J1.11 DEVELOPMENT OF AN IMAGE- AND CFD-BASED URBAN SCALE WIND FIELD AND DISPERSION SIMULATOR

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1. INTRODUCTION

The proliferation of chemical, biological and nuclear weapons has increased the probability that these agents may be intentionally or inadvertently released in a heavily populated urban environment. Models currently exist that predict the wide area dispersion of toxic substances, for example Gaussian-Puff models such as SCIPUFF, in the Hazard Prediction and Assessment Capability package, HPAC. Gaussian-Puff models are well tested, are in wide use, and have been successfully applied for the large area dispersion problems. Puff-based dispersion models rely upon an existing wind field to transport the simulated agent. Application of this type of approach at the building to city blocks scale is questionable, since the flow environment is highly recirculative and is dominated by bluff-body vortex shedding.

An attractive approach to the urban scale modeling is to apply Computational Fluid Dynamics (CFD), which is the approach taken here. A CFD-based approach directly solves a suitably time-averaged form of the governing Navier-Stokes equations in the Urban environment, and makes far less approximations with respect to the wind and turbulence fields. Due to this, more complex phenomena of concern to the urban area may be naturally accounted for, such as:

- Channeling due to street canyons
- Non-skimming type flows
- Plume splitting and settling
- Drag due to foliage
- Buoyancy effects
- HVAC effects (e.g. entrainment and infiltration)

As the ratio of performance to cost of computers keeps rapidly increasing, CFD-based analyses are becoming quite tractable for a wide variety of disciplines. For nearly all applications of CFD, and particularly so for the complex geometry of the Urban environment, the most time consuming part of the simulation process is the generation of the CFD model itself. We have implemented a unique image-based approach coupled with a hierarchically-structured mesh generation strategy that automates the model generation process. The automated model generation, CFD simulation and control all reside within an easy to use graphical interface that runs on Windows and Unix platforms. This Urban Dispersion Simulator prototype, UDS, has been developed with support from the Defense Threat Reduction Agency. This paper describes the development of this prototype, a validation study conducted, and some sample demonstration problems concerning the dispersion of CB agent in urban areas.

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2. COMPUTATIONAL FLUID DYNAMICS APPROACH

The heart of the simulation process in the UDS is CFD-ACE+. CFD-ACE+ is CFDRC's commercial, Multi-Disciplinary/Multi-Physics suite of simulation software. This analysis package is based upon a collection of Finite-Volume, Finite-Element and Boundary-Element methods which solve the following physical phenomena, in either a loosely or strongly coupled fashion:

- Mass, momentum and conductive heat transfer
- Radiative heat transfer in participative media
- Gas-phase surface and volume chemistry
- Eulerian-Lagrangian particle tracking
- Electromagnetics
- Structural mechanics

For the urban wind and turbulence field predictions, the Reynolds Averaged Navier-Stokes (RANS) equations are solved in a Finite-Volume framework upon polyhedral-unstructured grids using an implicit, co-located pressure-based approach. The polyhedral-unstructured approach taken in CFD-ACE+ permits the solution of conservation laws (such as mass, momentum and energy conservation) upon arbitrarily constructed control volumes. This freedom permits the application of such modern techniques as geometric and solution-adaptive mesh refinement and allows solution upon hierarchically refined meshes, such as those generated by 2^N tree algorithms, which are used in the model generation phase, shown below.

3. MODEL GENERATION

The geometrically complex cityscape generation in the UDS is handled by a voxel-based solid model engine coupled to a 2^N tree-based mesh generator. The voxel representation is performed by processing an image corresponding to a height map of the area of interest, which generates a solid model. The solid model, represented in voxel form, is then processed using a hierarchical data structure, a binary tree, to create a polyhedral, unstructured finite-volume mesh. The advantages of using this approach lies in the ability to model complex geometries very rapidly, and allow the suppression of features below a resolvable scale. Other mesh generation approaches are being explored presently, and will be presented at a later date.

4. VALIDATION TO MACDONALDS WATER TUNNEL DATA

Here, we compare results computed upon grids generated by the UDS to the Macdonald data [Macdonald (2000)]. In [Macdonald, (2000)], Macdonald et al. performed a series of hydraulic flume experiments simulating obstacle arrays at 1:200 scale. The data measured consists of mean velocity and turbulence profiles, where the flow conditions and obstacle dimensions result in a Reynolds number (based upon obstacle height and “free stream” velocity) of approximately 4200. The flow entering the test section was preconditioned using various roughness elements, giving an ABL-like profile. The inflow profile and turbulence level were well characterized and are presented in the report. The objects considered were cubes and “billboards”, where the planform and frontal area density of the arrays were varied from densely packed to loosely packed arrays. In [Coirier, (2000)] the UDS was compared to the Macdonald data for cubes and billboard arrays, of which the following are illustrative of the results. (More complete details are shown in [Coirier (2000)]).

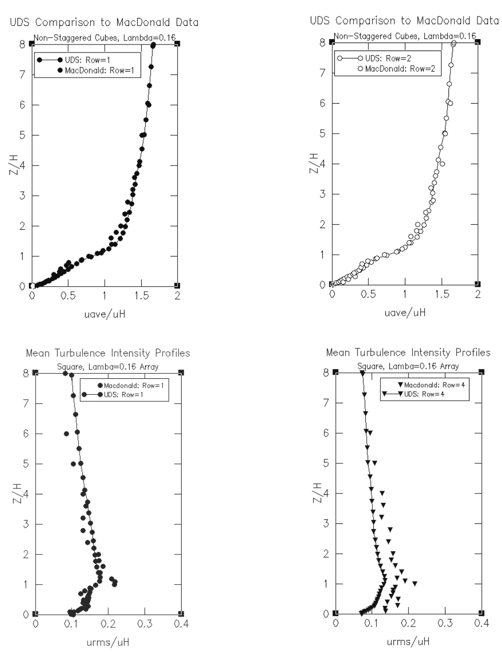

Figure 1: Probe averaged mean flow (top) and turbulence intensity (bottom) comparisons to the Macdonald data [Macdonald (2000)].

Overall, when suitable inflow turbulence profiles were prescribed, the mean velocity profiles were predicted quite well, while the turbulence intensity tended to be predicted well near the fronts of the arrays, and underpredicted farther downstream. This behavior has been observed in [Yee (2002)] for billboard (tombstone) arrays.

5. DEMONSTRATION: DISPERSION NEAR LAFAYETTE PARK

The UDS was used to simulate the mean wind and turbulence field in Washington DC, near the vicinity of the White House. CAD data obtained from the National Imagery and Mapping Agency was used to generate a height map, from which the cityscape geometry was generated. Steady state and unsteady dispersion calculations were made for wind from the North, at a velocity of approximately 3.5 m/s at 50 meters. The predicted flow patterns show many secondary flow paths, recirculation regions, and channeling effects from the side streets. Results from these simulations and others are shown in [Coirier (2000)].

6. CONCLUSIONS

A simulation tool has been developed to simulate the wind fields, turbulence fields, and the unsteady dispersion of NCBR substances in urban areas on the building to city blocks scale. This Computational Fluid Dynamics (CFD)-based approach has been shown to accurately simulate the urban wind and turbulence fields with minimal approximations, and has been demonstrated by modeling the flow fields and simulated release of CBW agent near the Lafayette Park, Washington DC. This note outlined the modeling approaches taken, including both CFD and solid model generation, and showed results comparing computed and experimental data for the flow over obstacle arrays simulating the urban environment. The UDS is being further developed under an SBIR Phase II contract with the Defense Threat Reduction Agency.

7. ACKNOWLEDGEMENTS

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