



MRV Challenge 3: velocity and passive scalar comparison in a 3D turbulent flow

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Abstract

The third iteration of a magnetic resonance velocimetry (MRV) challenge comparison activity consisting of 3D flow measurements for a turbulent flow in a water channel moving past centrally positioned cubic obstacles is reported. In this challenge iteration, MRV measurements are coupled with either temperature or concentration measurements to extend the diagnostic utility. Five research teams from around the world conducted the measurements on a single shared apparatus. The water channel included partial elements along the channel sidewalls that varied in height and precluded easy optical accessibility. In addition to a turbulent mainstream flow, a secondary flow entered the channel between the second and third cubic elements from a square injector hole at the channel bottom wall. The injector jet interacts with the mainstream flow and mixes turbulently as it advects downstream. For the selected flow regime and water solutions used as working fluids, the mixing of the higher temperature or concentration through the secondary flow with the mainstream flow satisfies the same dynamics so that both temperature and concentration fields behave as passive scalars and can be directly compared. The measurements are explained in detail by each participating team, and the results are interpolated onto a common grid and compared using line profiles, contour plots, and isosurfaces.

1 Introduction

Magnetic resonance velocimetry (MRV) uses nuclear magnetic resonance techniques to measure fluid motion (Elkins and Alley 2007). Advantages of the methodology include no requirements for probes or optical accessibility, allowing for arbitrarily complex geometries to be studied. Although limitations on flow velocities exist, laminar and fully turbulent flows have been successfully studied and compared with more traditional fluid diagnostics, increasing confidence in MRV as an important capability in fluid mechanics studies. Khodarahmi et al. (Khodarahmi et al. 2014) experimentally validated MRV measurements of laminar flow through a stenotic phantom of the human iliac artery. Lee et al. (Lee et al. 2017) validated MRV measurements of turbulent flow through a circular pipe using empirical data. The measurements can be fully 3D, including three component velocity fields, as well as turbulent kinetic energy and, in specific applications, the Reynolds stress tensor (Dong, et al. 2024; Dong, et al. 2023; John et al. 2025; Romig et al. 2025). Gas phase MRV studies have been successfully completed (Elgersma et al. 2023; Sadeghi et al. 2020; Sankey et al. 2009),

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although flows using water are far more common. In addition to MRV, related techniques with applications in engineering flows have been added to expand the capabilities of the human clinical systems often used in these measurement campaigns to obtain other quantities of interest. For example, Borup et al. used a magnetic resonance particle concentration technique to study particle concentrations in a turbulent flow (Borup et al. 2018). Several works have explored magnetic resonance concentration (MRC) techniques for scalar concentration measurements from applications as diverse as atmospheric flows to gas turbine engine components (Banko et al. 2020; Benson, et al. 2013; Benson, et al. 2020a; Benson, et al. 2010; Ling, et al. 2013; Owkes et al. 2020). Approaches for temperature measurements using magnetic resonance thermometry (MRT) have also been developed, with several recent works (Bruschewski et al. 2022; Winter et al. 2016) further expanding the overall utility of magnetic resonance imaging (MRI) systems in engineering contexts.

Although the fluid measurements described here are valuable in many applications, the MRI data offer broader use than merely detailing 3D flow behaviors. As computational capabilities continue to expand and calculation times reduce, large experimental datasets have increased utility in validation, verification, and uncertainty quantification (VVUQ). Recent work by Nguyen et al. (Nguyen et al. 2025) conducts detailed comparisons using both laser and MRI based measurements in conjunction with computational fluid dynamics simulations with applicability to VVUQ activity. Improvements in VVUQ to include three-dimensional velocity field validation for simulations are also in development as described in related works (Benson et al. 2025; Bruschewski et al. 2021), with the latter report specific to nuclear fuel assemblies and components.

The published growth in MRV, MRC, and MRT utilization by research groups has lagged that of laser diagnostics in engineering applications, likely due in part to a perceived complexity for conducting measurements and related analyses. As an example, Tavoularis and Nedić (Tavoularis and Nedić 2024) did not mention MRV in their recent summary of fluids measurement techniques. To combat this perception, the MRV challenge was initiated in 2019 to showcase velocity field measurements of an experiment that was shared around the world by four research groups and measured using different procedures and systems (Benson et al. 2020b). Extensive details on the measurement settings are included to aid future researchers who may have an interest in replicating the test for benchmarking purposes. The flow in this first comparison was fully turbulent and negotiated a tight U-bend turn that created flow separation and ensured a highly 3D flow field. In a subsequent challenge (MRV Challenge 2), five teams from around the world measured a turbulent flow in a square water channel with cubical obstacles

along the center plane (Benson et al. 2023). Additionally, an injected flow oriented perpendicular to the flow direction and operating on a duty cycle was included. The flow across several phases of the periodic cycle of the injector was measured and compared, highlighting the gated scan capability of the systems in a measurement campaign. In the present work, the newest version of the challenge incorporates both MRV and either MRC or MRT by many of the same groups involved in the first two iterations. As with the previous MRV challenges, MRV Challenge 3 has the specific aims of increasing awareness of the capabilities of additional types of MRI measurements beyond MRV, documenting measurement and data processing approaches, highlighting best practices for 3D data comparisons, providing insights into measurement uncertainties, and pushing the state of the art for this fluid measurement approach for the research and engineering community in a well-documented approach.

This paper targets scientists and engineers in fluid mechanics who may have an interest in using MRI-based techniques for research. The participating institutions include a combined team from Stanford University and the United States Military Academy (USMA), the University of Rostock (UR), Hanyang University (HYU), the University of Illinois Urbana-Champaign (UIUC), and Oak Ridge National Laboratory (ORNL).

2 Experimental methodology

2.1 Apparatus and Flow Circuit

The test article geometry is the same as the one used in MRV Challenge 2 (Benson et al. 2023). Figure 1a shows an engineering drawing of the apparatus at a mid-plane,

which consisted of an upstream flow conditioning section, a test section, and an injector. In the direction of the main flow (left to right as pictured), the flow (1) enters through a honeycomb to reduce secondary flows, (2) expands across several grids with rectangular bars and approximately 40% open areas to increase flow uniformity, (3) enters a second honeycomb grid, (4) passes through a settling section and accelerates in a 4:1 area ratio contraction to ensure uniform flow, (5) passes through the test section, and (6) leaves through the outlet. The extensive flow conditioning sections are required to make the flow entering the test section similar for each team, regardless of the different supply flow networks used across the teams. The main flow direction is defined along the x -axis, with y coordinates representing the height relative to the channel floor, and z is used as the spanwise coordinate. The coordinate origin is the center of the square injector opening at the floor. Figure 1b depicts a cross-sectional view of the test section for enhanced visibility of the partial side elements and the flow injector, and

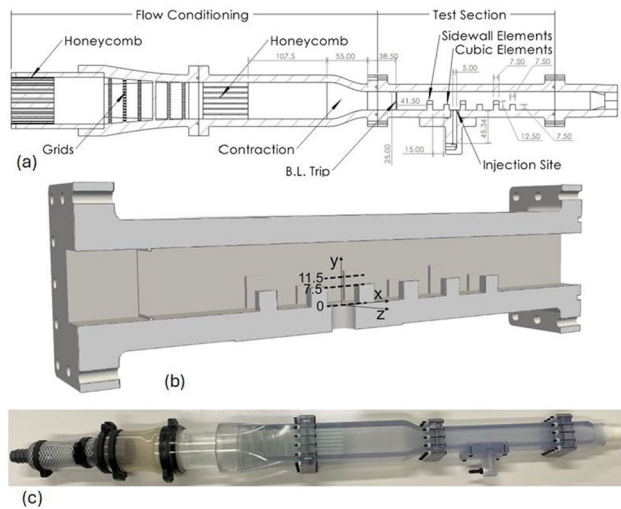


Fig. 1 (a) Flow diagram (dimensions in mm) and (b) isometric view of test section with three partial datum lines (referred to as Lines 1–3 from the surface to 1.5 mm) for comparison heights. Assembled photo in (c)

the illustration includes three datum lines at different elevations used in comparisons. Line 1 is the intersection that the center plane ($z=0$) makes with the floor of the test section. The photograph in Figure 1c depicts the non-metallic assembled geometry with tubing connections at the inlet and outlet shared among teams. Note that MRV measurements are determined by averaging the signal within small voxels, interpolated in this case to an isotropic 0.5 mm for all groups, so some spatial averaging will always be necessary for the channel floor ($y=0$) velocities. Line 2 lies at $z=0$ as well and is located one building height (7.5 mm) above Line 1. Line 3 is 11.5 mm above the floor at the $z=0$ plane.

The test section has a square cross-sectional height of $H=25$ mm. A 1 mm boundary layer trip is present on all four walls of the test section near the entrance, with the front edge positioned 37.5 mm downstream of the end of the contraction. This is to generate a new turbulent boundary layer with known developmental length before flow passes the cubic elements. Two types of features are included in the test section: sidewall elements and spanwise central cubic elements. The motivation for the design was to generate a flow with regular roughness features or even an array of small uniform buildings at a small geometric scale. The presence of the alternating height sidewall elements obscures regions from easy optical accessibility and enhances 3D flow features, highlighting a comparative strength of the MRI diagnostics employed.

The working fluid for all teams was water with a dilute solution of CuSO_4 . Concentrations varied for each team. For each team, whether MRV, MRC, or MRT was performed, the main flowrate was nominally 22.2 L/min, which made the bulk velocity of flow at the test section inlet 0.6 m/s.

