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WEST POINT

Detailed Experimental MRI Measurements and Simulations in Oklahoma City: Joint Urban 2003

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Abstract

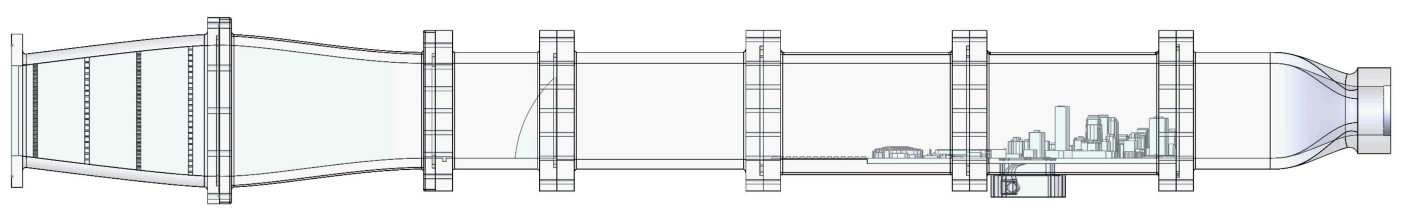
Magnetic resonance imaging (MRI) techniques were used to collect three-component velocity and concentration data at nearly 10 million locations across a 1:2515 scale model of 2003 Oklahoma City. The experiments included the low-momentum release of a passive scalar at the intersection of Broadway and Main street in order to mimic the field tests of the Joint Urban 2003 (JU03) study's Intensive Observation Period 8. Magnetic Resonance Velocimetry (MRV) and Magnetic Resonance Concentration (MRC) techniques measured the time averaged field with experimental uncertainties of 5.5% and 4% respectively, providing a candidate validation data set for atmospheric flow models. Velocity and concentration results are analyzed, and initial comparisons are made between the MRI data, the JU03 field test, and Sandia National Laboratories' SIERRA/Fuego low Mach dispersion model.

Magnetic Resonance Imaging for Velocity and Concentration

In most MRI techniques, radio frequency (RF) sequences are used to perturb the spin of hydrogen protons from their resonant frequency. This perturbation creates magnetic gradients that allow the protons to broadcast RF waves back to the MRI receiver. By altering the emitted RF sequences and analyzing the return signal phase, amplitude, and/or frequency, the experimenter can determine information about the proton field characteristics. Velocity field data is computed by utilizing a "phase-contrast" sequence, while concentration field data uses a "fast-spoiled gradient echo" sequence. By using various solutions of copper sulfate and pure water to account for background noise, concentrations can be measured down to about 1.0% at a spatial resolution of 0.8 mm.

Methods

Additive manufacturing was used to construct the water channel (details listed below), cityscape test insert, and 15-degree injection apparatus with a high degree of precision and customizability. Solutions of copper sulfate and water are circulated through the channel and injector (details tabulated below) while the MRI machine takes time-averaged readings of the water channel section containing the cityscape. These readings are then post-processed to compute the velocity and concentration fields throughout the scanned domain. Single MRI scans take several minutes to complete, and sufficient data to fully characterize a flow field can be collected in less than a day.

