Numerical and Physical Modeling of Bluff body Flow and Dispersion in Urban Street Canyons

Cheng-Hsin Chang and Robert N. Meroney

Wind Engineering and Fluids Laboratory, Department of Civil Engineering
Colorado State University, Fort Collins, CO 80523

ABSTRACT

To develop reliable computer models for the bluff body flow and transport of pollutants or chemical and biological (CB) agents in urban environments requires accurate measurements of the basic flow fields for carefully controlled, well-known conditions. Fluid modeling in an Industrial Wind Tunnel provides an opportunity to produce accurate simulations of the bluff body flow and transport of urban pollution or of CB agents associated with urban terrorism incidents. A basic building shape, the Wind Engineering Research Field Laboratory building (WERFL) at Texas Tech University, is used for this study. The urban street canyon was build by a 1:50 scale WERFL model that was surrounded by models of similar dimensions. These buildings were arranged in various symmetric configurations with different separation distances and different numbers of surrounding building. A series of measurements is made over a generic urban street canyon arrangement using flow visualization, anemometry, pressure transducer and gas chromatography. The experimental data include visualization, velocity and turbulence intensity profiles, surface pressure on the building and dispersion of releasing gas. Results are compared to three-dimensional numerical models of the same configuration using the commercial code, FLUENT 5.3. The effects of grid resolution, boundary conditions, source placement and selection of turbulence model (kappa-epsilon, RNG kappa-epsilon, Reynolds stress, etc.) are examined in a series of sensitivity calculations.

Key words: urban street canyon, dispersion, bluff body flow, numerical modeling

1. INTRODUCTION

The flow patterns that develop around individual buildings govern the wind forces on the building and the distribution pressure about the building and pollution about the building and in its wake. The superposition and interaction of flow patterns associated with adjacent buildings govern the final distribution of facade pressures and the movement of pollutants in urban and industrial complexes. Street canyon depth and width, intersection locations, canyon orientation to dominate wind directions and building geometries will determine peak pollution incidents (Theurer [1]).

The high suction on the roof corner of a low-rise building by oblique winds has been associated with the formation of conical vortices. Many studies have shown that the worst mean and peak suctions on flat building roofs occur for cornering or oblique wind angles. At such angles, conical or delta wing vortices form along the roof edges, which induce higher suction pressures, associated with the strongly curved separation streamlines (Banks et al., [2] [3]). Yet the presence of nearby buildings is expected to deflect streamlines, modify local circulation patterns and induce modified patterns of suction and stagnation pressure, as well as different convection patterns for pollutants. Several previous studies have compared measurements made during physical modeling with numerical predictions. Meroney et al. [4] [5] examined the behavior of line-source diffusion over two-dimensional arrays of simple rectangular model buildings. Leitl and Meroney [6] compared model car exhaust dispersion in street canyons measured by Rafailidis et al. [7] with numerical simulations including the effects of pitched roofs and finite length cross-wise streets. Leitl et al. [8] considered the numerical simulation of concentration and flow distributions in the vicinity of U-shaped building structures. They compared their calculations against detailed wind tunnel measurements produced by Klein et al. [9] and an array of other numerical predictions.

1.1 *Fluid Modeling*

This study uses as a basic building shape the Wind Engineering Research Field Laboratory building (WERFL) at Texas Tech University, Lubbock, which is a metal building of simple rectangular prism shape (9.2 m x 13.8 m x 4.0 m tall). Pressure fields, flow and dispersion patterns about this isolated building have been extensively measured both at full scale and over various model scales immersed in an equivalent turbulent shear layer (Bienkiewicz [10]; Birdsall [11]; Cochran [12]; Ham [13]).