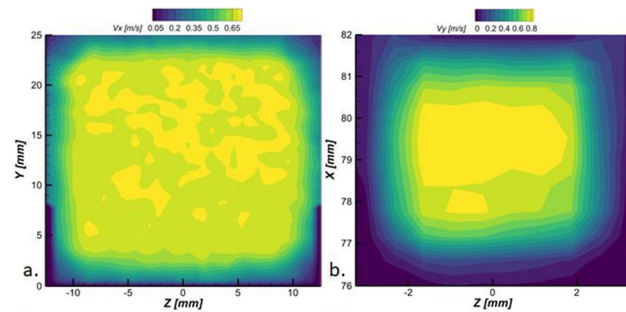


Fig. 2 Contours of inlet velocity from ORNL data: a) Streamwise velocity midpoint between turbulence trip and first cube, b) Vertical velocity from square injector at surface exit

Accordingly, the main flow Reynolds number is $Re=15,000$ based on hydraulic diameter, $D_H=25$ mm, the bulk velocity, and the kinematic viscosity of water at 21°C. The main flowrate ensures that the boundary layer after the trip is fully turbulent. The injection flowrate was steady and set at 1 L/min. Figure 2a depicts the inlet velocity at a position at $x=20.75$ mm, which is midway between the turbulent trip and the first cube as indicated in Fig. 1a. The turbulent boundary layer on all sides is similar with a rapid rise to the mean velocity, consistent across the height and breadth of the contours. The bulk velocity through the injector was 0.67 m/s, which is depicted in Fig. 2b. From the bulk velocity of the injector and main flow, the blowing ratio was calculated to be 1.12, and the injector Reynolds number is 3,400, based on injector diameter and bulk velocity.

Figure 3 depicts a generic layout for the setup of both MRV and MRC/MRT testing common among research groups. Notably, only the experimental apparatus in Fig. 1 was common among groups. The tubing, pumps, flow metering, and reservoirs were individually selected and differed across the various research teams.

2.2 Scalar analogy and normalization

The scalar analogy—which essentially exploits the similarity between heat and mass transfer in systems meeting specific criteria—is employed and is detailed in various works (Spalding 1960; Coletti et al. 2013). The key elements required include decoupling heat and mass fluxes, matching the Lewis number, maintaining constant fluid properties, and using nonreacting elements, all of which are met herein. The result of using the scalar analogy is that normalized temperature and concentration fields are expected to match. This holds true because heat and mass transfer share the same non-dimensional convection-diffusion equations in which diffusion is driven by gradients in the scalar field. Normalized scalar fields are defined by scaling the temperature or concentration difference with respect to the test section inlet,

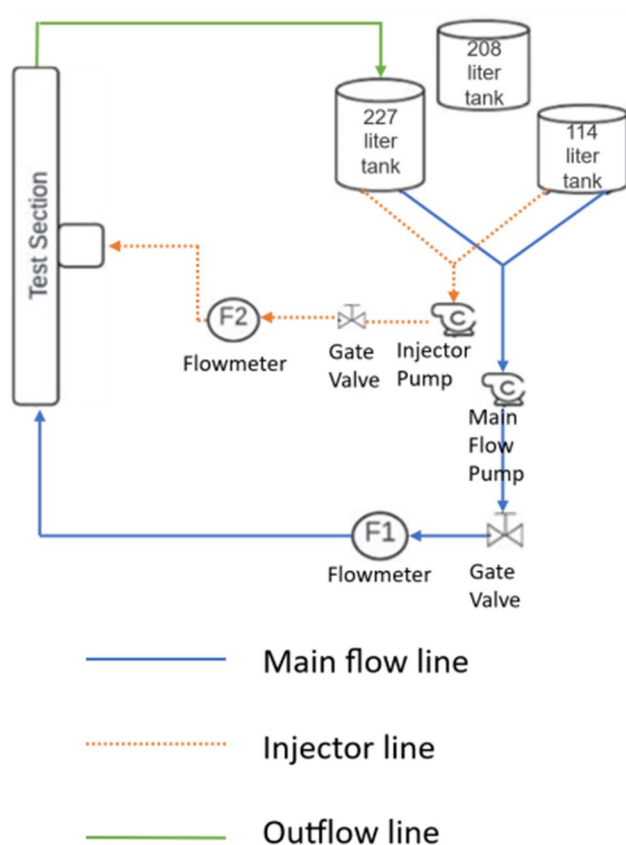


Fig. 3 Generic test layout diagram

by the difference between the values at the injector plenum and the inlet reference. This normalization is consistent with that of the governing equations and ensures normalized scalar fields are between 0 and 1.

2.3 MRI-based measurement techniques

Each team measured the mean velocity field using MRV and the passive scalar either using MRC or MRT. All three methods will be described briefly here, with additional details specific to each team's implementation provided in the supplementary materials appendix. MRI measurements produce a complex signal, where, depending on the sequence used, both the magnitude and the phase can contain information about the flow parameters of interest. MRV, MRC, and MRT have all been extensively validated through comparisons with other experimental methods. Most recently, MRV and MRC verification and validation using two laser diagnostics and two computational fluid dynamics simulations using the current experimental geometry were conducted by Nguyen et al. (Nguyen et al. 2025).

All teams used the phase contrast method for MRV. This technique relies on the fundamental principle that hydrogen protons moving in the presence of magnetic field gradients

acquire a phase shift proportional to their velocity. By applying a bipolar magnetic field gradient, stationary fluid accumulates a net zero phase, while moving fluid acquires a measurable phase shift. The velocity is then calculated from the phase difference between two measurements with different gradient moments. The VENC (velocity encoding) represents the velocity associated with a phase shift of π . To correct for background effects in the phase (such as those induced by eddy currents and magnetic field inhomogeneities), stationary scans, called flow off scans, with the same sequence are used and subtracted from the flow-on scans. A more comprehensive description of the fundamental principles of MRV is provided by Elkins and Alley (Elkins and Alley 2007).

MRC exploits the fact that the signal magnitude linearly depends on the concentration of CuSO_4 in a certain concentration range (Benson et al. 2010). Given that the participating teams utilized different MRI scanner hardware and pulse sequence settings, the exact upper limit of this linear range varied across institutions. Consequently, each team conducted independent calibration experiments to determine their specific optimal reference concentration—ranging from 0.01 M to 0.0175 M across the groups—to ensure a strict linear relationship between the signal magnitude and CuSO_4 concentration. As described in Sect. 2.2, although the participating teams utilized different absolute molarities, all measured scalar fields were subsequently normalized to enable a direct, cross-platform comparison. Three configurations of flow were commonly used during MRC tests: *reference*, a closed-loop configuration with CuSO_4 , circulated from one reservoir; *background*, a closed-loop configuration with plain water, circulated from a second reservoir; and *standard*, a mixed configuration in which CuSO_4 was fed to the injector line, plain water to the main line, and the combined output dispensed into some form of waste reservoir. During standard runs, plain water was usually added to the appropriate reservoir, whereas waste solution was removed to minimize any contamination. Some teams included additional standard-high and super-high tests, which are essentially higher molarity CuSO_4 solutions than those used in standard cases to increase the signal-to-noise ratio, particularly at low concentration levels. The portions of these datasets where the mixed concentrations are within a linear range with signal magnitude are used to increase the resolution of the concentration above the noise floor in a systematic data stitching/blending routine, as described in Banko et al. (Banko et al. 2020).

The MRT measurements employed the proton resonance frequency (PRF) shift method, which relies on the principle that the magnetic resonance frequency of water depends linearly on the temperature in a certain temperature range (Buchenberg et al. 2016). To map the temperature field, two sets of scans are required: a heated scan (where only

the injector line is heated) and a nonheated baseline scan (where neither the main nor the injector lines are heated). This temperature-induced frequency shift results in a measurable phase shift in the MRI signal, enabling the local temperature difference to be determined from the phase difference between the heated and nonheated scans. The two teams performing MRT utilized a baseline fluid temperature of 20.5 °C and heated the injected fluid to 36 °C (UR team) and 33.5 °C (HYU team). These temperatures were selected to ensure a sufficiently large temperature difference to generate a reliably measurable phase shift with adequate signal-to-noise ratio, while avoiding excessively high temperatures that could lead to thermal deformation of the apparatus. To further mitigate thermal accumulation in the flow loop and minimize magnetic field drift, MRT scans were conducted in an interleaved manner, alternating between heated and nonheated conditions. Additional time between configuration changes was required in these tests to ensure the system reached a quasi-steady-state condition prior to initiating measurements.

It should be noted that MRV, MRC, and MRT scans typically require several minutes for data acquisition. Consequently, the resulting velocity and scalar fields represent time-averaged quantities over the scan duration rather than instantaneous flow structures.

2.4 Spatial resolution analysis

In the current study, the MRV portion of the experimental campaign reports 3D3C velocity fields, but not other turbulent characteristics such as the turbulent kinetic energy and dissipation rate. Therefore, numerical results of the same experimental configuration from a previous study by Nguyen et al. (Nguyen et al. 2025) obtained from RANS k-epsilon realizable simulations are used to compute key characteristic length scales of the flow such as boundary layer thickness δ , integral length scale L_h , Kolmogorov length scale η , and the Taylor length scale λ . These length scales are computed for a point P located 2h upstream of the first cube and along the channel centerline at mid-channel height, i.e., $P(x = 26.5, y = 12.5, z = 0)$ mm, also shown in Fig. 4.

