J3.4 DISPERSION AROUND AN L-SHAPED BUILDING: COMPARISONS BETWEEN WIND TUNNEL DATA AND THE RUSTIC / MESO MODELS

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1. INTRODUCTION

Under DARPA sponsorship, a fast-running urban airflow model named RUSTIC (**R**ealistic **U**rban **S**pread and **T**ransport of **I**ntrusive **C**ontaminants) has been developed. The code fills a gap between slow-running CFD codes and fast-running, but lower accuracy, mass-consistent flow models. CFD codes can take many days of computer time to handle a large urban area with sufficient resolution to resolve eddies around even mid-sized buildings. Conversely, mass-consistent flow models are quite fast, but lack much of the relevant physics. The program goal is the development of tools that can predict the flow and dispersion of contaminants with “good enough” accuracy on a PC in less than an hour for a 1 km x 1km urban area. For contaminate transport, RUSTIC has been coupled with another code called MESO that uses Lagrangian tracer techniques. This paper outlines a preliminary validation effort for the two codes. Burrows et al. (2004) give a more complete description of RUSTIC elsewhere in the articles of this conference.

2. MODEL DESCRIPTION

To simplify computation, RUSTIC combines the continuity and thermodynamic equations into a single pressure tendency equation. The prognostic equation for pressure is then written in a form with the speed of sound c identified in a manner that allows it to be greatly reduced to permit a large time step. Experimentation has confirmed that the exact value of c has little or no effect on the final velocity and turbulence fields predicted. RUSTIC includes a k-ω turbulence model with a turbulence kinetic energy (TKE) production term for buoyancy, permitting the study of atmospheric stability effects. Execution speed is further enhanced with an expanding grid capability and with the ability to allow cells far from the most turbulent regions to “coast” for n cycles whenever the acceleration is found to be below a preset criteria. A modified Cartesian grid structure is used and the solution is obtained with finite-volume techniques. Although the cells are rectangular for increased computation speed, partial cells are used at building edges to improve the accuracy. A technique for running RUSTIC with several different grids of increasing finer resolution is being developed with the goal of providing rapid convergence to a “useful” solution within as short of a period of time as possible. To initialize the grid, and to supply the wind profile and turbulence energy and dissipation at the inflow boundary, a 1D numerical algorithm that contains the k-ω turbulence equations is included. The algorithm computes the flow as a function of altitude over a rough surface based on the sensible heat flux and surface roughness. RUSTIC can be run with an upwind heat flux that differs from the heat flux value around the larger buildings.

To model transport and dispersion (T&D) of contaminants, RUSTIC flow and turbulence fields are passed to a second code named MESO, which is based on Lagrangian stochastic tracer techniques. Although the code has been primarily sponsored by the Naval Surface Warfare Center Dahlgren Division (NSWCDD) for general purpose T&D applications, new urban capabilities have been recently added under DARPA sponsorship. Tracer techniques have a number of advantages over standard grid advection methods. One is the reduction of advection errors in highly sheared flow, which is quite important when using coarse grid cells to reduce run time. Another is the elimination of artificial diffusion, which is particularly important for biological agents that can cause fatalities even for extremely small quantities. A third advantage is the ability to naturally handle large size distributions and droplet settling. MESO contains a full suite of tools for handling chemical and biological agents including droplet evaporation.

To move tracers with the flow, MESO first determines the RUSTIC cell in which the tracer is located. The tracer velocity is then estimated by interpolating between the eight corners of the cell. The interpolation scheme assumes the flow is detached at the building edges and corners. To improve the flow accuracy around corners and in tight eddies, the tracers are advanced with a predictor-corrector numerical scheme. Care has been taken in the development of MESO to include a terrain-tracking capability to prevent tracers from artificially depositing or impacting building walls, which is of particular importance in turbulent flow. To model urban dispersion, each tracer undergoes numerous random-walk excursions in each coordinate direction. In the limit of large numbers of tracers, the technique models a gradient transfer

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process. As shown by Diehl et al. (1982), the random walk technique satisfies the well-mixed condition, which in effect means there is no artificial drifting of the tracers in areas of high diffusion gradients. For improved accuracy, the diffusivity *K* between cells is modeled with linear segments, rather than as a series of stair step changes.

MESO includes an accurate heat flux algorithm that uses the heat budget at the surface/canopy to estimate the sensible heat flux, which is needed for estimating contaminate deposition, as well as for handling the RUSTIC grid inflow boundary. Of particular importance for small biological particles, MESO contains an accurate method of estimating particle deposition including canopy "filtration." Each ground cell of the flow grid can have its own surface characteristics, including canopy type, so the deposition rate can be modeled on a cell-by-cell basis.