A plastic model of the WERFL structure was constructed to a 1:50 scale and instrumented with

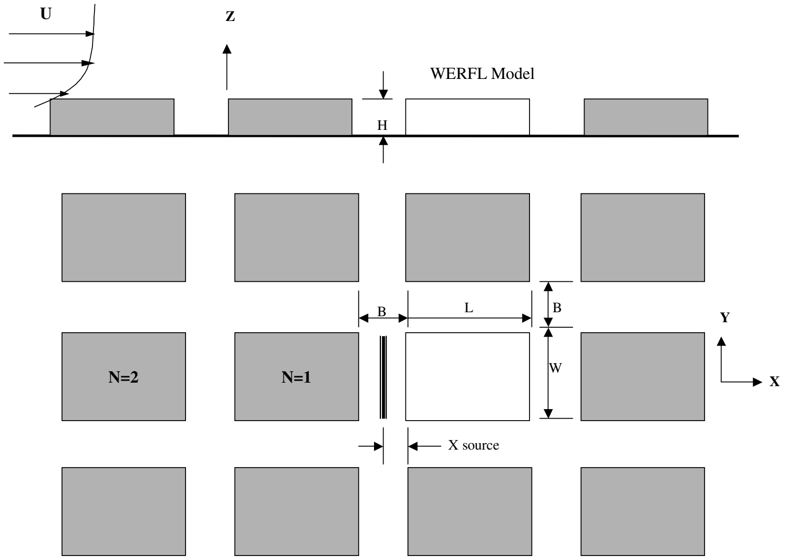

Figure 1: Schematic of Urban Street-canyon Model Arrangement

B/H	λ_{area}	$\lambda_{\text{frontal area}}$	N rows	Structure	Flow
0.5	.72	.21	1,2,3,&8	City center	Skimming flow
1.0	.54	.16	1,2,3,&8	City center	Skimming flow
2.0	.34	.10	1,2,3,&8	Suburban	Wake interference
4.0	.17	.05	1,2,3,&8	Urban 1-2 stories	Wake interference
6.0	.10	.03	1,2,3,&8	One story houses	Isolated

$\lambda_{\text{area}} = \Sigma$ Areas covered by buildings / total urban area
$\lambda_{\text{frontal area}} = \Sigma$ Building area normal to wind / total urban area

Table 1: Array of model structures studied, $X_{\text{source}} = B/2$

multiple pressure ports. A large number of "dummy" models of similar dimensions were constructed of plastic foam and wood to represent surrounding buildings. These buildings were arranged in various symmetric configurations with different separation distances, and placed in the Industrial Wind Tunnel of the Fluid Dynamics and Diffusion Laboratory, Colorado State University. Typical building patterns are noted in Figure 1 and associated arrangement patterns are listed in Table 1.

Wind Velocity measurements were made with single hot-film probe and anemometry equipment manufactured by Thermo-Systems, Inc. (TSI). Flow visualization was accomplished with a laser-light sheet produced by 5-watt Coherent Innova 7005 Argon ion water-cooled laser. Images were recorded by using the Panasonic Omni vision II camera/recorder system. Pressure taps on the 1:50 scale building model were connected to a 48-channel PSI transducer unit, also mounted inside the model. Concentrations of tracer gases (C_2H_6) released from point and line source regions were measured using an Hewlett Packard 5710A Flame-ionization Gas Chromatography. An automated sampling system using 50 syringes captures samples simultaneously for sequential processing through the gas chromatography. Transducer voltages were integrated and recorded automatically by a LabVIEW based data acquisition system.

1.2 *Numerical Modeling*

Flow and dispersion over various building pattern arrangements were also simulated with the FLUENT suite of computational fluid dynamics software. This software is based on a finite volume discretization of the equations of motion, an unstructured grid volume made of either rectangular prisms or tetrahedral cells, various matrix inverting routines, and, in this case, either kappa-epsilon (κ-ε) or renormalized group theory kappa-epsilon (RNG,κ-ε) turbulence model. Steady state solution was sought for several flow configurations and the data generated were displayed on various isopleth contour plots of velocity, turbulence and concentration. Particle trajectories were also generated to elucidate the effects of building spacing and street configurations.

2. RESULTS

As noted previously multiple building configurations were considered (See Figure 1 and Table 1). Depending on the street width to building height ratio (B/H), the flow in the street canyons can be classified as skimming flow (B/H=0-1.2), wake interference flow (B/H=1.2-5.0), or an isolated roughness flow (B/H>5.0) as originally proposed by Oke [14]. Results differed substantially depending upon whether the master building was surrounded by only a few or many surrounding buildings. If the surrounding depth of buildings about the central structure were only one or two circuit deep, the approach flow was characterized by the open-country roughness surrounding the complex. But if multiple building circuits existed, then an equilibrium urban roughness situation existed.