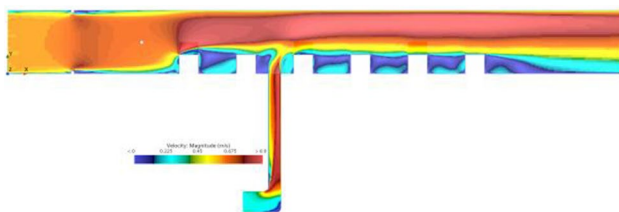


Fig. 4 RANS simulation result depicting velocity magnitude from the data of Nguyen et al. (Nguyen et al. 2025). Point P is identified with a white dot

Boundary layer thickness = 8.75(mm)

Integral length scale : $L_h = C_\mu^{(3/4)} k^{(3/2)} / \epsilon = 14.5(\text{mm})$

Kolmogorov length scale : $\eta = (\nu^3 / \epsilon)^{(1/4)} = 0.12(\text{mm})$

Taylor length scale : $\lambda = \sqrt{10\nu \frac{k}{\epsilon}} = 1.88(\text{mm})$

where C_μ is the model coefficient of k-epsilon realizable turbulent model ($C_\mu = 0.09$), k is the turbulent kinetic energy, ϵ is the turbulent dissipation rate, and ν is the fluid kinematic viscosity. A summary of the length scales normalized by the cube height is in Table 1.

In the study by Hearst et al. (Hearst et al. 2016) of a turbulent flow around a wall-mounted cube, the authors reported their incoming flow conditions with the characteristic length scales for $Re_h = 15,900$, such as the boundary layer thickness $\delta/h = 2.13$ and the integral length scale.

$L_h/h = 0.34$. It is, however, noted that in that study (Hearst et al. 2016), the cube was placed on an artificial floor having a boundary layer trip positioned approximately 100 cube heights upstream of it. In the current MRI experiments, the axial distance between the boundary layer trip and the first cube's center is 5.5h. This could explain the smaller value of boundary layer thickness and greater value of integral length scale in this study compared to those reported in Hearst et al. (2016). Given the spatial resolution of 0.5 mm presented in this study, it is argued that the MRV/MRC/MRT measurements provide time-averaged spatially resolved large- and small-scale turbulent flow structures for the studied configuration.

3 Measurement details

All teams measured mean three-dimensional velocity and scalar fields on the same flow apparatus while independently choosing the measurement approach. This section succinctly describes the experimental methods used by the different teams including the flow loop setup, MR sequences, and data post-processing, as well as each team's reported measurement uncertainty. For a detailed description, please refer to the Supplementary Material. Table 2 provides a summary of the most important measurement and experimental details across all teams. The teams used different scanners: Philips (ORNL, HYU), Siemens (UR, UIUC), and GE (USMA). Despite the

Table 1 Summary of key characteristic length scales

Cube height h	Re_h	δ/h	L_h/h	η/h	λ/h
7.5 (mm)	4700	1.17	1.93	0.016	0.25

Table 2 MRV experimental details summary

	USMA	UR	HYU	UIUC	ORNL
Scanner type	3.0 T GE Healthcare Discovery MR750	3.0 T Siemens Magnetom	3.0 T Philips Achieva	3.0 T Siemens Magnetom Prisma	3.0 T Philips MR 7700 (MRV), Philips Ingenia 3.0 T Elition X (MRC)
Coil type	Single-channel head coil	2-channel body matrix, 2 spine coils	16-channel torso coil	18 channel body coil and 4-channel flex coil	16-channel head coil
Velocity encoding (VENC) for x, y, z (cm/s)	110, 120, 84	81, 81, 81	100, 100, 100	130, 125, 80	140, 120, 84
Voxel resolution of x, y, z (mm)	0.8, 0.7, 0.7	0.5, 0.5, 0.5 (MRV), 1, 1, 1 (MRT)	0.5, 0.5, 0.5	0.57, 0.57, 0.6	0.7, 0.7, 0.7
Raw image matrix size	320 × 124 × 60	512 × 96 × 224 (MRV) 256 × 48 × 112 (MRC, MRT)	512 × 192 × 140	446 × 154 × 52	368 × 132 × 60
Echo time (TE), repetition time (TR) (ms)	2.2, 5.9 (MRV) 1.8, 5.4 (MRC)	2.9, 7 (MRV) 1.83, 8 (MRC) 4, 7 (MRT)	2.9, 5.3 (MRV) 3.5, 6.8 (MRT)	3.71, 5.84 (MRV) 1.57, 9.5 (MRC)	3.0, 6.7 (MRV) 2.6, 11 (MRC)
Single scan time (min:s)	2:02 (MRV) 1:40 (MRC)	20:09 (MRV) 11:28 (MRC) 10:02 (MRT)	10:00 (MRV) 8:00 (MRT)	1:59 (MRV) 1:16 (MRC)	2:45 (MRV) 1:13 (MRC)
Number of flow-on/off scans	9/10	10/2	2/1	10/4	15/6
Number of reference/background/standard/standard-high/super-high scans	20/20/20/20/20	28/28/28/0/0	N/A	20/20/20/20/20	30/23/23/22/23
Number of heated / nonheated scans (cycles · averages per scan)	N/A	7 · 4 / 7 · 4	12 · 7 / 12 · 7	N/A	N/A
Mainstream pump power (W), type	370, magnetic drive	600, centrifugal	900, centrifugal	373, centrifugal	373, centrifugal
Injector pump power (W), type	116, magnetic drive	200, servomotor gear pump	50, gear pump	93.2, centrifugal pump	37, magnetic drive
Flowmeter type (main flow/injector flow)	Ultrasonic/ultrasonic	Magnetic inductive/magnetic inductive	Electromagnetic/electromagnetic	Paddle/ultrasonic	Ultrasonic/ultrasonic
Concentration (mol/L)	0.06 (MRV) 0.015, 0.06, 0.18 (MRC)	0.006 (MRV, MRT) 0.01 (MRC)	0.02 (MRV, MRT)	0.06 (MRV) 0.014, 0.06, 0.112 (MRC)	0.06 (MRV) 0.0175, 0.07, 0.175 (MRC)
Temperature (°C)	20.5 (MRV, MRC)	20.5 (MRV, MRC) 20.5, 36 (MRT)	20.5 (MRV) 20.5, 33.5 (MRT)	20.5 (MRV, MRC)	21 (MRV, MRC)
Flip angle	15 (MRV) 55 (MRC)	15 (MRV, MRT) 35 (MRC)	15 (MRV, MRT)	25 (MRV) 45 (MRC)	15 (MRV) 55 (MRC)

variation in proprietary nomenclature across these vendors, the fundamental pulse sequence framework remains consistent across all datasets.

3.1 Boundary conditions

Each research team adjusted the flow rates using valves or frequency-controlled pumps and monitored them using flow meters. The water temperature was measured and

adjusted using coolers and, in the case of MRT, heaters. All teams used a closed-loop system for the MRV measurements. For MRC, most teams (ORNL, USMA, UIUC) used open-loop systems to avoid the contamination of the main line fluid. UR had a closed-loop system and changed the water at a contamination level of about 7%. For MRT, both teams (HYU, UR) changed the supply reservoirs for the injector line between heated and nonheated scans.

3.2 Measurement specifications and reconstruction

3.2.1 MRV

All teams used 3D gradient recalled echo (GRE) phase-contrast (PC) sequences, which employ bipolar gradients to achieve velocity sensitivity. Usually, a four-point encoding scheme is used to encode the three components of the velocity vector (UR, ORNL, USMA, UIUC). HYU utilized a six-point encoding scheme that results in an overdetermined system of linear equations and aims to reduce noise and systematic phase errors. Generally, small TEs reduce measurement errors, so partial readouts were used by some teams to shorten the TE (UR, ORNL), leading to a partial k-space. UR conducted additional scans with inverted readout gradients to capture both sides of the echo, and the partial k-spaces were combined according to Romig et al. (2025) (Romig et al. 2025). Other teams used cutting corner techniques (USMA), elliptical k-space filters (ORNL), or GRAPPA-acceleration in phase direction (UIUC) to reduce scan time.

During postprocessing, the teams went two different ways: Either they first averaged the datasets before subtracting the averaged flow off data from the averaged flow on data (UR, HYU, UIUC, ORNL), or they first subtracted every flow off from the corresponding flow on dataset and then averaged these differences (USMA). Although only needed for the latter procedure, most teams scanned interleaved flow on and off (ORNL, USMA, UIUC). This allows assessing potential drifts due to coil heating and correcting for them if needed.

Some teams did some additional steps during reconstruction (Romig et al. 2025). HYU additionally denoised its data using the split-and-overlap singular value decomposition method (Kang et al. 2024) with a subdomain size of 5 and a 75% overlap ratio. UIUC applied in-house developed corrections to account for geometric distortion (Jovicich et al. 2006) and phase distortion (Markl et al. 2003) caused by magnetic field nonlinearities.

3.2.2 MRC

The sequences for MRC were 3D GRE sequences without velocity sensitivity (ORNL, USMA, UIUC) or were specifically velocity compensated (UR). Again, some teams used partial readouts for shorter TE (UR, ORNL, USMA). UR measured with a second inverted readout and combined the partial k-spaces (Romig et al. 2025), while USMA used the homodyne reconstruction to recover the missing k-space points.

All teams conducted calibration scans to find the reference concentration of CuSO_4 , ensuring a linear relationship between the signal magnitude and the CuSO_4 concentration.

As this range depends on the specific sequence parameters, particularly the flip angle and TR, the teams chose different reference concentrations.

