

PROJECT 14-6552

FINAL REPORT

High-resolution time-resolved Experiments on mixing and entrainment of buoyant jets in stratified environments

Prepared by:

Dr. Annalisa Manera¹ (PI) (manera@umich.edu)

Dr. Philippe Bardet² (Co-PI) (bardet@gwu.edu)

Dr. Victor Petrov¹ (Co-PI) (petrov@umich.edu)

Sunming Qin¹ (Ph.D. Student) (sunming@umich.edu)

**¹Department of Nuclear Engineering and Radiological Sciences
University of Michigan**

**² Mechanical & Aerospace Engineering
The George Washington University**

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TPOC: Stephen Lomperski

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EXECUTIVE SUMMARY

Fluid jets interacting with a stratified layer play an important role in the safety of several reactor designs. In the containment of nuclear power plants, fluid jets dominate the transport and mixing of gaseous species and consequent hydrogen distribution in case of a severe accident. The mixing phenomena in the containment are driven by buoyant high-momentum injections (jets) and low momentum injection plumes. Mixing near the postulated break is initially dominated by high flow velocities. Plumes with moderate flow velocities are instead relevant in the break compartment during the long-term pressurization phase, or in any of the apertures between two connected compartments if the mass flows are sufficiently high and the density differences between efflux and ambient are sufficiently low. Phenomena of interest include free plumes (as produced by the efflux from the break compartment in a larger room or directly from a break flow), wall plumes (such those produced by low mass flows through inter-compartment apertures), and propagating stratification fronts in the ambient (for any stably stratified conditions). These phenomena have been highly ranked about nuclear reactor design, especially regarding of safety protocols. During a Pressurized Thermal Shock (PTS) scenario, the interaction between the cold ECCS injection plume and the stratified fluid present in the cold (or hot) leg is important in order to determine the temperature at the time-dependent temperature at the inlet of the reactor pressure vessel (RPV) and the potential to cause a thermal shock on the RPV wall. In sodium-cooled fast reactors (SFRs), core channels are typically hydro-dynamically isolated so that there exists a considerable temperature variation at the exit of adjacent fuel assemblies. All the above phenomena are characterized by the interaction of buoyant jets with the stratified flow.

In stratified layers baroclinic forces create significant redistribution of turbulent kinetic energy and scales, which leads to anisotropy. This important physical phenomenon is highly three dimensional and is challenging to capture even with high-fidelity CFD simulations, due in part to lack of sufficiently resolved validation data. Furthermore, the experimental data available in the open literature do not feature the level of fidelity needed for an extensive validation of turbulence models in lower order CFD.

To shed new lights into the crucial phenomena object of the present research project, it was proposed to conduct coordinated experiments and simulations at the University of Michigan and the George Washington University. The project has resulted in an experimental database of high-resolution time-resolved measurements of jets in uniform and stratified environments. The novel experimental data will be used to validate computational fluid dynamic (CFD) codes, including both Large Eddy Simulations (LES) and unsteady Reynolds-averaged Navier-Stokes equations (URANS) methodologies.

In the Experimental and Multiphase flow (ECMF) laboratory at University of Michigan, we built two experimental facilities to investigate also the effect of scaling. The first facility, DESTROJER (Density Stratified Turbulent ROund free Jet ExpeRiment), featuring a contoured jet nozzle with a diameter of $D=12.7mm$ and a $1m \times 1m \times 1m$ cubic tank, which is made of acrylic glass for optical access. The ratio between the tank width and the nozzle diameter is equal to 78, which ensures that there is no direct interaction between the jet and the side walls. A second, modular experimental facility, features three different tank sizes of size $10 \times 10 \times 30$, $20 \times 20 \times 30$, $30 \times 30 \times 30$ cm³ respectively (all tanks have the same height of 30 cm), and a jet diameter of 2mm. For the modular facility, tank-to-nozzle ratio of 50, 100, and 150 are obtained respectively. Experiments with different-density jet impactions and sharp interface with a density difference of 3.16% have been successfully conducted in the scaled facility.

In the Laboratory at George Washington University, complementary experiments have been carried out at a facility featuring the same dimensions as DESTROYER. Experiments with different jet diameters have been carried out as well.

High-resolution time-resolved measurements have been performed at all facilities using high-speed particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF). In this way, simultaneous measurements of velocity and density fields have been carried out. At the University of Michigan, wire-mesh sensors have been designed and built to gather high-resolution, time-dependent data of the stratified front in the tank. These measurements are important to provide accurate initial conditions for the CFD simulations.