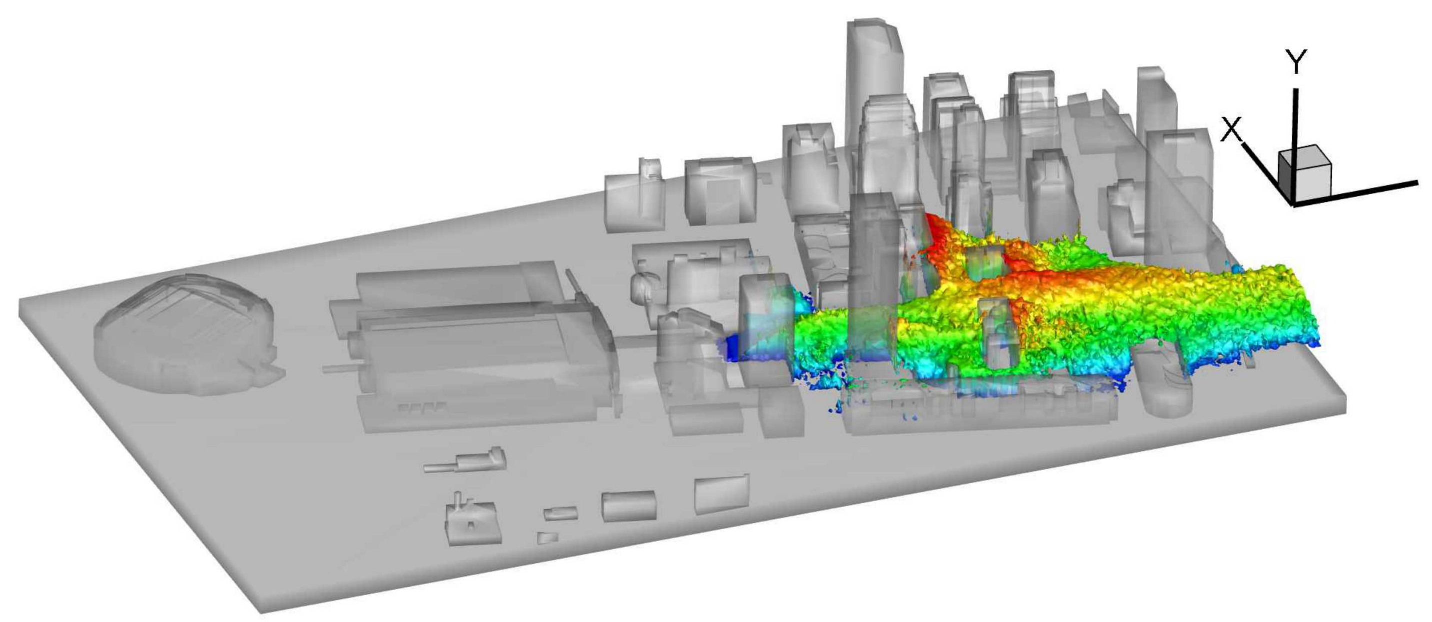


Elements of the water channel used to conditions flow were modeled after the standard EPA wind tunnel. They include:

- An expansion to slow flow.
- A honeycomb grid network to reduce swirl without separation.
- A contraction to a constant cross-sectional area.
- Four Counihan vortex generators to re-energize flow.
- Cylindrical roughness elements to thicken the floor boundary layer.
- Additively manufactured cityscape to characterize flow patterns.

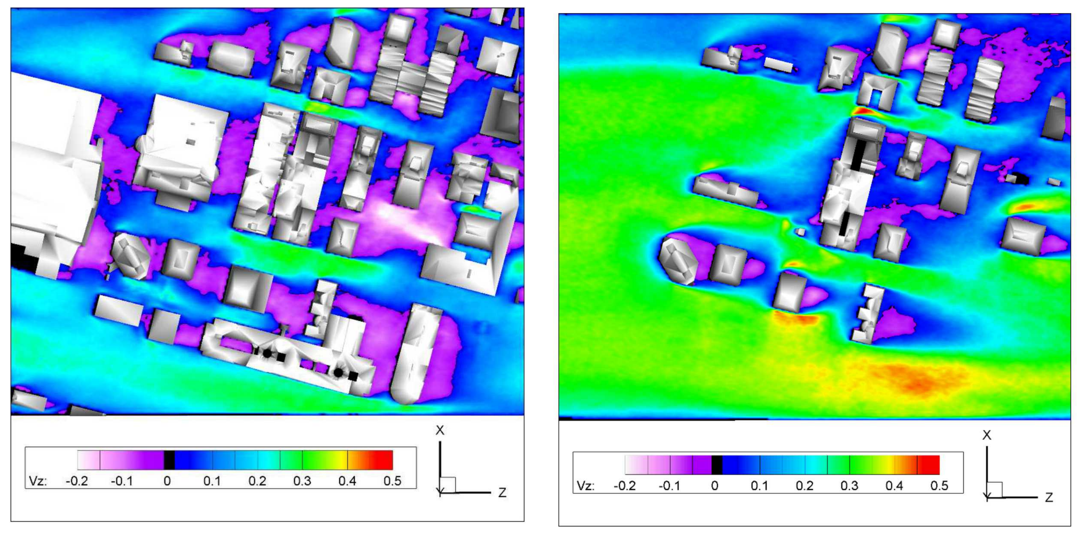
Flow Characteristics	
Working Solution	0.02 M $CuSO_4$
Bulk Flow Rate	410 L/min
Bulk Flow Reynold's Number Based on Hydraulic Diameter (Based on Tallest Building)	36,000 (12,000)
Injector Flow Rate	0.6 L/min
Injector Reynold's Number Based on Hydraulic Diameter	1,280
Standard Density Ratio	1.0