All teams except UR did standard-high and ultra-high scans with higher CuSO_4 concentrations, resulting in a higher measurement sensitivity to lower concentrations to reduce the noise level in regions of low concentration. The data processing was done according to Banko et al. (2020): the background data were averaged and subtracted from both the averaged reference and the standard data. Then, the standard data were divided by the reference data. UR also applied correction factors for contamination of the main flow as the only team that used a closed-loop flow setup. The other teams (ORNL, USMA, UIUC) with open-loop setups also acquired the standard-high and ultra-high datasets and did the stitching of the different datasets according to Banko et al. (2020).

3.2.3 MRT

MRT experiments were conducted by UR and HYU. 3D GRE sequences were used, but without velocity sensitivity. UR used partial readouts and combined the k-spaces (Romig et al. 2025). Both teams scanned heated and non-heated scans in an interleaved manner. After each switch between tanks for heated and nonheated measurements, the UR team started measurements only after the fiber optic sensor, shortly upstream of the measurement section in the jet line, confirmed stable jet flow temperatures. UR did the reconstruction according to Bruschewski et al. (2022), where the phase drift was corrected by subtracting the mean phase in an upstream region unaffected by heating for each scan pair separately. Unlike UR, where the temperature was calculated for each scan pair separately, and those temperature maps were then averaged, HYU first averaged all heated scans and then subtracted the phase of the average of all nonheated scans. HYU denoised their temperature data in the same way as the velocity data (Kang et al. 2024).

3.3 Measurement Uncertainty

One way to estimate the measurement uncertainty is described by Bruschewski et al. (2016) and called the difference approach. If the same parameter is measured multiple times using MRI methods, one measurement can be subtracted from another on a voxel-by-voxel basis. As both measurements are conducted in the same flow, only noise remains. This noise can be estimated by the standard deviation of the 3D voxel-by-voxel difference data. This method can be used for MRV, MRC, and MRT, and results in a volume-averaged value for the uncertainty in the region of interest.

Another way is to compute maps of velocity measurement uncertainty voxelwise as the standard deviation across independent background-subtracted scans and use Student's *t* 95% confidence intervals. This can also be applied to MRC, where either only the standard, standard-high, and ultra-high scans are considered, or also the background and reference scans are used, and uncertainty is propagated through the concentration calculation.

3.3.1 MRV

UR and HYU used the difference method and found that their velocity uncertainty was below 3% of the VENC. ORNL, USMA, and UIUC also found that their velocity uncertainty was below 3% of the VENC using the *t*-Student method.

3.3.2 MRC

With the difference method, UR calculated an uncertainty of 0.5% for the MRC data. All other teams used the Student-*t* method and calculated uncertainties of 4.1% or lower across the entire FOV (ORNL), of 3.5% as a representative average uncertainty within the plume (USMA), and below 3.5% downstream within the plume, but up to 10% near the injector (UIUC).

3.3.3 MRT

Both teams (UR, HYU) used the difference method to calculate the uncertainty of the normalized temperature difference. The UR data has an uncertainty of 3.3%, and the HYU data has an uncertainty of 3.1%.

3.3.4 Additional sources of measurement uncertainty

The uncertainties reported above are based on confidence intervals derived from statistical comparisons of repeated scans. Additional uncertainties and biases may also be present in phase-contrast (MRV, MRT) and magnitude-based (MRC) imaging. Prior studies have quantified such effects on individual systems by varying either flow conditions or imaging parameters. That type of parameter study is beyond the scope of the present work, which instead emphasizes inter-system comparison. Nevertheless, key parameters such as voxel size, TR, TE, and flip angle vary by roughly 10–100% across the datasets in Table 2. The agreement between datasets described later suggests that the statistical uncertainty captures most of the observed inter-team differences for the present flow conditions and scan settings. We therefore limit the discussion below to a qualitative overview of additional non-statistical sources of measurement uncertainty.

In phase-contrast techniques, additional uncertainty and bias can arise from systematic non-zero phase offsets that appear as velocity bias in MRV or temperature bias in MRT (Elkins and Alley 2007; Buchenberg et al. 2016; Benson et al. 2019; Elkins et al. 2004). Examples include eddy currents, concomitant gradient fields, gradient nonlinearities, and main-field drift or inhomogeneity. Eddy-current and field-drift effects were mitigated through reference-scan subtraction, such as the flow-off scans used in MRV, and in some cases by the sequence design itself, such as multi-point encoding. Gradient nonlinearity and main-field inhomogeneity can also distort the reconstructed geometry and are more difficult to correct because they require either measurement or modeling of the true spatial field variations (Lorenz et al. 2014). In general, these effects depend on the magnitude of the field non-idealities, which in turn depends on factors such as main-field strength, gradient strength, and gradient waveform design; these are also related to specified or derived imaging parameters such as VENC and TE.

Flow-induced artifacts may further bias MRV because phase-contrast encoding assumes constant velocity during the encoding interval and effectively reports a voxel-averaged velocity (Elkins and Alley 2007). Regions of strong acceleration can therefore generate higher-order phase errors, leading to both velocity bias and apparent geometric displacement (Frayne and Rutt 1995). The magnitude of this effect depends on the bipolar gradient timing and waveform and is influenced by sequence parameters such as TE and the encoding design. In addition, unresolved spatial velocity gradients within a voxel can bias the measured mean velocity, while turbulent or stochastic subvoxel velocity fluctuations can cause intravoxel dephasing and signal loss, increasing uncertainty (Rothenberger et al. 2022). These effects are generally reduced by finer spatial resolution and by shorter TE.

The uncertainty structure for concentration imaging differs because concentration is inferred from signal magnitude rather than phase. In general, image magnitude is a nonlinear function of concentration, with the low-concentration linear range depending on the concentration-dependent relaxation rates T_1 and T_2^* as well as on TR, TE, and flip angle (Banko et al. 2020; Benson et al. 2010; Brown et al. 2014). Each team designed its experiment so that the analyzed data remained within this approximately linear regime. Under that assumption, background subtraction and reference image normalization provide a simple post-processing approach without requiring voxelwise calibration. This also helps remove spatially varying intensity bias caused by spatial field inhomogeneity or deviations from the prescribed flip angle. Remaining sources of uncertainty include susceptibility-related signal loss in regions of high concentration (Schenck 1996), as well as measurement noise and reconstruction artifacts in *k*-space (i.e., for partial *k*-space

acquisitions) (Banko et al. 2020; Noll et al. 1991). The latter effects non-locally disperse signal across the image and may be reduced through complex averaging of k-space data across multiple scans. Additionally, the sequences used here are referred to as fast-imaging in the steady-state (Brown et al. 2014), and therefore the signal magnitude is inaccurate prior to achieving steady state as the spins enter the excited volume. To avoid this bias, the region of interest was placed near the center of the field of view.

Finally, MRT relies on reference hot and cold scans to infer the temperature-dependent phase shift (Buchenberg et al. 2016; Benson et al. 2019; Brown et al. 2014; Rieke and Butts Pauly 2008). Geometric misregistration between these scan types can occur because of thermal expansion of the apparatus, leading to spurious phase differences and therefore biased temperature estimates. This is particularly important when the temperature calculation is based on voxelwise subtraction, since the hot and cold scans may no longer correspond to the same material location. The magnitude of this bias increases with thermal expansion, temperature difference, and geometric dimensions relative to voxel size. Some of this effect can be reduced in post-processing by registering the scan geometries before voxelwise phase subtraction. In addition, MRT is sensitive to other nonthermal phase contributions such as main-field drift.

4 Results

The dataset from each team was linearly interpolated onto an isotropic Cartesian grid of 0.5 mm resolution. This common grid is less than or equal to the resolution of the dataset of each team. Unlike MRV Challenge 2 (Benson et al. 2023), each team used their own injection pump. This section is divided into two parts. The first compares data from various regions of the flow obtained by each team; the second focuses on flow structures that give insight into transport phenomena.

4.1 Velocity and concentration data comparisons

Figure 5 shows the wall-normal velocity component (V_y) of the flow across the injector region at the three datum lines shown in Fig. 1. This region was selected for comparison because the vertical velocity suggests the penetration extent of the injector as it interacts with the crossflow. Data are displayed centered on the injection site and include 8 mm in both the upstream and downstream directions. The group average shown includes a 3% measurement uncertainty shading which was the maximum for the teams, calculated from the average VENC setting used by all teams.

