on Figures (4) and (5). The concentrations measured reveal that:

- Substantial concentrations are always measured on the roof of the upstream building. This indicates that some pollutant gases are drawn 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 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 Figures (4) and (5) suggests that the flow inside the canyon can not 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.

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 Figure (6) 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 Figure (5) with (6). 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 (7a) and (7b) for the case B/H = 1. These drawings summarize observations during a visualization study 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 floor. 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.

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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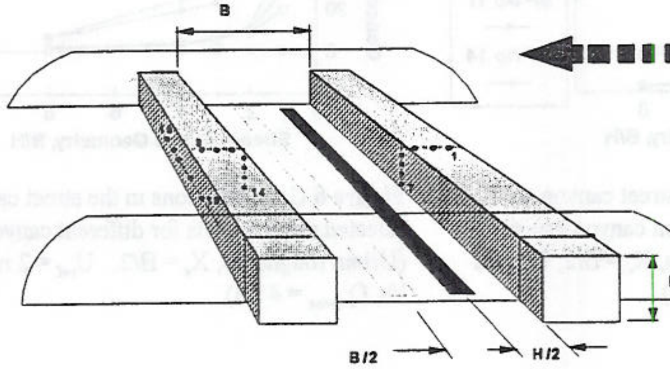

Figure 1a Schematic of model street canyon, line source and sample port locations as installed in Blasius Wind Tunnel, U. Of Hamburg.

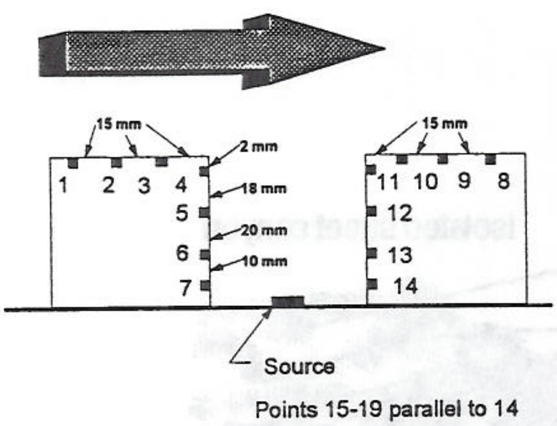

Figure 1b Location of sample ports on surface of model street canyon buildings.

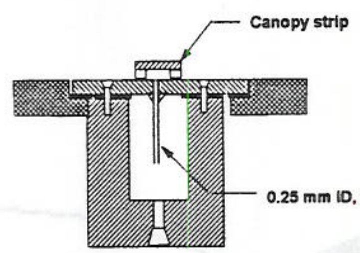

Figure 2 Schematic of line source design. Line source used 302 hypodermic tubes over a 1 meter length.

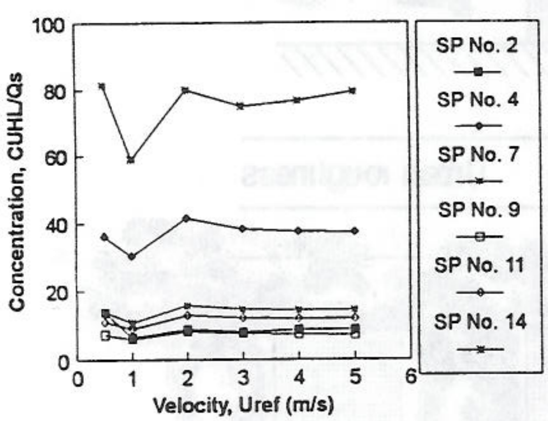

Figure 3 The effect of different wind velocities on pollutant concentrations in a model street canyon at selected sample port locations. (Open country roughness, B/H =1, Q_{air} = 100 l/h, Q_{ethane} = 4 l/h.)

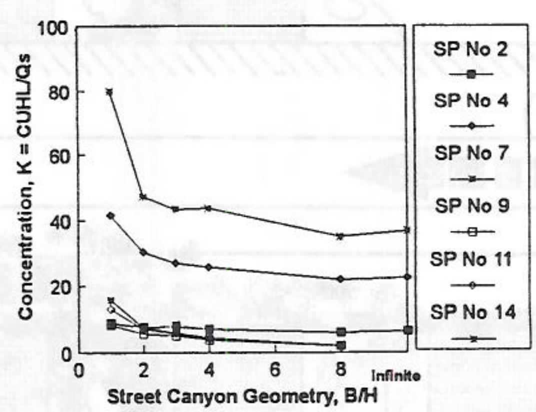

Figure 4 Concentrations in the street canyon at selected sample ports for different canyon aspect ratios. (Open country roughness, X_s = H/2, U_{ref} = 2 m/s, Q_{air} = 100 l/h, Q_{ethane} = 4 l/h).