Concentration Results



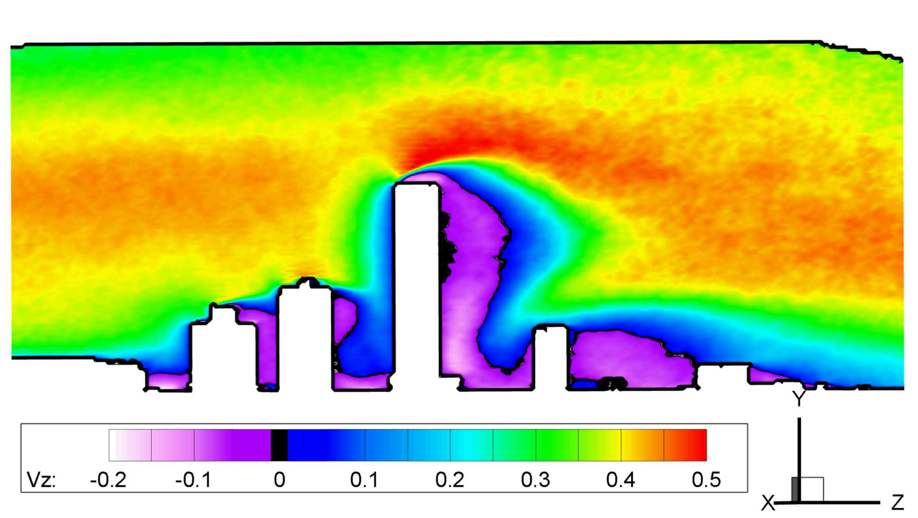
A concentration isosurface at 4%, colored by vertical elevation, demonstrates the ability of MRC to capture data at low concentrations and far from the release area. This image also shows several general trends in dispersion: contaminant shows significant lateral channeling down side streets; there is evidence of limited vertical mixing to about 60 meters, which is more evident behind buildings; and a slight growth in plume height with streamwise distance can be seen until around the last row of buildings.

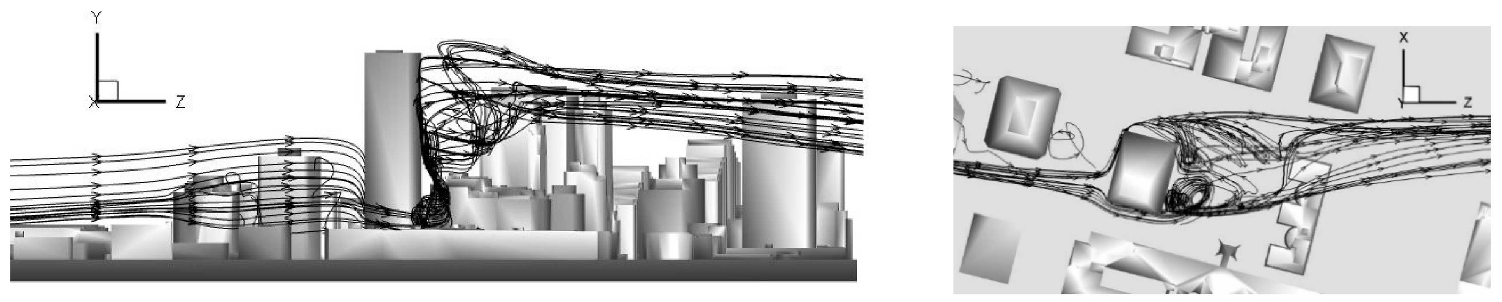
Velocity Results



Contours depicting the streamwise component of velocity measured at 8 meters (left) and 40 meters (right) show separation and reversed flow behind buildings and flow acceleration down street canyons.