2.1 *Open Country Case*

Characteristics of flow, pressure and concentration distributions were examined. It was noted that:

- Visualization using smoke and vertical light sheets revealed that clean air is drawn into the canyon by intermittent eddies circulating down into the canyons or along the upwind street canyon intersections.
- Significant pollution concentrations were measured on building faces upwind of ground level sources and along rooftops.

- Stagnation pressure occurred on the upwind face of the test building, but their magnitudes were reduced by the sheltering effect of upwind model structures.

2.2 *Urban Roughness Case*

Experiments were also performed on the dispersion within extended urban roughness associated with additional up- and down-stream dummy buildings. The overall characteristics discussed for the open country case were identified also in canyons amidst large urban roughness, but some significant differences were observed.

- For closely spaced multiple street canyons, skimming flow dominates, advection in and out of the canyons appears intermittent, and mixing over the street-canyon top streamline appears to primarily by turbulent mixing.
- As the street widths widen with respect to building height wake-interference flows dominate the advection and dispersion of pollutant plumes.
- Once the street width to building height exceeds about 5, the flow field even for a multiple building arrangement appears to be perturbed by individual isolated buildings.

2.3 *Numerical Simulation*

Version 5.3.18 of the FLUENT code and version 1.2.0 of GAMBIT unstructured grid code were used for numerical simulations. The code was run on an AMD Athlon 750 MHz PC using a Microsoft Windows 2000 Operating System. Four separate turbulence models, standard k-ε, RNG k-ε, Reynolds-stress and LES, were examined for each case. Calculations were performed with unstructured grid generation (Fig. 2). The line source inlet was modeled as $dx = 0.5$ cm in width and W = 18.4 cm in length and set as a constant velocity inlet with no turbulence. The inlet velocity of $w_{source} = 0.01$ m/sec, according to the source emission rate used in the wind tunnel simulation. A tracer mass fraction of 1 was applied to the line source inlet during the calculation.

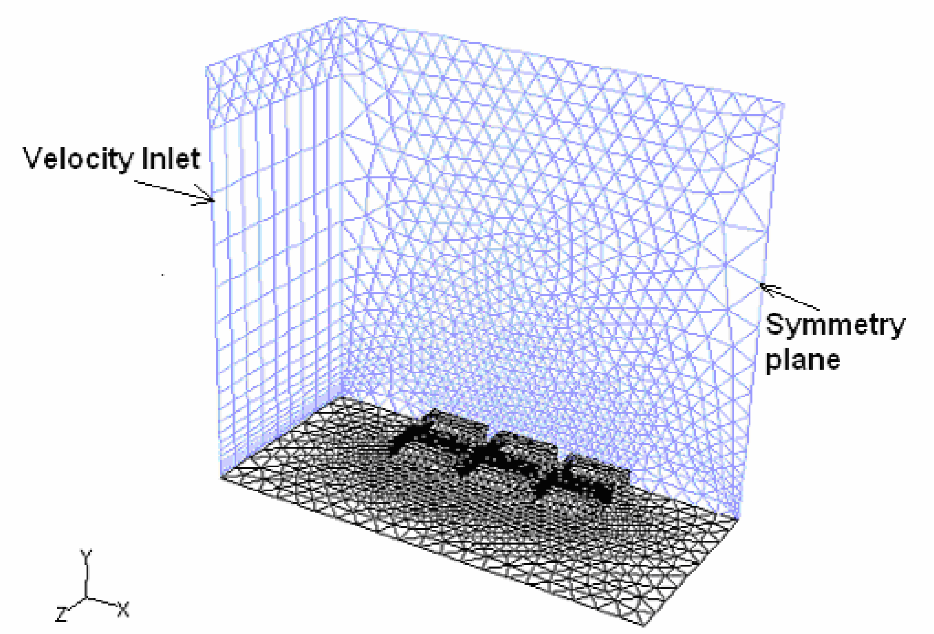

Fig. 2. Unstructured boundary mesh used for tetrahedral mesh generation.

The wind tunnel profiles of velocity and turbulence intensity (CSU-B2) could be used for calculating boundary conditions for inlet profile.

