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Measurement of the Bent Discharge Pollution Dispersion around Step-up Street Canyon

B.S. Shiau[1,2], B.J. Lee[1]

[1]Department of Harbor and River Engineering
National Taiwan Ocean University, Keelung 202, Taiwan

[2]Institute of Physics
Academia Sinica, Taipei 115, Taiwan

Abstract

The bent discharge pollution dispersion measurement around step-up street canyon was conducted in wind tunnel. The height ratio of up-wind building and down-wind building for the step-up street canyon is 2. The bent discharge was located at the rear of up-wind building top. The source horizontally discharged pollution. Concentration measurements around the canyon with different ratio of street canyon widths were performed in the experiments. Effects of the street canyon width on the dispersion characteristics, such as the canyon downwind building surface concentration distribution, concentration distributions in canyon region, and dispersion parameters around the canyon were investigated.

Introduction

Air pollution threats human health. The dispersion of air pollution around the street canyon in urban area is an important issue for assessing air pollution impact on city living environment. The pollution dispersion in the urban street mainly depends on the oncoming flow, discharging angle, and the shape of building structures. Down-wash phenomena and increased turbulence also strong influenced not only the mean flow field but also the diffusion parameters. Study on the air pollution dispersion around street canyon can offer assessment to improve air quality in urban region.

Yassin [16] had studied the effect of building shape on the pollution dispersion. Kastner-Klein et al. [7] presented an overview of the influence of street architecture on the wind and turbulence patterns in street canyons. Nakayasa and Nagai [11] had used numerical method of large-eddy simulation model to develop atmospheric dispersion model. Pournazeri et al. [13] employed water tunnel and wind tunnel to study the scaling of building effects on plume rise and dispersion. The building downwash effect on the plume dispersion had been studied in wind tunnel, like Chung and Melbourne [2], Gupta et al. [4], and Hajra and Stathopoulos [5]. Hajra et al. [6] had assessed the plume dispersion from roof stack by comparison of numerical models and wind tunnel simulations. Lateb et al. [8] used numerical simulation to study pollutant dispersion around a building complex. Lateb et al. [9] also studied stack height and exhaust velocity affecting on pollutant dispersion in the wake of a building. Mavroidis et al. [10] applied wind tunnel to investigate plume dispersion around a single surface obstacle. Shiau and Lin [15] studied the pollution dispersion in urban environment.

In the present study, bent discharge of pollution dispersion around the step-up canyon was measured. The bent discharge was located at the top of the upwind building of the canyon. Effects of the street canyon width on the pollution dispersion around the canyon were investigated.

Experimental Set-up

The experimental measurements were carried out in the National Taiwan Ocean University's Environmental Wind Tunnel Laboratory. The wind tunnel test section has a cross section of 2 m wide by 1.4 m high and 12.6 m long. The tunnel is an open suction type and it contracts to the test section with an area ratio of 4:1. The turbulence intensity of empty tunnel in test section is less than 0.5 % at the mean velocity of 5 m/s.

Four spires of 140 cm height were placed horizontally with equal space. They were arranged at the entrance of test section succeed to regular deployment of roughness elements (5cm x 5 cm x 5cm) with 9 m long, which assured to generate a fully developed thick turbulent boundary layer flow which was used as the approaching flow. The flow had the free stream velocity of 4.21 m/s, and boundary layer thickness of about 100 cm. The Reynolds number based on the free stream velocity and boundary layer thickness of approaching flow was about $Re=2.88\text{x}10^5$.

Bent discharge source diameter is D=0.42 cm. And the discharging densimetric Froude number used in the experiment was $Fr=V_s/[gD(\rho_{air}-\rho_{mix})/\rho_{air}]^{1/2}=100$, where tracer discharging velocity $V_s=4.29$ m/s, gravitational acceleration $g=9.81$ m/s^2, ambient air density $\rho_{air}=1.205$ kg/m^3, tracer gas density $\rho_{mix}=1.151$ kg/m^3.

