Three-Dimensional Velocity and Concentration Measurements and Simulations of a Scaled Jack Rabbit II Mock Urban Array

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Abstract

Magnetic resonance (MR) techniques provide non-invasive, three-dimensional measurements of velocity and concentration fields. Applying MR techniques to measure flows of contaminants through urban arrays provides a wealth of information that is difficult to obtain with large-scale field tests. In this project, a 1:188 scaled model of the phase 1 Jack Rabbit II field test was replicated and studied using a water tunnel with properties chosen to mimic field conditions. Three-dimensional, time-averaged flow data was measured using magnetic resonance velocimetry (MRV) and magnetic resonance concentration (MRC) techniques. The scaled flow was also modeled with large-eddy simulations (LES) to provide a dataset for comparison with the MR based measurements. Despite a complex, three-dimensional flow field, both velocity and concentration show good agreement between the experimental measurements and simulation data. Measurement uncertainty was estimated to be $\pm 5\%$ of each of the measured velocity components at each location for MRV

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and ±4% of the measured concentration at each location for MRC.

Keywords: Magnetic Resonance Concentration, Large Eddy Simulation, contaminant Dispersion

1. Introduction

Dispersion of contaminant sources in built-up environments is an active area of research for the experimental, simulation, and modeling communities. The inclusion of relatively dense contaminant gases as compared to air, such as the commonly studied toxic industrial chemicals (TICs) ammonia or chlorine in their vapor phases, can further complicate the testing and analysis. The prevalence of these two toxic industrial chemicals is widespread, with a 2011 report indicating chlorine production in the United States alone exceeded 13 million tons [17], and chemical-related accidents rank chlorine second only to carbon monoxide. Precisely because of this threat, which includes risks during manufacturing, usage, and transportation, a series of large-scale experiments were conducted by a group of U.S. Federal agencies at Dugway Proving Grounds, Utah, USA, in years 2015 and 2016, collectively known as the Jack Rabbit II trials.

The Jack Rabbit II trials have been studied and documented in several works [11, 23, 22, 15, 13, 18, 24] among many others, and fully described in the accompanying introductory paper [16]. The field tests continue to be an important dataset for simulation and modeling, and included studies related to corrosion, personal protective equipment, and other impacts to emergency responders. McKenna and co-workers used two separate integral dispersion models in their study [18], and concluded that including rainout effects improved model performance when compared to field test data. Gant and co-workers use similar methods and extended the analysis to include a dense gas dispersion model from the U.S. National Center for Atmospheric Research [11]. Vik and co-workers conducted large eddy simulations to predict dispersion in the near field in and around the urban array [24] and included droplet transport and evaporation within their study for release trial number 5, finding good agreement with field test data.

While the bulk of the works presented to date has emphasized analysis of and comparison to field test data, this work focused on the complex flow in the near field for phase 1 tests with the CONEX container mock urban array. This work removes the dense gas and phase change complexities, enabling

detailed study of a single phase dispersion event. This simpler study was conducted using a scaled version of the field test geometry within a water tunnel that maintains the geometrical complexity of the Jack Rabbit II field tests.

The experiment used Magnetic Resonance (MR) measurements of the three-dimensional velocity field and contaminant. The MR datasets provide non-intrusive, three-dimensional measurements at a high spatial resolution of 0.8 mm (compared to the channel cross-section of 196×110 mm). Along with laboratory control and measurement of inflow conditions for both contaminant injection and freestream atmospheric flow, the measurements provide a dataset for comparison with the field study, reduced-order models, and simulations.

The measured inlet boundary condition and steady flow characteristics of the experimental work provide excellent validation data for simulation efforts. Once validated, model enhancements that incorporate the additional complexity of the field test data should perform more accurately. In addition, the number of measurements within the dataset – with literally millions of measurement locations with three velocity components and concentration – provide an unprecedented opportunity for comparisons. Indeed, existing metrics for comparisons will need to be expanded to leverage the full extent of the available data, with several proposed in this study. We match the geometrical complexity of the Jack Rabit II field tests but not the atmospheric conditions such as the chlorine phase change and interaction with the atmosphere.

A large eddy simulation (LES) was conducted for initial comparisons with the experimental work to demonstrate the MR measurements agree with high-fidelity simulations. The LES simulations were setup to mimic the MR experiment and used the same geometry of the water tunnel, buildings, and roughness area. The fluid density, viscosity, and flow rates were matched. An inflow velocity profile, measured with MR, was used as the upstream boundary condition. The LES includes a number of parameters and in this study we chose to use the default values with the goal of comparing results from the two methods. In this work, *no* effort was made to improve the LES results by adjusting model parameters. Future work will include improving the simulation parameters to best match MR results.

