FLUID MODELING AND NUMERICAL MODELING RESULTS FROM POINT AND LINE SOURCES RELEASED IN GENERIC ARRANGEMENTS OF BLUFF BODIES WITH STREET CANYON SEPARATIONS[1]

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Abstract:

Air pollution in urban street canyons resulting from exhaust emissions is a major urban problem. Often traffic pollution excess controls air pollution management decisions. There are a number of elaborate predictive models of pollutant dispersion and diffusion that address the effects of variable shapes of city buildings on pollutant concentrations, but few are fully validated. This paper presents ventilation behavior in different street canyon configurations as determined by physical and numerical modeling.

Introduction:

Dispersion of air pollutants in urban environments has posed a serious health problem for many centuries. During the middle ages King Edward I (1272-1307) forbade coal burning in London when Parliament was in session, King Edward II (1307-1327) put a man to torture due to pestilential odors of his coal fire, Kings Richard III and Henry V (1377-1422) placed taxation on coal and regulated transportation into London. In 1661 an Englishman, John Evelyn, wrote a paper on urban pollution titled "Fumifigation: or the Inconveneice of the Aer and Smoke of London Dissapated; together with Some Remedies Humbly Proposed." Later in 1877 Henry Stokes Eaton addressed the Royal Meteorological Society and noted that the urban heat island would influence London pollution. Hence, he proposed the city should disinfect and fumigate sewers during periods of strong urban convection to control noisome odors and public health. Our modern concern about urban pollution stems from a series of worldwide killer smog incidents between 1900 to 1965 that killed as many as 4000 in a single incident and sickened up to 9000 more (Meroney, 1999). Today, researchers seek to use urban dispersion measurements, fluid modeling and numerical modeling to understand, track and evaluate urban air pollution kinematics. This paper reports some new results concerning the behavior of generic arrangements of urban building elements based on fluid and numerical modeling.

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Urban Air Pollution Meteorology:

The flow patterns that develop above and around an urban complex are driven by nonhomogeneous distributions of heat and surface roughness over a city compared to the surrounding country side. Radial circulations at ground level directed inward toward the city center are associated with urban heat islands whenever there is a significant horizontal temperature gradient between the city center and the surrounding countryside (Plate, 1995). The difference between the urban and rural air temperatures is generally maximum at night, the differences during the day are usually much smaller (Arya, 1999). Circulations are essentially caused by rising warm air over the city center and sinking cold air over the surrounding countryside. The resulting circulation may extend up to the base of the lowest inversion, which may then acquire a dome shape. Early researchers observed a "cross-over" effect where temperatures at a given height above a city may actually be lower than those at the same height in the surrounding countryside due to mixing beneath the inversion (Duckworth & Sandberg, 1954; Bornstein, 1968; Oke, 1969; Oke & East, 1971; Oke, 1995). Fluid modelers have also reproduced this effect (Yamada and Meroney, 1971, 1974; SethuRaman & Cermak, 1974, 1975).

Urban Air Pollution Aerodynamics:

While important in determining the depth of mixing of pollutants above an urban area and the generally radial circulation under low wind conditions; these meso-scale flows do not usually determine the most severe pollution incidents. Most excessive pollution levels are associated with traffic pollutants caught between the city buildings within the urban "street canyons", where wind speeds are low and re-circulation may result in accumulation of pollutants at street level. These circulations are determined by "bluff-body aerodynamic" motions determined by separation and reattachment of streamlines around individual building elements and their associated turbulent motions (Meroney, 1982, 1984, 1988, 1999).

The flow patterns that develop around individual buildings govern the pollution about the building and in its wake (Li & Meroney, 1983a, 1983b). 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 (Hatcher & Meroney, 1971; Kothari et al, 1981). Street canyon depth and width, intersection locations, canyon orientation to dominate wind directions and building geometries will determine peak pollution incidents (Oke, 1987; Theurer, 1992, 1995; Brown & Streit, 1998).

Fluid modeling studies of flow about isolated buildings immersed in a wall layer reveal that plume dispersion is diverted by separation and reattachment regions, and augmented by increased mixing in their wakes, but the general mixing behavior may be scaled quite well by building dimensions and shear layer paramenters (Meroney, 1982). But when several buildings are grouped together, the situation becomes quite complex. Slight changes in building orientation, wind direction or source location can produce quite different concentration patterns. Nonetheless, it is useful to examine the transport and dispersion within urban areas by first considering simple generic building arrangements (2-d and then 3-d arrangements of rectangular block elements) and extrapolating insights gained to the more complex full-scale field situation. This also provides an opportunity to use fluid modeling results to validate various numerical modeling approaches in a modular and systematic manner.