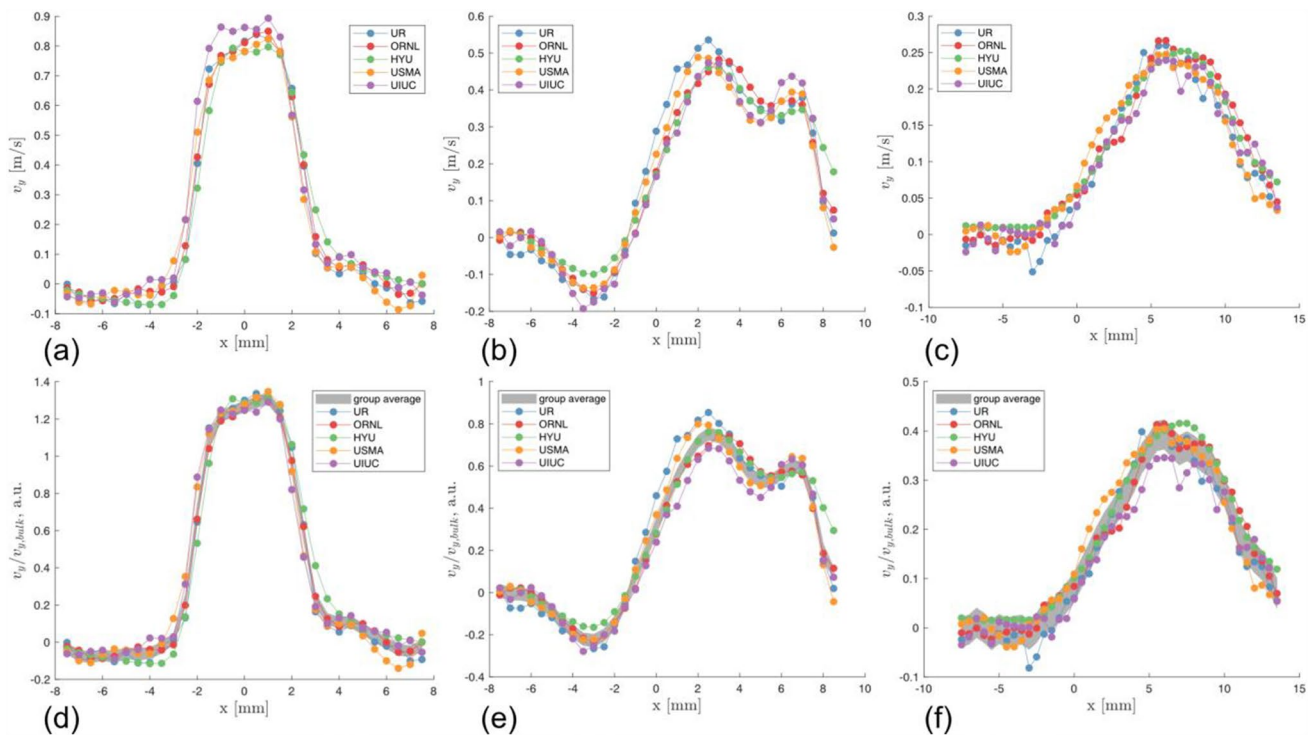


Fig. 5 (a–c) Vertical velocity profile comparisons, with (d–f) normalized versions with group-averaged uncertainty of 3% of the average VENC. By columns, (left) datum Line 1, (center) datum Line 2, and (right) datum Line 3 from Fig. 1

The datasets agree well on general shapes and where the vertical velocities are low but show differences across the central injector region, the largest of which occur at the Line 1 position. In Fig. 5a, all the teams show a rapid increase in vertical velocity at a similar position across the shear layer of the injector jet. The group average slowly climbs downstream between 0.8 m/s and 0.85 m/s across the jet breadth before a slightly asymmetric decrease at the downstream jet shear layer. Differences between the teams can be attributed to both boundary condition errors and measurement errors. Possible boundary condition errors can arise due to slight injector flowrate differences likely caused by the varied pump configurations, return line lengths, and flowmeter uncertainty. As in the previous challenges (Benson et al. 2020b; Benson et al. 2023), a normalization of the vertical velocity by the average measured bulk velocity from each individual team ($V_{y, bulk}$), leads to a collapse, as shown in Fig. 4d. For the Line 2 and 3 locations (Fig. 4e and f), the normalization does not lead to a better consistency between the teams. The good agreement for Line 1 is reached because the jet bulk velocities $V_{y, bulk}$ are calculated at the exact location of comparison, while the same jet bulk velocities are also used for normalization at the other positions. The jet bulk velocities exhibit a mean of 0.64 m/s and a standard deviation of 0.035 m/s over the teams. The standard deviation between the teams is hence in the same order of magnitude as the measurement uncertainty, which is 3% of the VENC, corresponding to 0.024 m/s–0.038 m/s for the teams. It is consequently hard to distinguish whether the deviations between the teams are attributed to measurement or boundary condition errors.

Figures 1, 5 Recall from Fig. 1 that the square injector has a hydraulic diameter of 5 mm—a feature which appears evident in the Line 1 comparisons in Fig. 5(a,d). 5(b,e), which are each just above the cube height, show increased differences between the upstream and downstream velocities that are well captured by the measured velocity profiles from each team. The influence of the wake behind the cube

upstream of the injector is apparent, with the slight negative velocities measured for several millimeters in the flow direction until the broader shear layer region is encountered as the flow reaches the maximum values in the plot. Interestingly, each group also depicts a vertical flow velocity inflection at the same position prior to this component of velocity decreasing near the cube located downstream of the injector. Last, the measurements above the building height along Line 3 show the reduced strength of the vertical component of flow as expected, without an inflection point associated with a nearby building and with increased symmetry between the upstream and downstream shear layers. It is interesting to see the V_y peak move between the channel floor at $y=0$ and approximately 6.6 mm in the streamwise direction at this height of $y=1.5 H$, which roughly corresponds to the expected horizontal transport length for the flow above the building height.

Normalized passive scalar results are plotted in Fig. 6 for each of the same datum lines as in Fig. 5. The group average shown includes a 4% measurement uncertainty on the normalized scalar, the maximum uncertainty within the field (Sect. 3). As the deviations between the groups' jet bulk velocities are within the range of measurement uncertainty of MRV, a minor influence on the passive scalar mixing is expected. For the datum Line 1 comparison at the injector exit, the USMA data show concentration 10% above the nominal maximum, where the rest of the teams have the expected concentration near 1.0. Each team shows slightly lower concentration at the downstream edge of the injector, suggesting that mixing begins even as the jet exits because of interaction with the stagnation region of the cube just downstream. The upstream region concentration is approximately double that of the downstream region outside the jet core. The maximum differences are located at the extreme upstream edge of the comparisons—likely a result of spatial uncertainty. The USMA data suggest that the voxel is within a wall region with zero concentration, whereas the UR data show a local maximum. This same

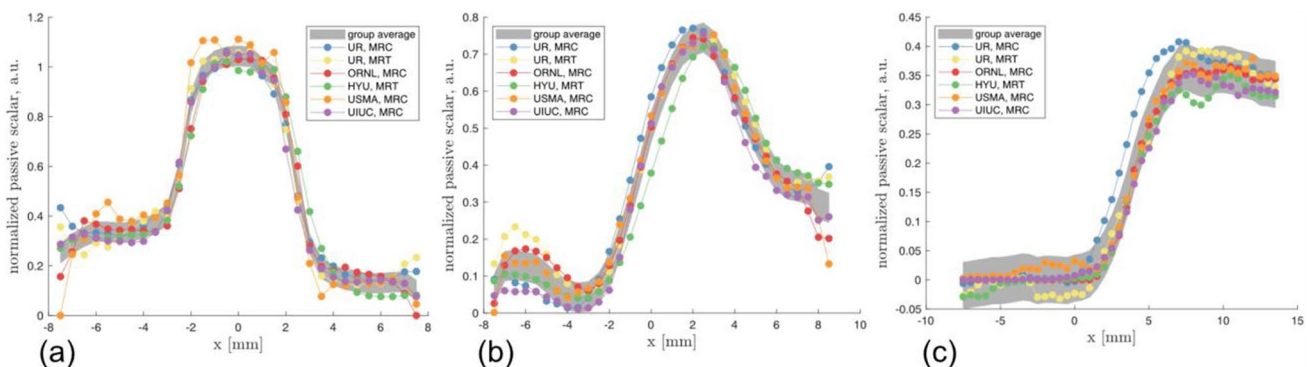


Fig. 6 Normalized scalar profiles. (a) Datum Line 1, (b) Datum Line 2, and (c) Datum Line 3

effect is magnified in the comparison at the cube height, where the last few data points for all the teams range from values near 15% to 45%. Interestingly, the UR data, which include both concentration and temperature-based measurements, show increased differences at the second datum line when compared to the first. All teams have similar scalar maxima values and are located within the 0.5 mm interpolated spatial resolutions. With the exception of the final 1 mm at the upstream and downstream edges, the profiles are similar, with each team within the approximate measurement uncertainty from the group averaged result. The third datum shows overall lower concentration levels, with HYU data just below the zero-concentration limit but within their measurement uncertainty. The UR MRC data show a slight offset from the rest of the group data. Although all the datasets have a monotonic rise to their maximum concentration, the USMA and HYU data suggest a small inflection region with a second peak, with UIUC potentially showing two inflection points at smaller scales. One speculation for this may be to assess this region as sensitive to vortex shedding, which may intermittently introduce higher concentrations captured at frequencies around the measurement TR that naturally varied across the teams based on scanner settings. For each of the datum comparisons, biased differences do not seem to exist between the concentration and temperature-based measurements, suggesting the assumptions of passive scalar behavior are substantiated by the similarity of the results.

To quantify the comparisons in Figs. 5 and 6, the root-mean-square differences are calculated comparing the vertical velocity data from each team from Fig. 5 with the group average and similarly comparing the scalar concentrations from Fig. 6. The calculation of these differences follows Eq. (1) for the normalized velocity data. In this equation, M represents the number of data points in each profile and is used in a point-by-point difference methodology between the normalized team and the normalized group-averaged vertical velocities. A similar approach for scalar concentration values follows in Eq. (2), where C represents normalized concentration or temperature as appropriate for the methodology used by the respective

team. The results are summarized in Table 3 for the respective line in the figures.

$$RMSE = \sqrt{\frac{1}{M} \sum_{i=1}^M (V_{iTEAM} - V_{iAVG})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{M} \sum_{i=1}^M (C_{iTEAM} - C_{iAVG})^2} \quad (2)$$

Figure 7 depicts the 2D normalized scalar for each team overlaid with tangential velocity vectors. The images are cropped to show the same flow regions, which helps to explain some of the subtle differences noticed in the scalar profile comparisons, all of which have common contour levels. First, the cube elements themselves have slight differences among the teams. In the USMA data, for example, the top surface of the cube does not appear perfectly flat, and ORNL shows similar issues in the streamwise direction, both caused by partial volume effects. Each team has some of these same behaviors at varying regions, suggesting that care must be taken in comparisons close to these solid surfaces. The upstream propagation of the contaminant is apparent in each image, but the concentration levels do vary among the teams, albeit slightly in most cases. Likewise, the region at the top of the first downstream cube also shows subtle variations in the comparisons. Finally, the apparent angles formed by the highest concentration band in the images are all quite similar, suggesting comparable turning, penetration, and other quantifiable features for potential comparison.