An x-type hot-wire incorporating with the TSI IFA-300 constant temperature anemometer was employed to measure the turbulent flow signals. Output of the analog signals for turbulent flow was digitized at a rate of 4 k Hz each channel through the 12 bit Analog-to–Digital converter. Since none of the analog signals containing significant energy or noise above 1 k Hz, with the Nyquist criteria, a digitizing rate of 2 k Hz was sufficient. The low pass frequency for the analog signals is set as 1 k Hz in all runs of the experiments.

Tracer gas was applied to use as the concentration indicator. Methane was used as tracer gas and it mixed with the standard gas. The mixed gas emitted from the bent discharge as the source in the experiments. The tracer gas was a mixture of volume ratio of 1:9 for methane and standard gas. So tracer gas was slightly lighter than the ambient environment of air. The designed rake of sampling tubes was employed to take tracer gas samples. The rake was composed many of tubes (e.g. 10 to 15 tubes). A cam system was applied to accomplish the work of pumping tracer gas. The system was performed to suck simultaneously the tracer gas through many tubes mounted on the rake, and the sampled tracer gas for each tube was connected to each corresponding airbag which was with a volume of three liters. The sucking time was three minutes in each run.

The collected tracer gas in each airbag was detected by FID (Flame Ionization Detector). The methane contained in the sampled tracer gas was quickly burned and detected by the FID, and the concentration of the sample was then yielded.

Figure 1 is the schematic diagram of the step-up street canyon model and bent discharge arrangement. The measurement coordinate system is also shown in the figure. In the figure, L denotes the height of bent discharge; H is the height of upwind building of street canyon; B is the height of downwind building of the street canyon; and S is the street canyon width.

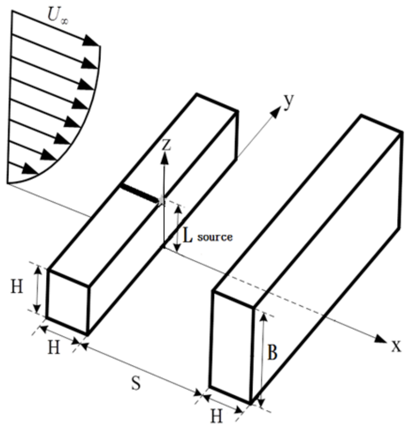

Figure 1 Schematic diagram of the step-up street canyon model and bent source arrangement, the measurement coordinate system is also shown in the figure.

Results

Approaching Flow

The mean velocity profile for approaching flow was measured and shown in Figure 2. The boundary layer thickness Z_{ref} is about 100 cm, and free stream velocity U_{ref}=4.21 m/s. The mean velocity profile of the turbulent boundary layer flow was fitted as the power law ($U/U_{ref}=(Z/Z_{ref})^n$) with an exponent n=0.27. This is in consistent with the range 0.23~0.4 as suggested by Counihan [3] for the turbulent boundary layer flow of urban terrain type.

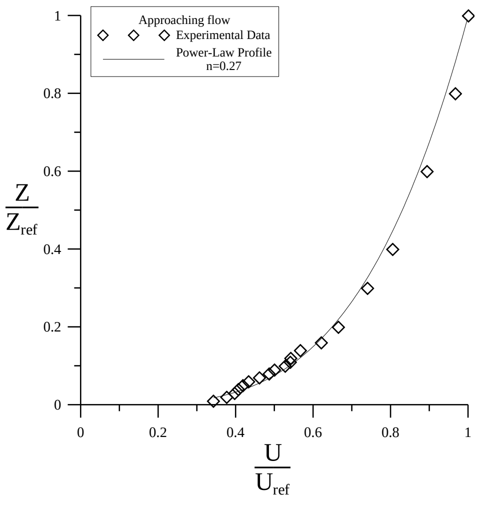

Figure 2. Mean velocity profile of approaching flow.

Concentration Distribution

The experimental measurements on concentration distributions for different street canyon widths were performed. The measured concentration C is scaled by the proper characteristic scales to be expressed in dimensionless form of K.

$$K = \frac{CL^2 U_H}{Q} \tag{1}$$

where C is the measured concentration in ppm; L is the height of pollution discharge in m; U_H is the mean wind velocity at the height of H upstream of the upwind building of street canyon in m/s; Q is pollution discharge rate in m^3/s.