3. WIND TUNNEL SETUP

The wind tunnel setup was the A1 case in Project EMU as described by Cowan et al. (1997) and by Castro et al. (1999). An L-shaped building with an inner side door was placed in a boundary layer flow with a surface roughness z_o of 0.12 m. Although the model was tested at 1/200 scale, only full-scale values will be given here. As shown in Figure 1, the building was 10 m in height with the wind direction head on toward the long end of the building. The wind speed at a height of 10 m was 5 m/s. Flow was also forced out the door at 1 m/s with a trace gas added to allow dispersion estimates downwind of the building. Since the door was fairly large, 4m wide by 5m high, the door flow had a substantial influence on the flow.

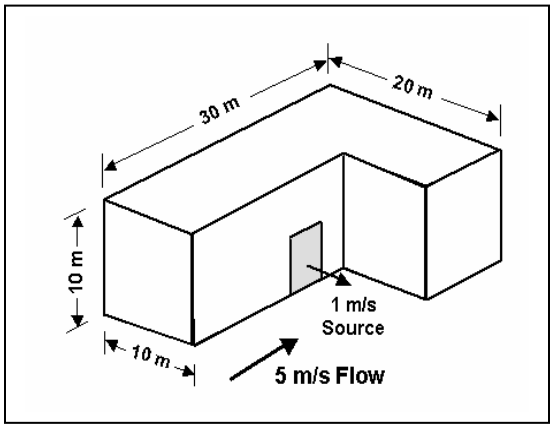

Figure 1. L-Shaped building geometry used in wind tunnel test A1.

4. MODELING RESULTS

The horizontal grid for the RUSTIC flow prediction is shown in Figure 2. In the vicinity of the door, the cell size was 1m x 1m, but was expanded to 2m x 2m until away from the structure, where it was again rapidly expanded. Vertically, the cells were 0.5 m in size from the ground up to the top of the door, but expanded to 1 m in size up to a height of 15 m. Above this level the cells were again rapidly expanded up to the top of the grid at a height of 42 m. The total number of cells along each axis was 67 x 62 x 30.

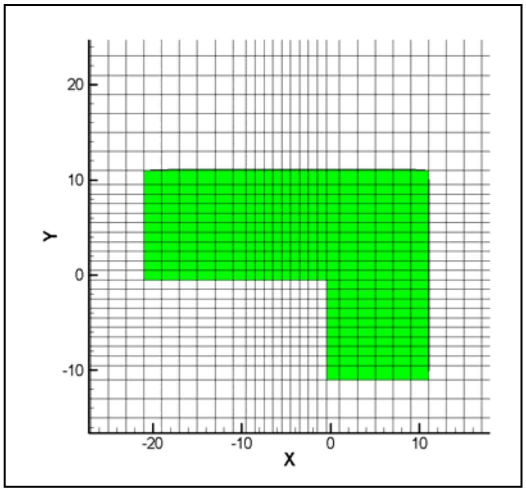

Figure 2. RUSTIC grid used for flow prediction.

Figure 3 shows the predicted velocity vectors at roughly 3 m above the ground after the flow has reached steady state. Also shown are TKE contours (J/kg), which are high, of course, in the strong shear regions at the front corners, and weak in the slow eddies behind the building. The TKE is also moderately high well away from the building due to the boundary layer. Two eddies can be seen at the rear of the structure, with the stronger of the two coming off the far rear corner. Although not shown, a relatively strong eddy also forms at the rear corner of the roof. Streamlines are shown for starting locations at the door. Although the streamlines would suggest that most material is carried out around the building rather than going over the roof, as will be shown, a significant amount of the trace gas goes over the roof because of the turbulence. A few of the streamlines follow small eddies in the region of the door where turbulence can displace them into the flow over the roof. At about one building height behind the structure, many of the streamlines curve back toward the building in the small rear eddy. Although quite close to each other, some of the streamlines instead travel with the main flow away from the building. Even a small difference in the starting location appears to make a difference in the concentration of trace gas behind the building. However, the turbulence is sufficiently strong to disrupt the path of a tracer along any given streamline.