Constraints on Fluid and Numerical Modeling:

Many of the constraints on fluid and numerical modeling are very similar. Both require the accurate representation of inflow conditions (velocity and turbulence profiles, integral scales, spectra, etc.), and both are limited by size of modeled domain, resolution within the domain, and Reynolds effects on turbulence mixing characteristics (Tamura et al, 2001; Ohya et al, 1997, 2001). Special attention must also be placed on the realistic simulation of the exhaust source itself. Auto traffic is known to modify the airflow in its immediate vicinity inducing local circulations, traveling wake regions and enhanced turbulence and heat release at street levels. Incorrect simulation of such sources can result in qualitatively appealing concentration patterns, that are, in fact, incorrect (Theurer, 1995; Meroney et al., 1996; Ahmad et al, 2001). Numerical calculations that emphasize the "steady-state" time independent solution to a concentration field can also provide misleading results. Many flow fields are inherently transient, cyclic or unsteady as a result of approach flow direction deviations, regular wake shedding by the component buildings or cavity "breathing" as the vortex circulation forms, collapses and is fumigated by the elevated wind flows intruding back into the street (Meroney et al., 1999; Lasher et al., 2001). Hence, steady-state calculations often predict excessive concentrations in the street canyon.

Recent Results: Idealized Two-Dimensional Street Canyons:

Since urban street systems are often constructed along a waffle-like regular mesh where street length dimensions are significantly longer than street width or building height, many researchers have examined a two-dimensional approximation to the mid-street circulation system. Corner and end effects are, of course, absent and along street circulations driven by oblique winds or surface roughness perturbations are assumed small. In addition, along-street line sources are constructed to approximate the presence of auto traffic (Meroney et al., 1996a, 1996b, 1999; Rafailidis & Schatzmann, 1996; Pavageau & Schatzman, 1999) , and, sometimes, moving floors, conveyer belts, tracks, or air guns are used to traverse auto models down the street to reproduce eddies associated with auto movement (Ahmad et al., 2001). Building dimensions, building shape, street width, traffic density, and up- and down-wind city extent are variable parameters in the studies.

As street width is increased the canyon flow fields change from skimming flow to wake interaction and then to isolated roughness behavior. For skimming flow situations over flat-roofed buildings upwind building faces are subjected to the highest concentrations; whereas for isolated roughness configurations downwind building faces see higher levels. But a different roofline configuration can invert these observations (Meroney et al., 1996a, 1996b; Rafailids & Schatzmann, 1996).

Leitl and Meroney(1997) compared numerical simulation of two-dimensional behavior to fluid model results. They found that whereas general flow field behavior was reproduced, predicted concentrations were too large since the "average" flow and transport predicted by a steady-state calculation did not realistically reproduce the combined dispersion and diffusion effects of an intermittently fumigating street canyon. Calculations were also performed to test the nature of the two-dimensional assumption by recreating the three-dimensional influence of end walls during the fluid modeling experiments.

Recent Results: Idealized Three-Dimensional Street Canyons:

Wedding et al. (1977) were among the first to examine dispersion over a model city made of similar block shapes, but no numerical modeling was attempted. Theurer et al. (1992a, 1992b, 1995) and Bachlin et al. (1988, 1991, 1992) considered diffusion within a model of an actual industrial complex in Germany, and they also proposed a semi-empirical laboratory/Gaussian plume methodology to predict concentrations.

Recently, Chang and Meroney (2000a, 2000b, 200a) at Colorado State University (CSU) performed a fluid modeling study of flow, pressure distributions and dispersion around the Wind Engineering Research Field Laboratory (WERFL) building maintained by Texas Tech University (TTU); next, they considered multiple blocks of the same dimension combined into a variety of waffle-like patterns to represent groups of buildings in an urban environment; and, finally, they compared these measurements to numerical model results of flow and dispersion produced by Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulation (LES) CFD programs. Some of the results of the CSU Building Block Study (BBS) are discussed further in the following sections.