The concentration distribution in horizontal plane at the height Z/H=1 for different street canyon widths (S/H=1, 2, 3) are shown in Figures 3 (a), 3(b), and 3(c) (up to down).

Figures 4(a), 4(b), and 4(c) (from up to down) are the concentration distribution in vertical plane Y/H=0, for different street canyon widths (S/H=1, 2, 3).

Oke [12] indicated that in the regular street canyon (B/H=1), flow regimes for aspect ratio S/H=1, 2, 3 were skimming flow, wake interface flow, and isolated roughness flow, respectively. As comparing the results of concentration distribution shown in Figure 3 and Figure 4, it was found the concentration accumulate around the canyon region as the canyon width decreased from S/H=3 (isolated roughness flow pattern) to S/H=1 (skimming flow pattern). The numerical simulation of step-up canyon with S/H=1 by Assimakopoulos et al. [1] showed a step-up notch formed in the canyon. This implies that the tracer was trapped, and then pollution happened to accumulate in the canyon region as canyon width became narrower.

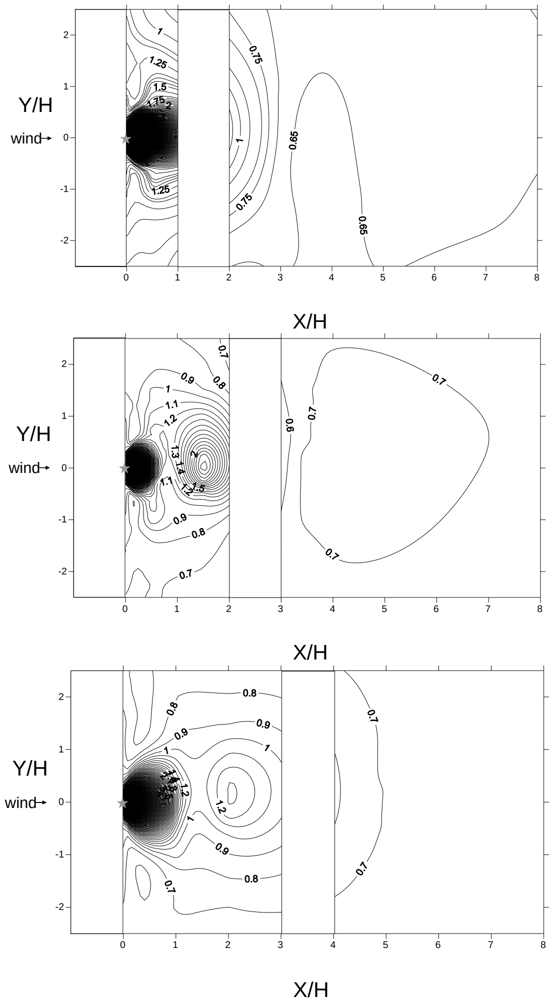

Figure 3. The concentration distribution in horizontal plane at the height Z/H=1 with canyon downwind building height B/H=2, and bent discharge height L/H=1 for various street canyon widths, (a)S/H=1, (b)S/H=2, (c)S/H=3 .

The surface concentration distribution of downwind building with the height of B/H=2, and bent discharge height of L/H=1 for different street canyon widths (S/H=1, 2, 3) were shown in Figures 5(a), 5(b), and 5(c) (up to down). When the canyon width decreased from S/H=3 to S/H=1, the downwind building choked the dispersion of pollution and therefore increased downwind building surface concentration. Results are clearly exhibited in Figures 5(a), 5(b), and 5(c). The concentration distribution patterns are found similar to the numerical simulation results obtained by Salim et al. [14].