Since the wind tunnel results of concentration measurements were provided in a non-dimensional form, **C** were normalized in the same way with source emission rate (w_{source}, dx), the height of the building, H, and reference velocity, $U_{ref.}$ (Eq. (1))

$$K = \mathbf{C}\, H\, U_{ref} / w_{source}\, dx \tag{1}$$

Comparing each set of data from wind tunnel simulation and numerical simulation, most of the results showed that CFD software, Fluent 5.3, can well predict the actual wind tunnel simulation data by choosing optimum boundary condition, grid resolution and turbulence model. Fig. 3 and 4 show the comparisons between wind tunnel measurements and calculations in both velocity and turbulence intensity profiles which were taken from the center of line source inlet. For this case, canyon width ratio B/H = 1, the calculated results agree well with the measurements in the wind tunnel by running κ-ε turbulence model.

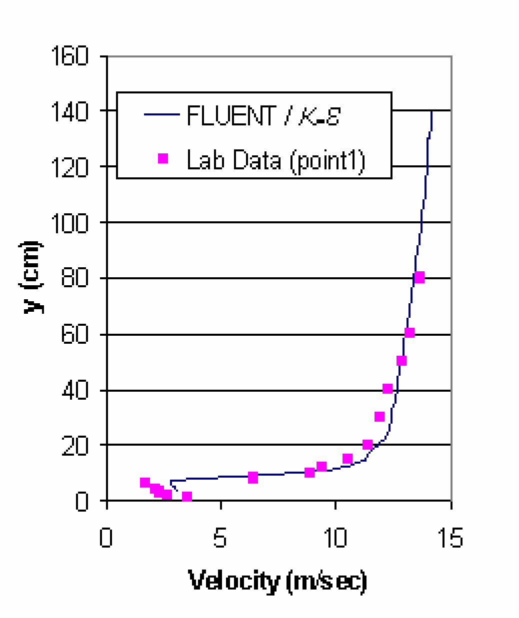

Fig. 3. Comparison of velocity profile between calculated and measured data.

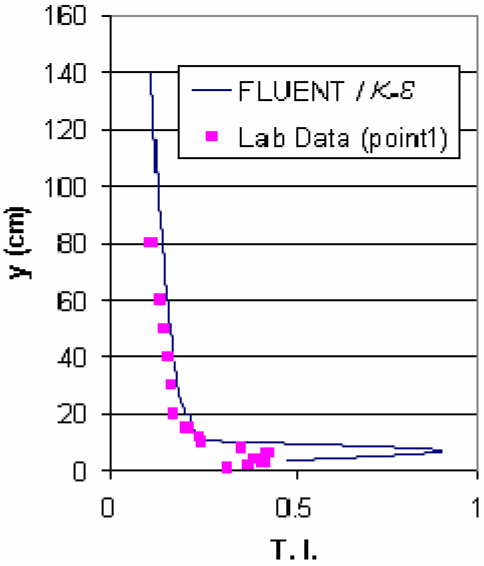

Fig. 4. Comparison of T. I. profile between calculated and measured data

Fig. 5 indicates the positions of concentration measured for the comparison of wind tunnel data and calculated data. Fig. 6 shows a direct comparison between measured and calculated concentrations on the central line of the upwind and downwind walls for street canyon where line source inlet located for case B/H = 1, N = 1.

Fig. 7 shows the comparison of concentrations on the central line of roof surface. The calculated concentrations (Standard κ-ε) for the upwind wall of the street canyon and the roof surface agree well with the data collected from the wind tunnel. At the downwind wall, the calculated values were significantly higher than the values measured in the wind tunnel.

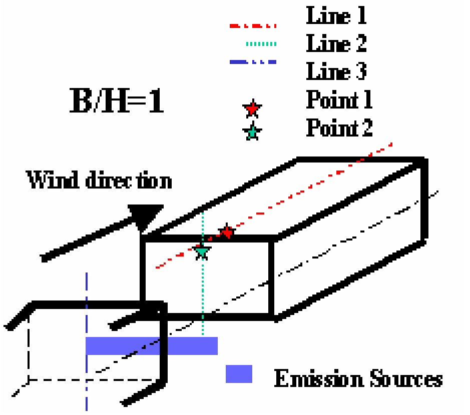

Fig. 5. Positions of concentration measured for the comparisons.