A contour plot of dimensionless concentration C* is shown in Figure 4. The concentrations *C* were

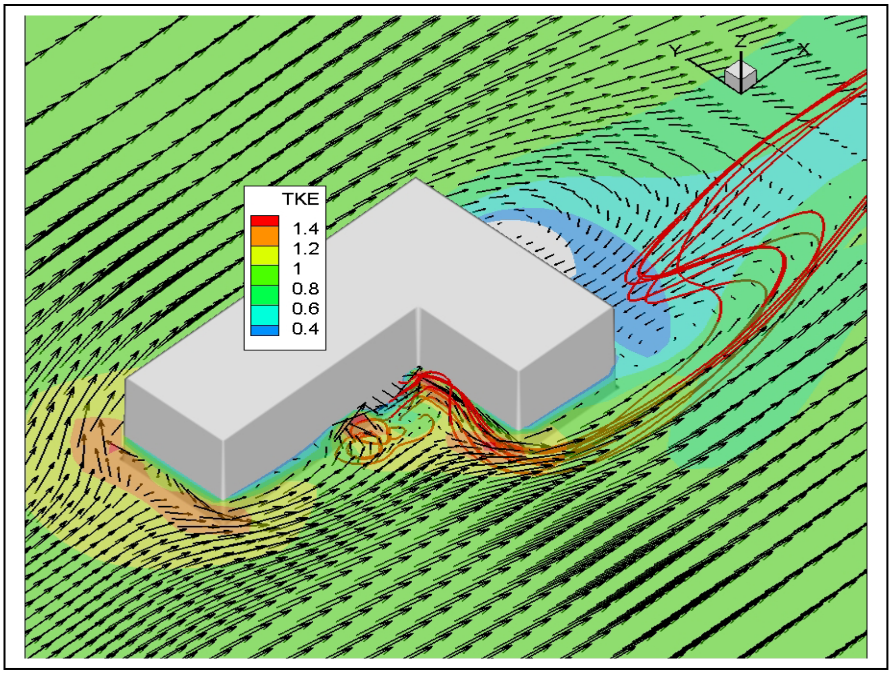

Figure 3. Flow vectors and TKE contours predicted by RUSTIC for an L-shaped building in flow with a boundary layer.

normalized by dividing by $Q/(uh^2)$ where Q is the source strength, u is the wind speed at the height of the building, and h is the building height. Turbulent eddies near the inside corner near the source carry trace gas upwind to near the front end of the structure. Primarily due to turbulence created at both upwind corners on the door side of the building, trace gas at low levels is carried out well away from the building side section. The effect of eddies behind the structure is also apparent.

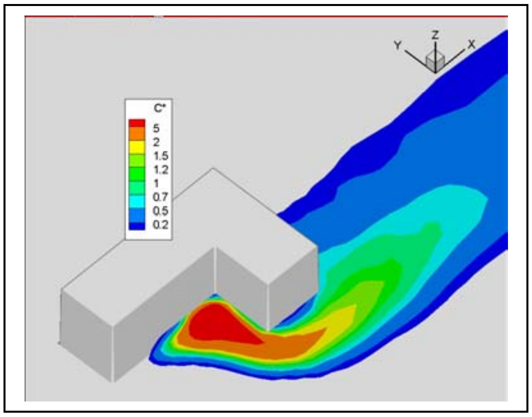

Figure 4. Contours of dimensionless concentration predicted by MESO/RUSTIC near the ground (z/h=0.16).

A plot of measured versus predicted concentration is shown in Figure 5 for three different scaled heights, *z/h*. The measurements were taken in a plane directly behind the building at a downwind distance *x/h* = 1. The crosswind distance has also been normalized by the building height. Thus, as indicated in the diagram in the upper right corner of the plot, the location y/h = +1 aligns with the long wall of the building, and y/h = -1 aligns with the small wall of the side extension. At all three altitudes the predicted curves agree reasonably well with the test data. The main exception is the predicted curve for z/h = 0.16, which does not extend as far out from the building toward negative y as the measured values.