2. Methods

2.1. Jack Rabbit II Trial

The Jack Rabbit II experiment consisted of many trials. Throughout the Jack Rabbit II field study, measurements were taken of the concentration and meteorological data, including wind direction and speed, humidity, and temperature. This work studied a scaled version of trial 5, chosen for its high chlorine mass released and favorable atmospheric conditions during the test. Additionally, trial 5 was determined to have the most quasi-steady release condition, a consistent wind speed and direction, and a relatively long and continuous release of contaminant. Since the MR experimental technique implemented in this study employed constant inflow conditions and a continuous contaminant release, trial 5 was the case most replicable in the laboratory.

2.2. Overview of Scaled Urban Array

The MR experiments and associated LES simulations were conducted with a scaled-down replica of the grid of the CONEX container mock urban array used in the field experiments. The scaled test section is placed within a water tunnel as shown in Figure 1, which contains a 5.08 cm diameter inlet that flows into a diffuser and honeycomb section to slow the flow and improve flow uniformity. The uniform flow passes over a roughness section that creates a boundary layer to mimic the atmospheric boundary layer in the field experiment. The roughness section contains cylinders that are 1.83 mm tall with diameters of 4.8 mm. The cylinders are organized in a grid aligned with the flow channel with 7.87 mm center-to-center spacing. The conditioned flow then passes over the test section, shown in Figure 2, and finally exits through the outlet. The test section is a 1:188 scaled section of the field experiment urban array. All the buildings are 13 mm tall except one that is 39 mm tall. The front half of the array is geometrically similar to the chlorine-based experiments, while the latter half incorporates a few subtle changes designed for comparison with sonic anemometry tests that occurred several months later. This size was chosen to balance the fraction of the scaled urban array that fit within the water tunnel and the size of the urban array buildings. The experimental flow channel components were 3D printed using stereolithography (SLA) additive manufacturing techniques with Accura 60 resin [2]. This material was chosen because 1) it is nearly

transparent, which allows optical viewing of the contaminant, and 2) is non-ferrous, a requirement for all materials used in an MR experiment.

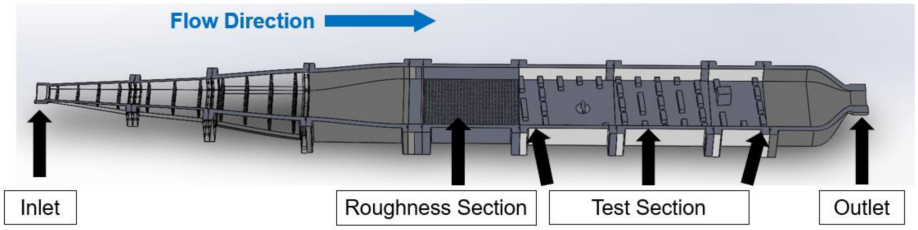
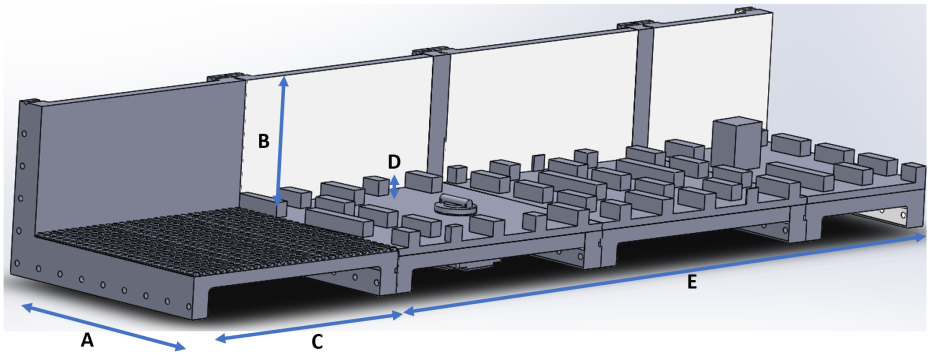


Figure 1: Sketch of water tunnel used for experiments, highlighting key components and flow direction.



Label	Description	Dimension
A	Internal Channel Width	196 mm
B	Internal Channel Height	110 mm
C	Roughness Section Length	237 mm
D	Standard Building Height	13 mm
E	Mock Urban Array Length	609 mm

Figure 2: Cut out of geometry including the roughness section and mock urban array test section used for experiments along with dimensions.

During trial 5 of the Jack Rabbit II experiment, the wind was not directly inline with the CONEX container array. On average the wind was measured to be 4.5 from the array centerline [12]. To account for this fact, the scaled urban array was rotated relative to the water tunnel by 4.5 degrees. This can be seen in Figure 2, as the rows of buildings in the test section are not