Figure 8 depicts a second contour comparison, this time at the second datum line that corresponds to the cube building height. A slight asymmetry of the injector flow is apparent in all cases, but it is more pronounced in some than it is in others. This asymmetry likely results from slight imperfections in the 3D printed flow channel in the injector region. In addition, important differences are noticeable in the building wake region downstream from the injector, with higher levels in the UIUC and ORNL datasets than in the others. These two teams, along with USMA, conducted some additional measurements at

Table 3 RMSE comparisons for normalized scalar contour data in Figs. 3–7

	UR, MRC	UR, MRT	ORNL, MRC	HYU, MRT	USMA, MRC	UIUC, MRC
Figure 3d (MRV)	0.0442	—	0.0242	0.0743	0.0587	0.0585
Figure 3f (MRV)	0.0253	—	0.0214	0.0258	0.0307	0.0329
Figure 4a	0.0458	0.045	0.0451	0.0581	0.0781	0.0366
Figure 5	0.0157	0.0161	0.0121	0.0191	0.0139	0.0148
Figure 6	0.0122	0.0138	0.0141	0.0190	0.0136	0.0122
Figure 7	0.0231	0.0232	0.0229	0.0347	0.0193	0.0329

Fig. 7 Normalized scalar contour plot comparisons at the channel center plane, $z=0$

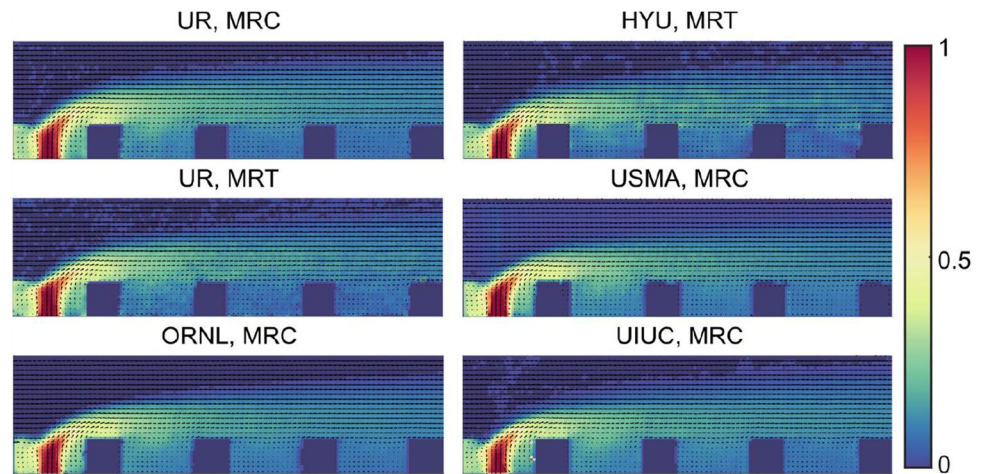
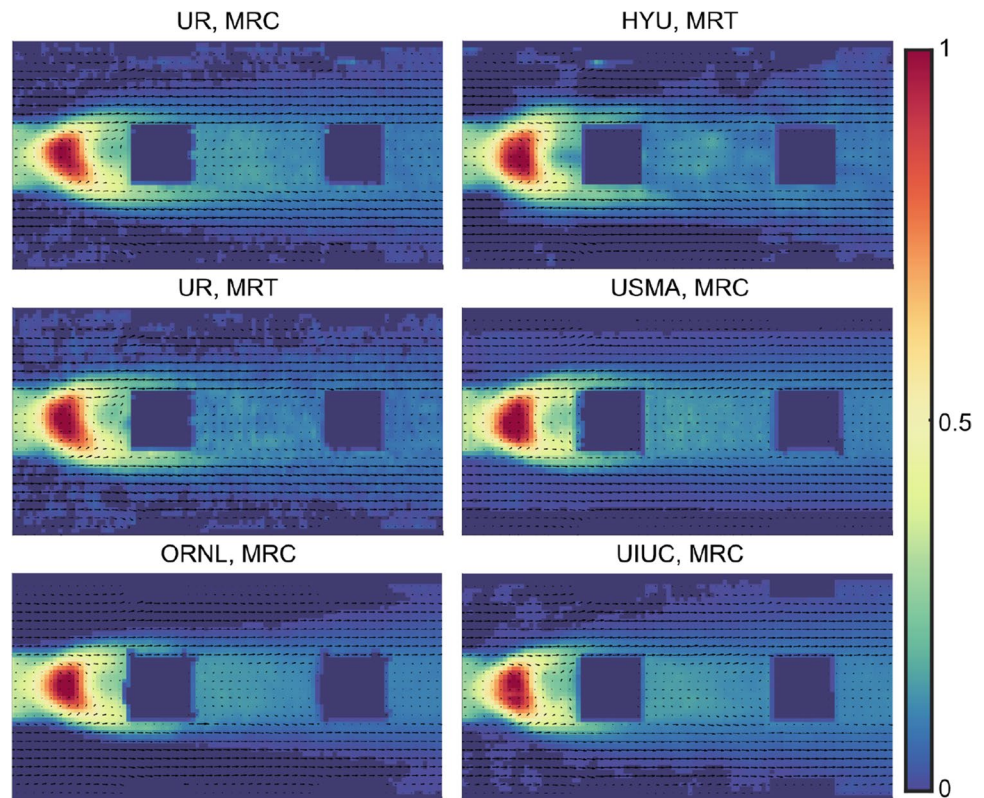


Fig. 8 Normalized scalar contour comparisons at the cube building height



higher concentrations and used data stitching routines to increase the signal-to-noise ratio of lower-concentration regions, which may have affected the results in these downstream regions. This was not done for the temperature measurements, which have the apparent lowest scalar values of the teams across most of the downstream domain. An interesting feature is apparent in each of the datasets, located at the upstream center of the cube element after the injector, where an approximately circular low-concentration region is apparent. This feature is very difficult to pick out of the previous contour comparison

but likely stems from the vertical velocity profile inflection previously noted in the discussion of Figure 5 (b,e).

Figure 9 depicts normalized scalar contours on a portion of a streamwise plane with in-plane velocity vectors at the downstream edge of the injector. The plume would be expected to have limited interaction with the freestream flow this close to the injector center, and the shapes in each image support this conclusion. The figure indicates that each team has a similar high-concentration region with vertical sides until approximately 1.5 injector widths, where the upper portions become more rounded. This rounding is somewhat

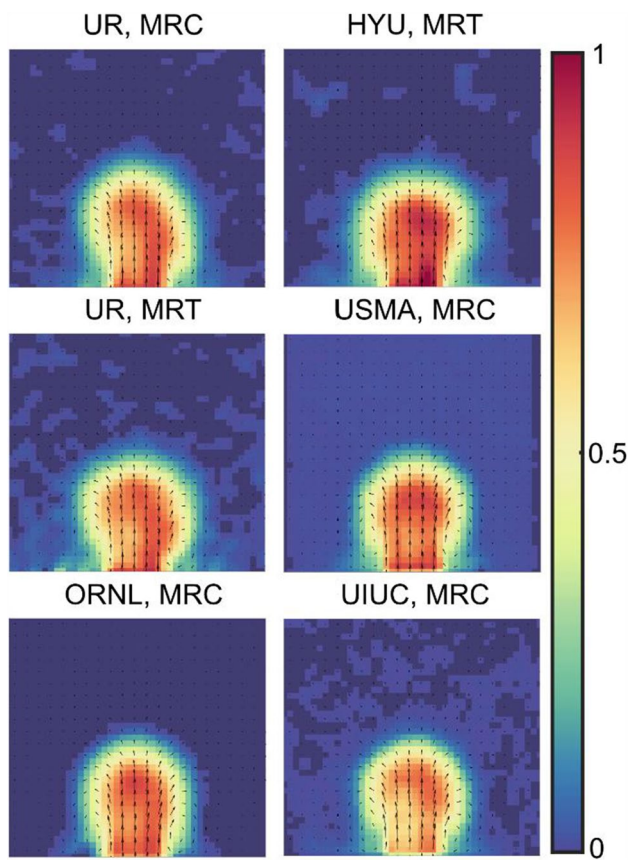


Fig. 9 Streamwise planar comparison with normalized scalar contours and tangential velocity vectors at the downstream injector edge

different among teams, with ORNL showing the least and the UR MRT data showing the most. Two teams, UR MRT and UIUC, also show some lateral variation in the highest concentration region just above the injector surfaces.

Quantifying the scalar concentration differences in Figs. 7–8 can be accomplished with a similar 2D version root-mean-square error (RMSE) effort that once again compares each team's result with the group average. The error is estimated using Eq. (3), where the scalar (temperature or concentration) is the variable C , and N and M represent the number of voxels in the two dimensions suggested by each figure.

$$RMSE = \sqrt{\frac{1}{NM} \sum_{i=1}^N \sum_{j=1}^M (C_{i,TEAM} - C_{i,AVG})^2} \quad (3)$$

Table 3 summarizes the calculated differences by group for each of the three figures. The largest variations exist for Fig. 9, likely because this region is not an entire streamwise plane but rather a focused region and therefore includes the fewest total voxels. Each team shows differences from the group average that lie within the quoted uncertainty for the measurements.