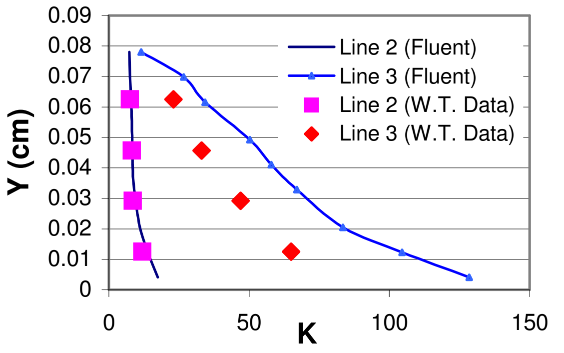

Fig. 6. Comparison between measured and calculated concentrations on the upwind and downwind walls.

A comparison of measured and calculated concentrations for the B/H = 1 with different number rows of shelter models is given in Fig. 8. Two concentration taps were chosen. One was on the downwind wall and the other was on the roof surface. Both measured and calculated results showed increased concentrations by the sheltering effect of upwind model structures.

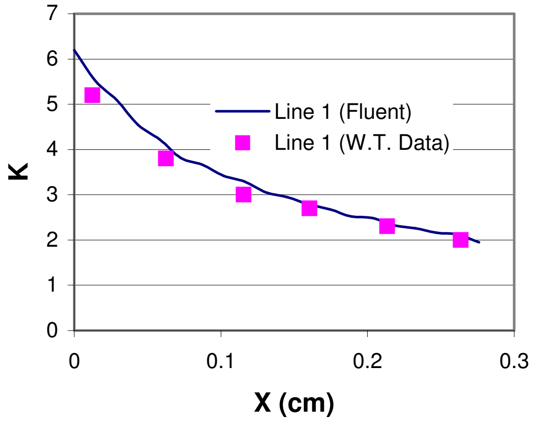

Fig. 7. Comparison between measured and calculated concentrations on the central line of roof surface.

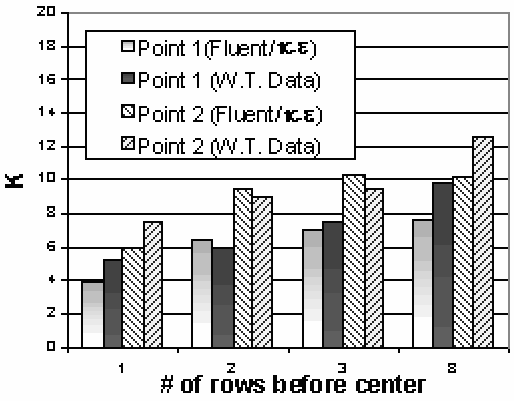

Fig.8 Calculated and measured concentration for different N

As noted previously by Meroney et al. (1998), it is not difficult to achieve a “correct” looking presentation of pressures and concentrations over a bluffbody; however, it is not a given that quantitative equivalence between experimental and numerical data will occur unless careful attention is paid to inlet profiles, grid adaptation and the turbulent model chosen. In the calculation produced to replicate some of the test cases studied above, it was found necessary to take upmost care in adapting the turbulent grids to assure that intense concentration gradients, separation locations and re-attachment locations were reproduced.

3. CONCLUSION

Wind-tunnel flow, pressure and diffusion tests performed about an idealized building arrangement replicated many of features of urban environment previously noted at full scale and in previous laboratory simulations. Numerical simulations using FLUENT reproduced these patterns, but only with care taken to provide adequate grid resolution, accurate inlet flow profiles, and improved turbulence models.

Conclusions of the results of the experiment with FLUENT can be summarized as followed:

- Fluent 5.3 can simulate the flow field in urban street canyons very well using κ-ε model.
- Standard κ-ε model and RNG κ-ε model give almost the same results.
- Predicted separation and reattachment areas agree well with results from visualization of wind tunnel simulation.
- Concentration magnitude is under-predicted by numerical models for cases of more rows of shelter buildings.
- Well setup of grid resolution gets faster numerical solutions converged.
- Adapted grids provides a convenient way to reproduce flow details of separation, reattachment, and high concentration regions without excessive calculation cells.

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