Contours depicting the streamwise component of velocity taken in a slice running parallel to Broadway (right) show another view of separation and reverse flow. Streamlines released downstream of the tallest building between ground level and 75 meters (bottom left) show vertical transport followed by release at greater than 75 meters. The same streamlines viewed from above (bottom right) show the presence of counter-rotating vortices.

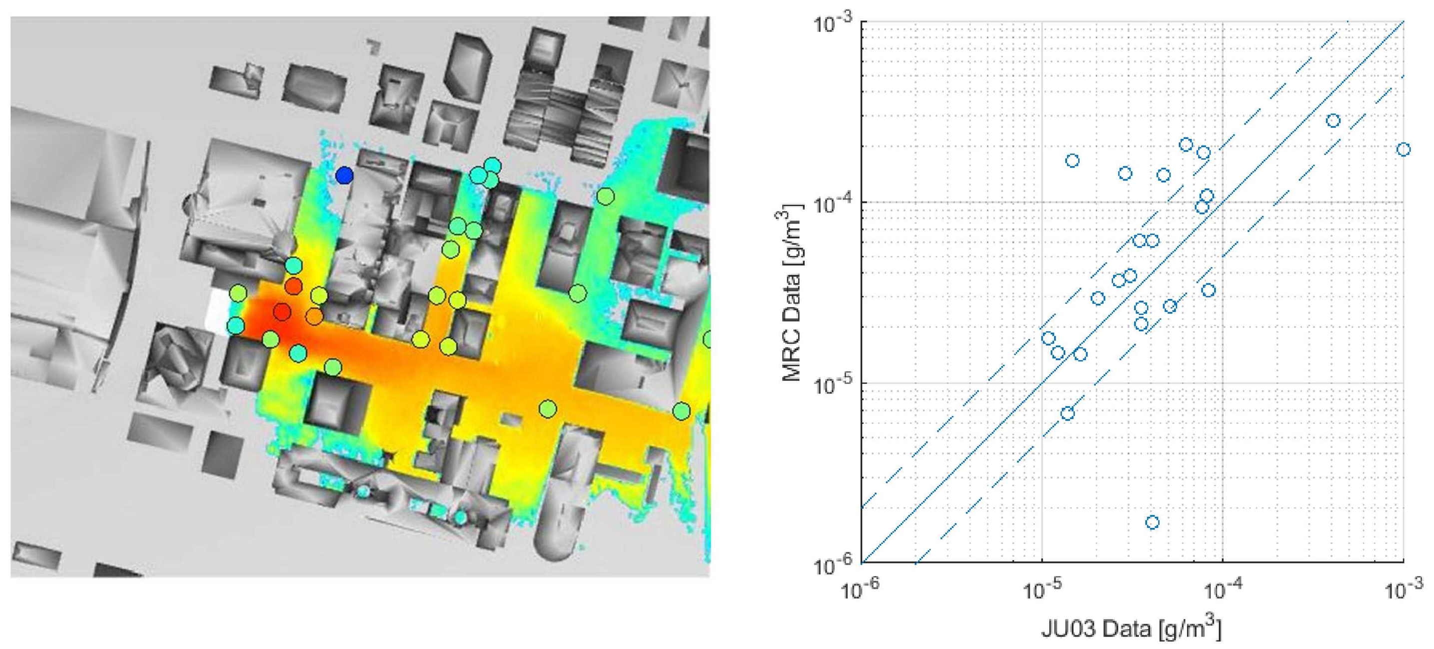




Uncertainty Quantification

Experimental uncertainty can be quantified for each of the nearly 10 million data points for both MRV and MRC. Multiple identical scans allow for the computation of statistical error, while measurement bias is derived from instrumentation and experimental procedure. The average overall uncertainties for velocity and concentration are 5.5% and 4%, respectively.