By giving the door flow reasonable turbulence values, RUSTIC predictions were found to improve. For the run shown in Figures 3,4 and 5, the door was modeled as a set of source cells supplying a TKE of 0.1 J/kg and a dissipation of 0.01 m^2/s^3. These quantities were estimated by simply taking values from a 1 m/s boundary layer at a level of 2 m with z_o = 5 cm. RUSTIC runs were also made with coarse 2m x 2m cells in the vicinity of the door area and building. As expected, the results were not as good and, in fact, the values of C* for z/h = 0.16 were over 50% too high in the region of the peak concentration. As discussed by Cowan et al. (1997), other CFD codes have produced poor comparisons for this test case. For example, even with fine cells, some of the predictions produced scaled concentrations with a peak as high as 2.9. Furthermore, the peak predicted by these other codes often resided near y/h = -1.0 rather than at y/h = -1.5. However, additional effort is needed to

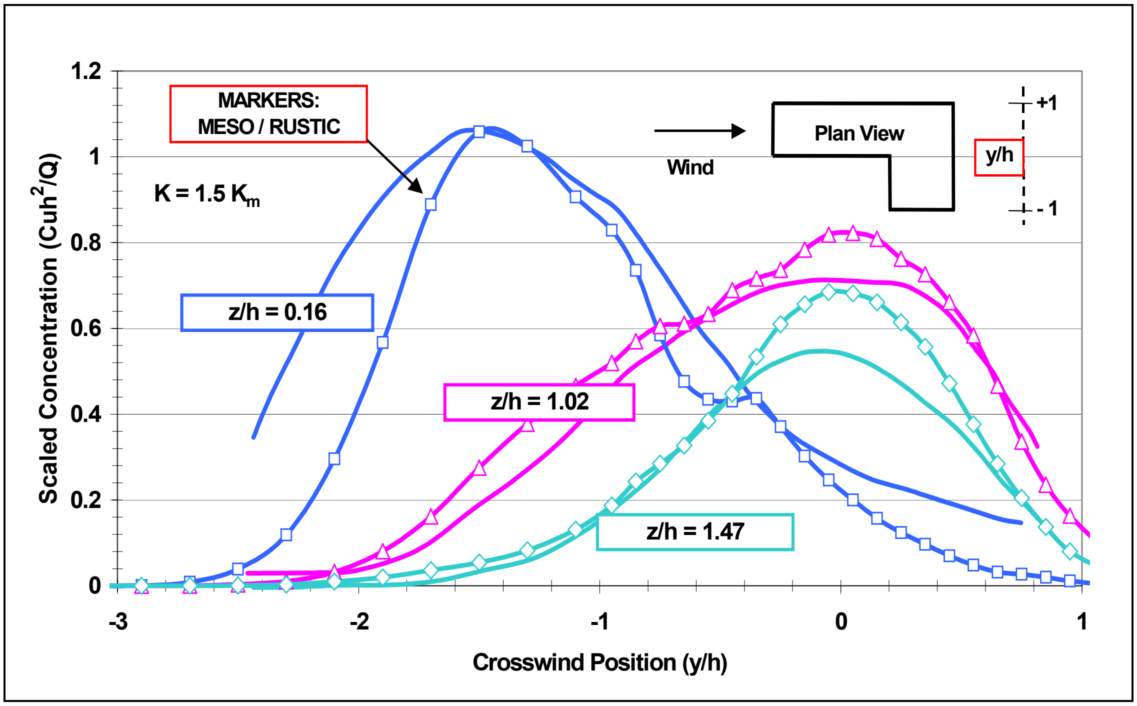

Figure 5. Comparison between measured and predicted trace gas concentration a distance of one building height *h* behind the L-shaped building. The curves represents normalized concentration data for MESO (with symbols) and for measured data (no symbols) taken in a downwind plane (x/h = 1 behind the building) at three heights: *z/h* = 0.16 (blue), *z/h* = 1.02 (magenta), and *z/h* = 1.47 (teal).

determine whether RUSTIC/MESO can also make accurate predictions for other test cases.

5. CONCLUSION

Although still in the validation stage, RUSTIC and MESO show promise as a valuable tool set for the prediction of urban dispersion. For the wind tunnel test discussed here, the models do a respectable job of predicting the dispersion around an L-shaped building with a complex emission source. Adding to the complexity, the building was set in a fully developed boundary layer. Furthermore, RUSTIC/MESO can make such predictions using a relatively coarse grid so computer time is greatly reduced. Runs for both neutral and unstable conditions have been made for the entire downtown area of large cities, requiring only a few hours of computer time on a 2 GHz PC using cell sizes of 5m x 5m x 5m with partial cells around the buildings. However, the fast convergence techniques and "coasting" techniques that are still under development promise to reduce this to only an hour or two. Of course, a small increase in the cell size will also greatly reduce the run time. Comparisons are currently underway between the models and the Joint Urban 2003 data set taken in downtown Oklahoma City. Preliminary results are discussed by Hendricks et al. (2004) in this set of AMS conference articles. Predictions for unstable daytime conditions are shown for a 1km by 1km area covering all the downtown region of Oklahoma City.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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