An important outcome of the project has been the development of novel techniques to achieve refractive index matching (RIM) of aqueous solutions with high density differences. RIM is crucial if optical techniques such as PIV are used to measure velocity fields. Previous to this project, experiments up to 3% density difference had been reported in the literature. With the methodology developed in this project, we have been able to push the envelope to density differences up to 9%.

The experiments have been used to validate Reynolds Averaged Navier-Stokes (RANS) turbulence models and Large Eddy Simulations (LES) models. Both NEK5000 and the commercial CFD code STAR-CCM+ have been used.

The experimental data will be made available to the community through the NE-KAMS database.

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INTRODUCTION

Turbulent round jets have been investigated since the 1920s. One of the very first theoretical investigations was published by Tollmien [1], who modeled the jets based on Prandtl's mixing-length theory. From then on, turbulent round jet flow, categorized as a branch of the canonical flows, has been studied extensively by the research community from both experimental and computational perspectives during the past several decades.

For a turbulent round free jet scenario, turbulence is generated at the jet boundary and diffuses towards the axis such that the width of the mixing zone increases with downstream distance, leaving the potential core region where the flow velocity keeps a top-hat profile. As the flow travels downstream, turbulence gets dissipated, and the jet flow transits into the fully developed region, where the flow velocity begins to form a parabolic profile shown in **Figure 1**.

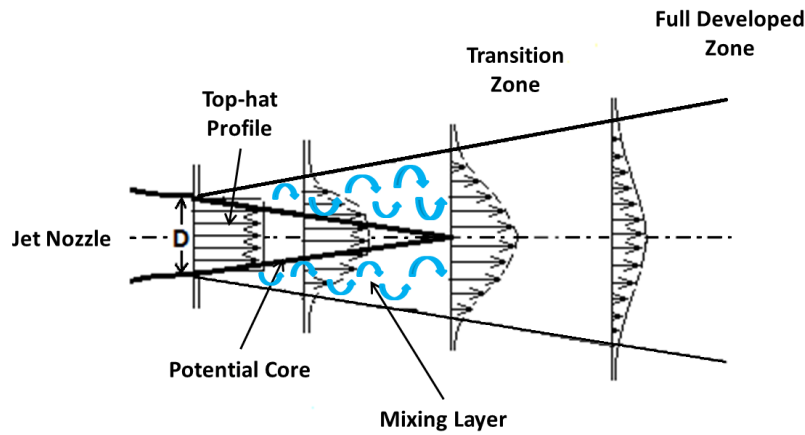


Figure 1. Schematic diagram of different zones for turbulent jet flow field in uniform environment.

Many investigations have focused on the statistical measures of the velocity fields. Hrycak et al. [2] showed that for an axisymmetric jet, the radial velocity profile when normalized by the centerline velocity, is mostly independent of the Reynolds number in the turbulent flow region. According to Nathan [3], only the jet inlet conditions will influence both the near-field and downstream flow fields because the influence of initial conditions contributes to the underlying structures of turbulent motions that are carried from the jet nozzle throughout the flow. For a self-preserving jet, according to Hussein et al. [4], the centerline axial mean velocity also decays linearly with the axial distance away from the jet nozzle, and for the self-similar region, the relation between the jet exit velocity U_0 and the centerline velocity U_c can be expressed as:

$$\frac{U_0}{U_c} = \frac{1}{B} \left(\frac{x}{D} - \frac{x_0}{D} \right) \quad (1)$$

where x_0 is called the jet virtual origin, and B is the jet decay constant. George [5] mentioned in his study of the self-preservation in jets that both x_0 and B may depend on the exit conditions of the jet (i.e., the jet nozzle shapes and initial boundary conditions).

The issue of realizability in turbulence is also essential because it illustrates whether the velocity field measurements are guaranteed to result in non-negative normal turbulent Reynold stresses and

satisfy appropriate constraints, such as the Schwarz inequality for Reynolds stress components. According to Hamilton and Cal [6], using the idea of Eigen-decomposition, the symmetric second-order tensor of the normalized Reynolds stress anisotropy can be transformed into a set of principle components λ_i and an associated vector basis Σ_{ij} . Regarding the eigenvalues, the invariants η which quantify the degree of anisotropy and the eigenvalues ξ which describe the characteristic shape can be expressed as:

$$\eta^2 = \frac{1}{3}(\lambda_1^2 + \lambda_1\lambda_2 + \lambda_2^2) \quad (2)$$

$$\xi^2 = -\frac{1}{2}\lambda_1\lambda_2(\lambda_1 + \lambda_2) \quad (3)$$

In **Figure 2**, the invariant map, also known as Lumley triangle [7], is shown. Each corner of the triangle describes a specific structure of turbulence (isotropic, 1D, 2D, 3D axisymmetric, etc.).