4.2 Flow structures and contaminant transport

The flow under study was selected because it was both turbulent and 3D in nature. As such, it contains flow structures that might not otherwise be experimentally observed using one- or two-dimensional experimental diagnostics. As with each of the other comparisons, the flow structures are generated using the time-averaged data sets obtained from teams as described.

Figure 10 depicts a contour plot of the scalar concentration overlaid with velocity streamlines from the ORNL dataset as an example, with the cube buildings imported from the geometric design file. Results for the other groups are similar, as indicated by the previous comparisons. The

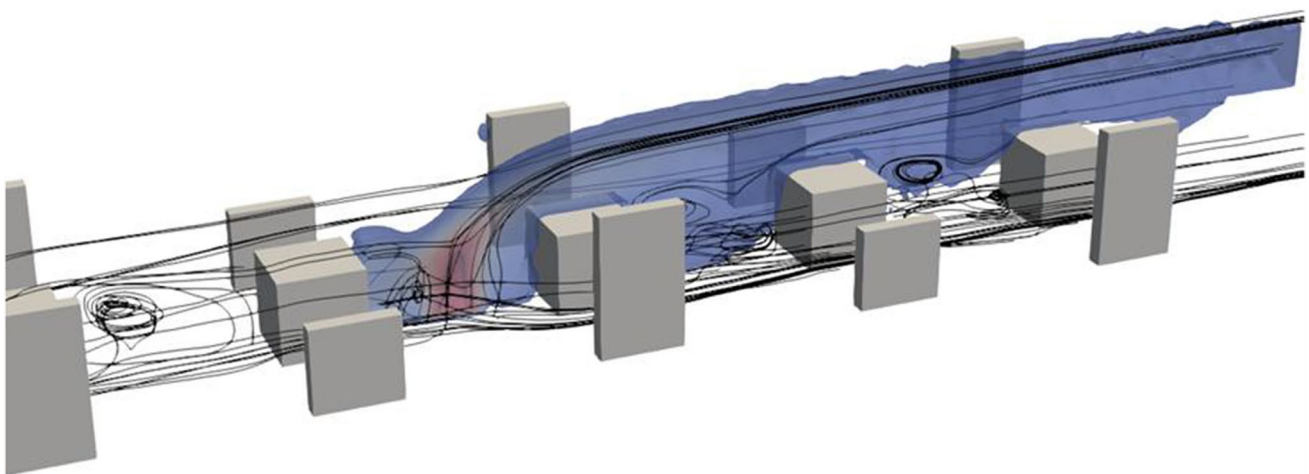


Fig. 10 Concentration contour at $z=0$ with velocity streamlines (ORNL data)

streamlines emphasize the centerline wake flow behind the cubes, which all have counter-rotating vortex pairs, but interestingly, the streamlines change toward the downstream portion of the domain compared with those of the upstream. Despite the cubes being of equal size, the vertical interaction of the wake recirculation tends to be suppressed as the flow advects downstream. Stated differently, all the upstream streamlines at the channel center plane move fluid above the cube element that follows them, a feature not apparent in the last wake region. This is more easily visualized in Figure 11, which shows a similar 3D view with transparent walls and includes an isosurface of velocity magnitude that readily identifies the increasingly large region of slower-moving fluid between cubes outside the injection region that evolves in the downstream direction.

A more detailed comparison of the complex vortex structures is shown in Figure 12. Isosurfaces of the Q -criterion are plotted for each group at the level $Q = 6400 \text{ s}^{-2}$, equal to the square of the characteristic shear rate defined as the ratio of the bulk velocity to the cubical building height. To compute Q , the velocity gradient tensor was first calculated using a second-order finite difference scheme, from which the L2 norms of the strain and rotation rate tensors were obtained. The Q fields were then low-pass filtered to remove high-frequency noise in the freestream regions.

In each dataset, the Q -criterion highlights the formation of a large, separated shear layer around the first building

along with a horseshoe vortex at its base. The strength of both the shear layers and horseshoe vortices decreases for the downstream buildings due to the sheltering effects and larger recirculation regions between them, as described above. A similar complex vortex structure is observed where the injection fluid penetrates the main flow. The large-scale Q -criterion structures show good agreement among the datasets, indicating similar overall flow topologies measured by each group. However, the HYU result contains fewer small, isolated Q -criterion structures than the other datasets. This difference is attributed mainly to the SOSVD denoising applied to the HYU velocity data during post-processing, since the Q -criterion is computed from the velocity gradient tensor and is therefore sensitive to denoising of the velocity field.

Extracting 3D, quantitative comparisons from experimental across flow volumes can present new opportunities for verification, validation, and uncertainty quantification (VVUQ) of CFD. MRI data for velocity and scalar concentration are particularly well-suited because the data are inherently 3D and contain millions of points. Early work as suggested by Benson et al. (2025) and Bruschewski et al. (2021) provides examples specific to MRV data. Several different approaches could be employed.

Examples of 3D metrics include the pointwise error (or difference) averaged over the flow volume. This yields a single root-mean-square error, or similarly calculated difference

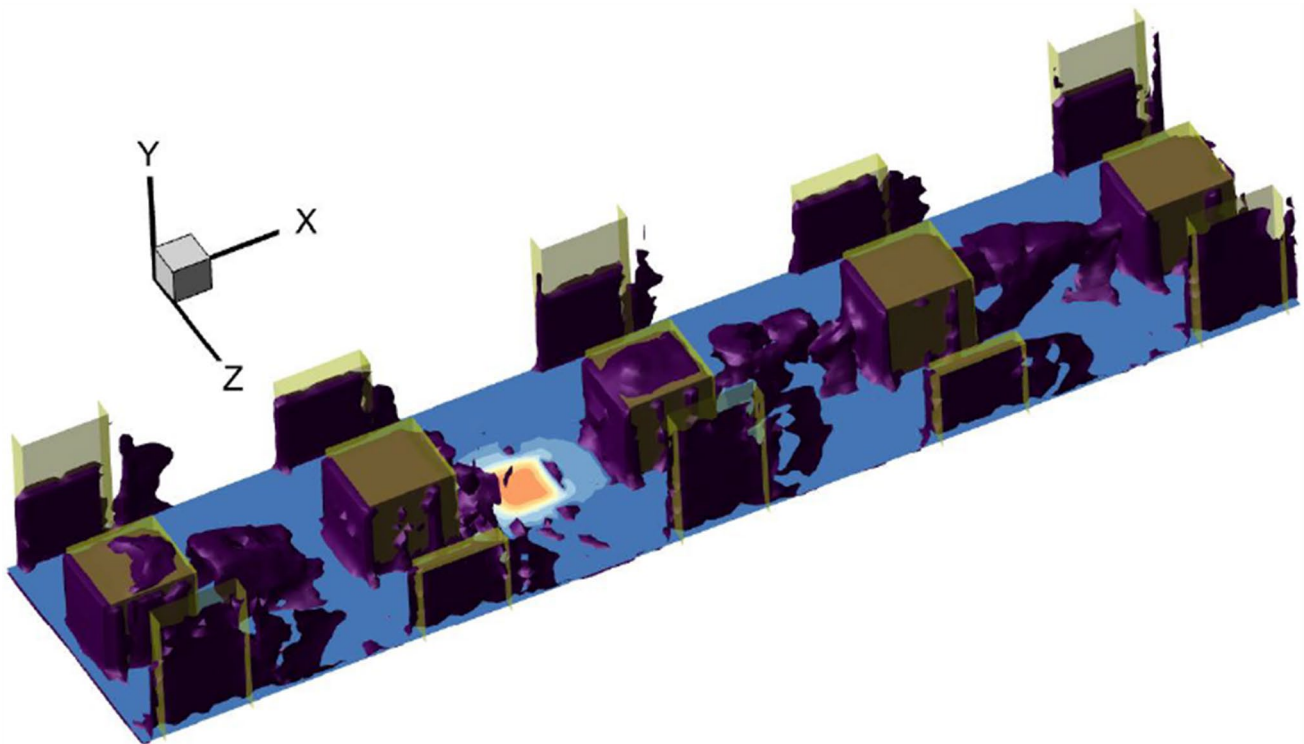


Fig. 11 Velocity magnitude isosurface at 0.1 m/s with concentration contour plane (ORNL data)