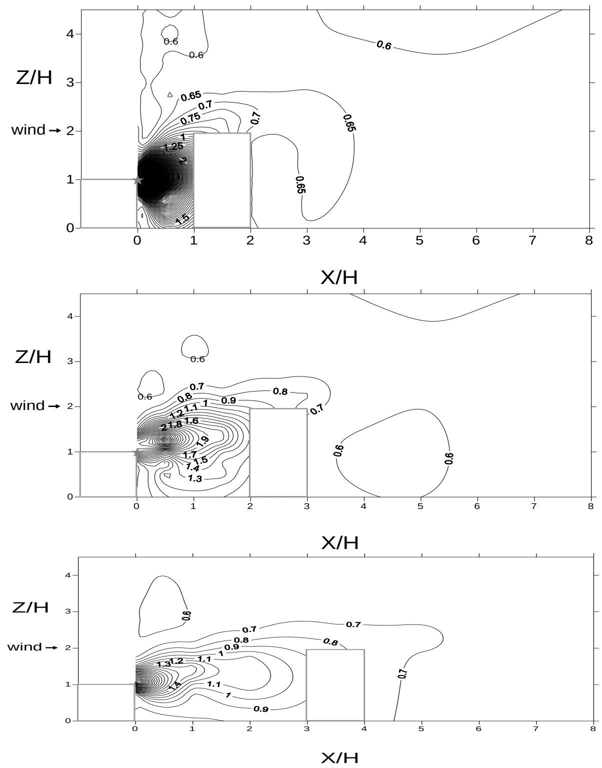

Figure 4. The concentration distribution in vertical plane Y/H=0, with street canyon downwind building height B/H=2, and bent discharge height L/H=1 for different street canyon widths (S/H=1, 2, 3).

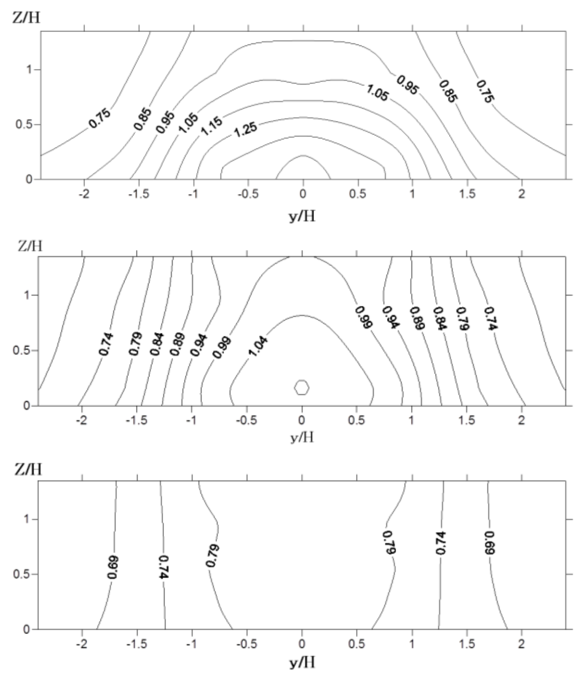

Figure 5. The windward side surface concentration distribution of street canyon downwind building height B/H=2, and bent discharge height L/H=1 for different street canyon widths (S/H=1, 2, 3).

Dispersion Parameter Analysis

Dispersion parameters σ_y and σ_z designate as the standard deviation of the concentration distributions in horizontal direction and vertical direction, respectively. The parameters represent the extents of spread for tracer plume in horizontal direction and vertical direction. Using the concentration distribution, the dispersion parameters σ_y and σ_z are computed as follows:

$$\sigma_y = \left[\left(\int_{-\infty}^{\infty} y^2 C dy \Big/ \int_{-\infty}^{\infty} C dy\right) - y_c^2\right]^{\frac{1}{2}} \tag{2}$$

$$\sigma_z = \left[\left(\int_{0}^{\infty} z^2 C dz \Big/ \int_{0}^{\infty} C dz\right) - z_c^2\right]^{\frac{1}{2}} \tag{3}$$

where C is the measured tracer concentration; y and z are the horizontal and vertical ordinates of Cartesian coordinates, respectively. y_c and z_c are locations of centroid for horizontal and vertical concentration distributions, respectively. z_c also represented as the plume average height. y_c and z_c are calculated by,

$$y_c = \left(\int_{-\infty}^{\infty} Cy dy\right) \Big/ \left(\int_{-\infty}^{\infty} C dy\right) \tag{4}$$

$$z_c = \left(\int_{0}^{\infty} Cz dz\right) \Big/ \left(\int_{0}^{\infty} C dz\right) \tag{5}$$

The horizontal dispersion parameters along the downstream distance of source for different canyon widths at the height of Z/H=1 are shown in Figure 6. Results show that horizontal dispersion parameters increase with the downstream distance. Around the canyon region at the height of Z/H=1, the horizontal dispersion parameters are found larger when the canyon width increases from S/H=1 to S/H=3.