CSU Building Block Study:

The Texas Tech WERFL field site was extensively studied in wind tunnels at Colorado State University during the NSF CSU/TTU Cooperative Program in Wind Engineering (CPWE), 1987-2001 (Bienkiewicz, 1955; Meroney and Mehta, 2001). This program included field measurements of pressures and flow about the WERFL site, fluid model simulations of similar and extended configurations of the WERFL geometry (eg. addition of parapets, roof HVAC equipment, roof vortex inhibitors, hip or gable roofs, and infiltration configurations (open doors or windows and porous walls). Numerical models of RANS and LES type were also validated using CPWE field and laboratory measurements.

The CSU BBS used the WERFL building configuration as a basic building block. Models of the WERFL building were constructed with pressure taps and concentration sampling ports, and surrounded with dummy buildings of similar shape. Approach wind profiles of velocity and turbulence were matched to mean behavior found at the TTU site. Chang and Meroney examined cases in which street canyon width to height ratio, B/H, ranged from 0.5 to 6.0; rows, N, up and downwind of the central building equaled 1, 2, 3 & 8; orientations from 0^o to 90^o in 10^o increments; and both point and line street level sources.

Conclusions from the CSU BBS Program:

Visualization using smoke and a vertical laser 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, and a rooftop eddy which begins at the upwind upstream building roof corner can suck canyon gases onto the roof. These characteristics do not change significantly with different wind approach velocities, suggesting that the canyon dispersion behavior is Reynolds number independent.

As the street widths widen with respect to building height, wake-interference flows dominate the advection and dispersion of pollutant plumes, until at even greater street widths the plumes are perturbed as by isolated buildings. Conclusions, specific to these new studies are:

- Three-dimensional configurations when the dominant flow is normal to the street canyons (0^o to 90^o) duplicate many features of flow behavior observed during two-dimensional tests. That is skimming, wake interference and isolated roughness flows were observed along canyon midplane when street width to building height ratio (B/H) were 0.5-1.2, 1.2-5.0 and > 5.0 , respectively.
- Circulation within the three-dimensional configurations also replicate two-dimensional concentration patterns. For example, for B/H=1 concentrations decrease on the leeward side of the upstream building from a maximum at the base of the building to lower values at roof level. On the windward face of the downstream building, the concentrations are significantly less, and usually diminish from those at roof level to lower values at street level. For the isolated roughness case, B/H=6, maximum concentrations occur on the upwind face of the downwind building.
- For rural roughness configurations ($N < 2$), roof-top separation eddies over the upwind building are significant. Hence, street level gases are often diverted upward into these eddies, resulting in significant roof-top concentrations.
- For urban roughness situations ($N \geq 2$), upwind roof-top concentrations are relatively small or absent for skimming flows; however, gases are diverted into roof-top separation eddies for wake interference and isolated roughness configurations.
- Oblique building orrientations tended to reduce street canyon concentrations, but flow asymmetries guide gases into side streets previously pollution free. Nonetheless, oblique flows produce lower average downwind concentrations.
- Even under skimming flow configurations street canyon flows are not completely steady. Intermittently, the flow within the canyon washes upward out of the canyon, followed by a short period when the vortex circulation re-establishes (canyon breathing). This transient flow results in lower average concentrations than would otherwise occur for a completely steady flow field, where the only mechanism to diminish street level concentrations would be diffusion across the shear layer between the canyon vortex and the boundary flow above the buildings.
- Ground-level point sources located at canyon midpoint produce remarkably similar normalized concentration patterns to ground-level line sources that extend over the entire street canyon length.
- Concentration patterns at canyon intersections are strongly modified by separation regions and associated eddies produced at the end of the street canyon. Flow along streets oriented parallel with the wind quickly convect pollution out the ends of the source canyon and downwind, where the gases infiltrate other cross streets.
- RANS type CFD models produce mean velocity, pressure and turbulence distributions over and within the various canyon configurations that are essentially equivalent to the fluid model measurements. However, in situations where the flow is significantly intermittent the numerical programs often predict higher concentrations than were actually observed.
- LES type CFD models considered produce much more realistic appearing flow, pressure

and concentration patterns. Mean concentration magnitudes along upwind faces were more realistic. However, although reasonable inlet velocity profiles were chosen, the simulation of the approach flow turbulence inlet conditions were flawed since the calculations relied on inherent numerical instabilities to produce the correct free-field eddy distribution. Hence, a complete verification of the role played by the transient motions on peak and rms concentrations within the street canyons could not be confirmed.

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