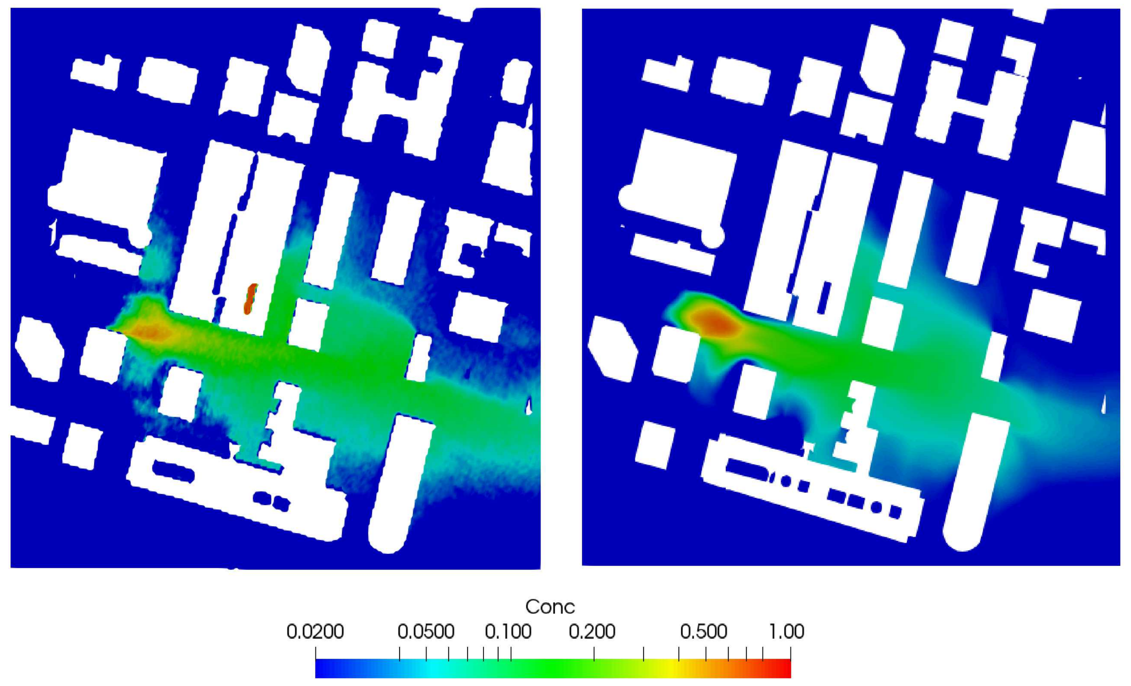
Concentration Comparison with JU03 Field Study



MRC data were compared to twenty-six ground level measurements taken during the JU03 IOP8 release and plotted as both an overlay (left) and a scatterplot (right). Further, Hanna and Chang propose several acceptance criteria for model validation, all of which are computed and met for this experiment, as presented in the table below. These qualitative and quantitative comparisons show good agreement, despite the complexity of the urban environment, nonuniformity in real-world wind patterns, and differences in scalar composition and release mechanism.

Criteria	MRC Value	Acceptance Threshold
Fractional Bias (FB)	0.497	< 0.67
Normalized Mean Square Error (NMSE)	2.17	< 6
Fraction within a Factor of 2 (FAC2)	0.600	> 0.3
Normalized Absolute Difference (NAD)	0.344	< 0.50

Concentration Comparison with SIERRA/Fuego Numerical Model



SIERRA/Fuego is a highly parallelized, low-Mach number CFD solver used by the Department of Energy to model fires, plumes, multiphase and heat transport, and particulate dispersion. Simulations were run on identical geometries to the additively manufactured cityscape and results are compared above. For a more detailed comparison between MR and modeled data—including comparisons of velocity fields, quantitative analysis, and model parameters—please see Dr. Alex Brown's poster "Detailed Advection and Diffusion Validation of CFD with MRC/MRV 3D Data."

Acknowledgements

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