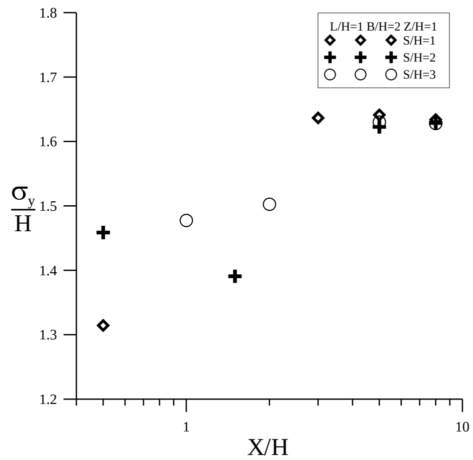

Figure 6. Horizontal dispersion parameters along the downstream distance of source for different canyon widths at the height of Z/H=1.

Figure 7 is the horizontal dispersion parameters along the downstream distance of source for different canyon widths at the height of Z/H=2. The horizontal dispersion parameters are shown increasing along the downstream of the canyon downwind building. Around the canyon region, the horizontal dispersion parameters are found smaller than that of the downstream of the canyon downwind building.

The vertical dispersion parameters along the downstream distance of source for different canyon widths at y/H=0 are shown in Figure 8. The figure indicates that around the canyon region the vertical dispersion parameter is larger as the canyon width is wider.

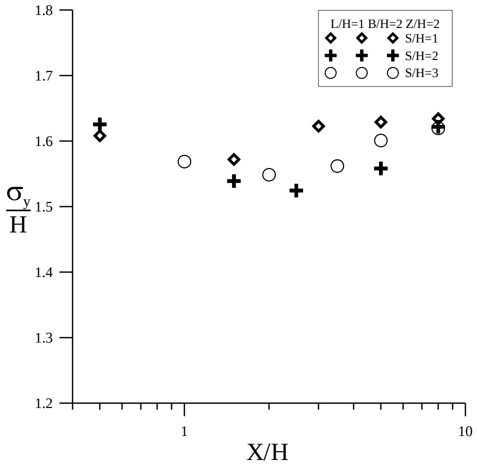

Figure 7. Horizontal dispersion parameters along the downstream distance of source for different canyon widths at the height of Z/H=2.

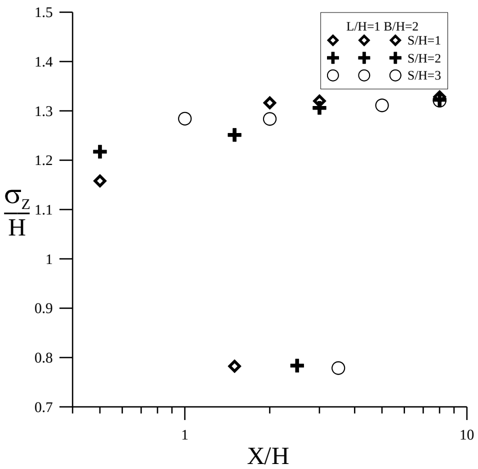

Figure 8. Vertical dispersion parameters along the downstream distance of source for different canyon widths at y/H=0.

Conclusions

Wind tunnel measurements are made and results are concluded as:

(1) The concentration accumulate around the canyon region as the canyon width decreased from S/H=3 (isolated roughness flow pattern) to S/H=1 (skimming flow pattern). The tracer was found to be trapped in the canyon region as canyon width became narrower.

(2) The measured surface concentration distribution of windward building exhibited higher when the canyon width decreased from S/H=3 to S/H=1.

(3) Horizontal dispersion parameters are shown increase along the downstream of the canyon downwind building. Around the canyon region at the height of Z/H=1, the horizontal dispersion parameters are found larger when the canyon width increases from S/H=1 to S/H=3. And at the height of Z/H=2, the horizontal dispersion parameters are found smaller than that of the downstream of the canyon downwind building.

(4) Around the canyon region the vertical dispersion parameter is larger as the canyon width becomes wider.

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