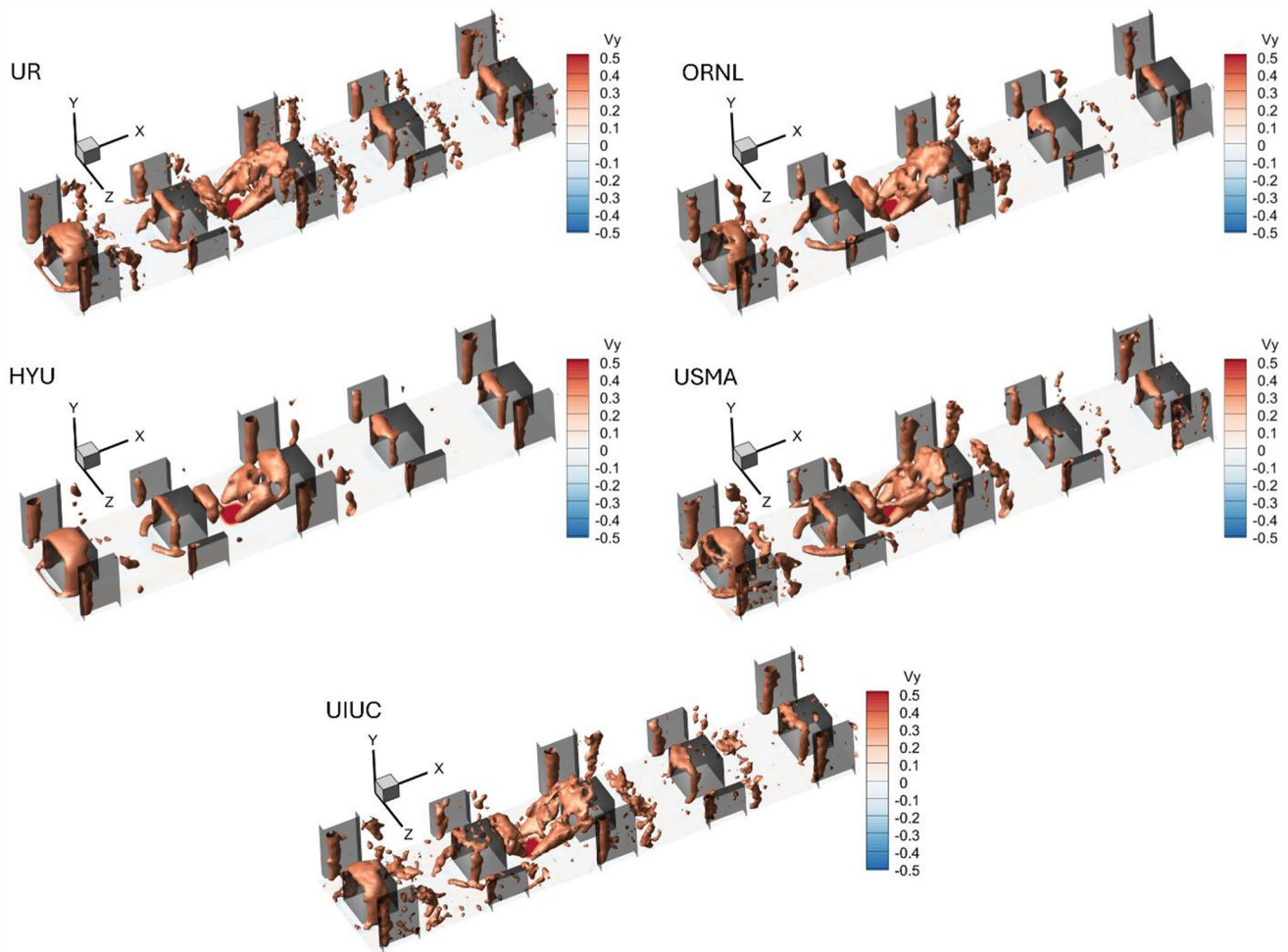


Fig. 12 Isosurfaces of Q-criterion for each group for $Q=6400 \text{ s}^{-2}$. The injection location is highlighted by the contours of vertical velocity (m/s) plotted on a plane near the base of the cuboids. The geometry is shown in the semi-transparent gray surfaces

metric. A second approach comparing isosurface volumes for 3D scalar quantities of interest, such as velocity magnitude, was investigated in Benson et al. 2020b. The threshold used to specify the isosurface can be varied, producing a global comparison as a function of the scalar value and providing information on the size of the flow structure or scalar plume. While the isosurface approach does not quantify pointwise error, it does have the advantage of being insensitive to spatial misregistration, which can be challenging in complex flows with strong spatial gradients, depending on the voxel resolution. In general, no single comparison metric may be optimal, but rather a suite of 3D comparison metrics is likely preferred for robust VVUQ. Integral metrics take into account the entire flow volume which can be difficult to visualize for complex flows and complement line plot or contour plot comparisons such as those shown earlier.

Figures 13 and 14 illustrate the isosurface-based comparison metrics for velocity magnitude and normalized scalar concentration, respectively. For each dataset, a threshold on

velocity magnitude and concentration was specified, and then the volume of all voxels with a value greater than or equal to the threshold was integrated. The threshold was then varied over the range of observed velocity magnitudes and scalar concentrations. In these figures, the vertical axis shows the isosurface volume, and the horizontal axis indicates the threshold.

The 3D comparison suggests reasonable agreement across the entire range of measured velocities for most teams, with some deviation from the USMA data in the velocity magnitude plot—potentially a function of the normalizing volume that was extracted from the datasets by integrating regions with zero velocity for each team.

The comparisons in both Figs. 13 and 14 match well across the entire range of possible values, with agreement that shows more spread for the group datasets within the scalar concentration range from approximately 15% to 25%. The largest of these differences is still within a few percent of the group mean. Determining the uncertainty for this volume comparison

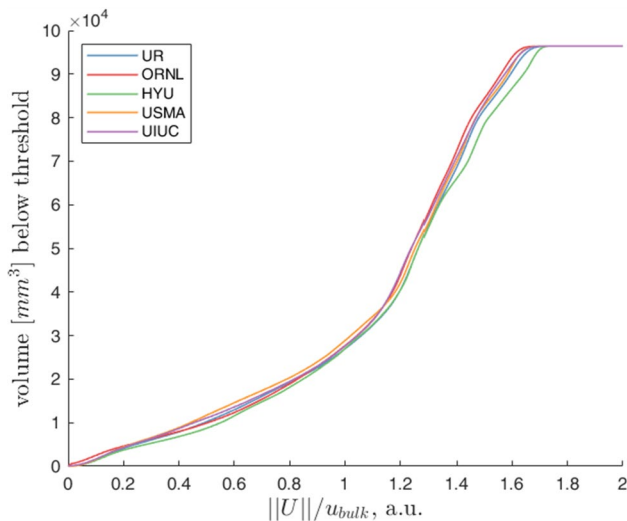


Fig. 13 Velocity magnitude volume comparisons across normalized velocities

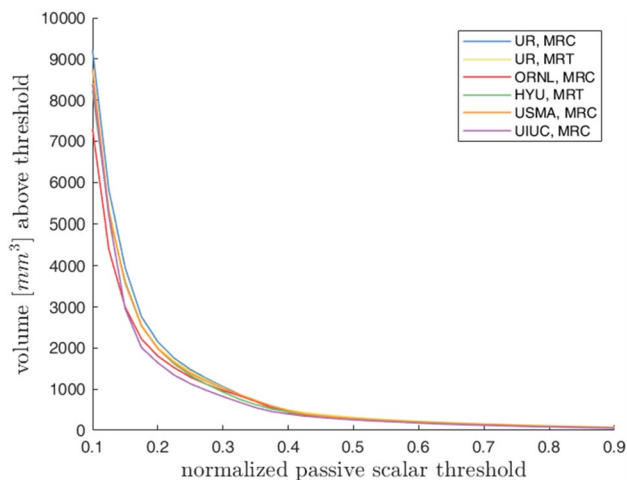


Fig. 14 Isosurface volume as a function of scalar concentration values

remains a challenge due to the spatial interpolation combined with the uncertainty in the velocity or the normalized passive scalar. Nonetheless, the isosurface volume comparison metric may be a useful tool, particularly for the development of new VVUQ metrics, and a host of additional comparisons can be constructed to further investigate details, including additional derived quantities such as vorticity and helicity.

5 Conclusion

Five research teams from groups worldwide conducted 3D velocity and either concentration or temperature measurements on a common apparatus and at matched experimental

conditions. The turbulent flow across and around six repeating cubic obstacles positioned centrally with alternating height sidewalls was developed to pose a challenge to traditional fluid measurement techniques and demonstrate a diagnostic capability with currently limited use by the fluid measurement community to date. Temperature and concentration measurements were conducted for a regime that was dominated by advection-diffusion and not by buoyancy effects, meaning that the fields should compare as passive scalars governed by identical partial differential equations. A detailed set of comparisons was conducted for the velocity and scalar fields, illuminating the repeatability of the sets of measurements conducted by each team and limitations associated with specific features such as near solid walls. Details regarding experimental uncertainty are described for both the MRV and MRC/MRT measurements, yet the uncertainty in spatial alignment associated with partial volume effects also remains an important consideration that extends the overall uncertainty in those specific regions. It is acknowledged that mitigating these partial volume effects would primarily reduce measurement bias and spatial alignment uncertainty, leading to clearer near-wall and peak velocity gradients. Nevertheless, even within current limitations, the large-scale flow structures compared in this study remain qualitatively consistent.

The comparisons show that across line profiles, contour plots, and even 3D isosurface volumes, the measurements are remarkably similar despite the complexity of conducting different experiments and combining the data. Information from the MRV and MRC/MRT aggregate measurements greatly increases the utility of the non-optical measurement diagnostic, and extensive details are provided that can aid researchers in employing the techniques across a diverse array of potential applications. Despite the overall similarity, important differences were identified—several of which occurred in regions in the domain with high gradients, such as near solid surfaces in the flow. Although care must be taken in the conduct of these types of measurements, this work is intended to broaden accessibility of the measurement diagnostic to extend its utilization in fluid mechanics research across the community of interest.

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Author contributions M.B. was the primary manuscript author and project coordinator. T.N. reviewed the manuscript and assisted with ORNL data collection. S.R. prepared most of the final version figures and assisted with Rostock data collection. L.D. assisted with ORNL data collection and prepared draft versions of Figs. 2, 10, 11. D.B. assisted with ORNL data collection and experimental uncertainty. M.Br., K.J. and S.G. assisted with the Rostock data collection and description. S.S. and H.D. collected Hanyang data and wrote that description. A.B. and C.E. assisted with the USMA/Stanford data collection and descriptions. L.V., T.B., and B.S. assisted with the UIUC data collection and descriptions. All authors reviewed the manuscript.

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Data availability Data will be published on a publicly accessible website.

Declarations

Competing interests The authors declare no competing interests.

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