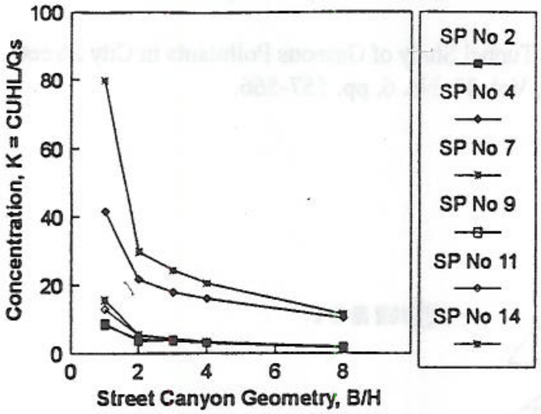

Figure 5 Concentrations in the street canyon at selected sample ports for different canyon aspect ratios. (Open country roughness, $X_s = B/2$, $U_{ref} = 2$ m/s, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

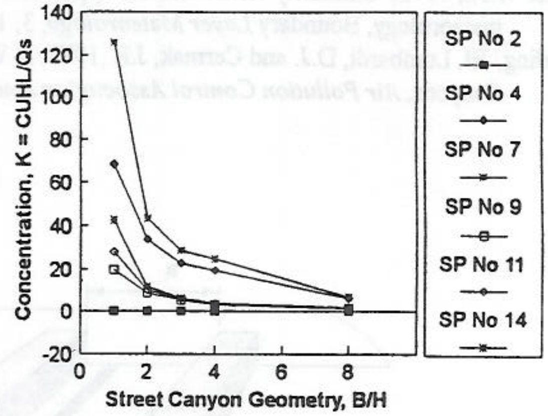

Figure 6 Concentrations in the street canyon at selected sample ports for different canyon aspect ratios. (Urban roughness, $X_s = B/2$, $U_{ref} = 2$ m/s, $Q_{air} = 100$ l/h, $Q_{ethane} = 4$ l/h).

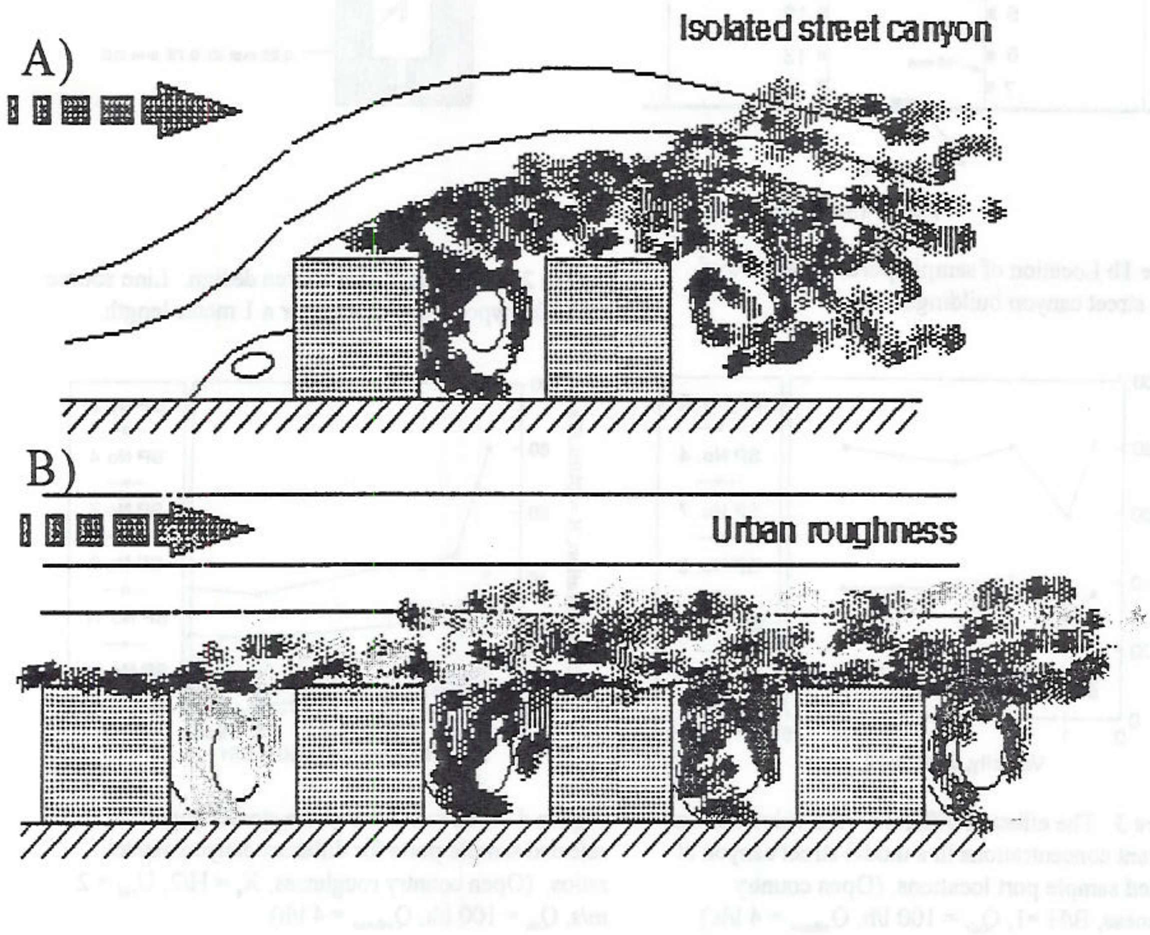

Figure 7 a) Streamlines and dispersion patterns from line source in street canyon placed in open country roughness, compared to **b)** multiple sources in street canyons placed in urban roughness.