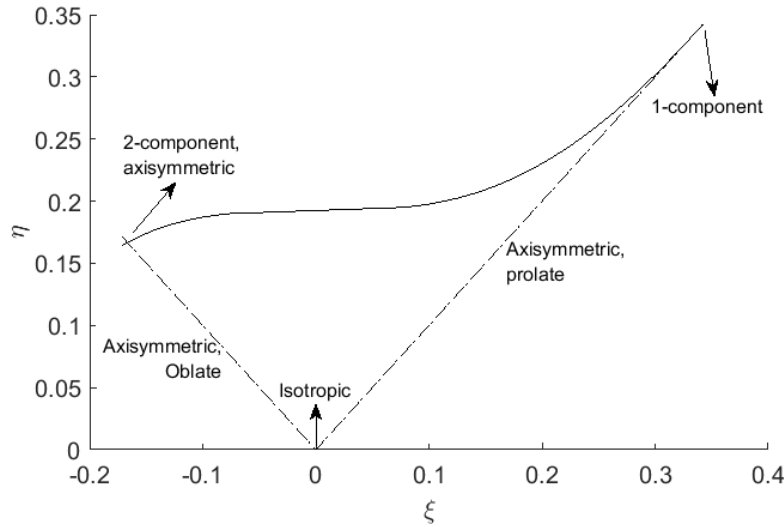


Figure 2. Lumley triangle.

Velocity signals measured in turbulent flow usually have a broad range of frequencies, which indicates that the signals consist of the temporal information from the fluid parcels in the flow or eddies with different sizes. Therefore, analyzing the velocity spectrum provides information about the contributions to the intensity of velocity signals from various length scales. Kolmogorov in 1941 [8] proposed that the three-dimensional velocity spectrum in the inertial sub-range should follow the form of:

$$E(\kappa) = C\varepsilon^{2/3}\kappa^{-5/3} \quad (4)$$

where C is known as the Kolmogorov constant and $\kappa = 2\pi f$ is the wave number. In this report, the normalized axial velocity spectra $E_{11}(\kappa_1)/(\lambda_k u_{\lambda_k}^2)$ are plotted versus normalized wave numbers $\kappa_1 \lambda_k$ to characterize the relationship between the various length scales and the energy intensities.

The spectra are normalized by the Kolmogorov length scale λ_k and Kolmogorov velocity scale u_{λ_k} . According to Fellouah and Pollard [9], the -5/3 slope is associated with the range of frequencies in which the energy cascade is dominated by inertial transfer, the -3 slope reflects what may be expected for two-dimensional turbulence flow, and the -7 slope characterizes the dissipation range at the near-field region where viscous forces dominate as shown in **Figure 3**.

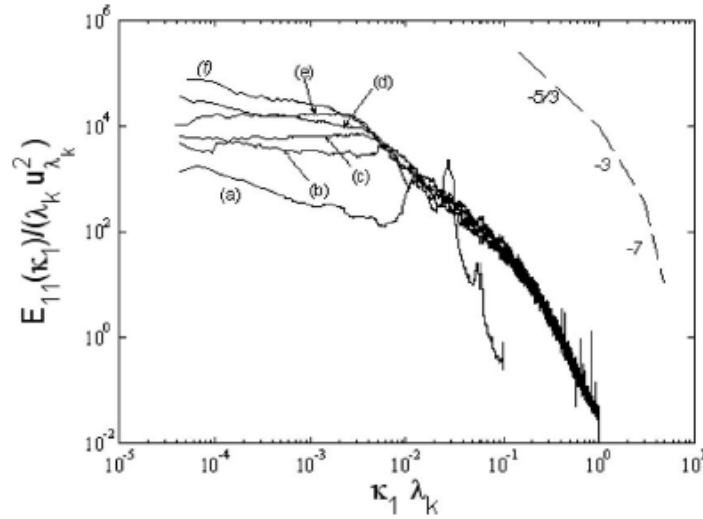


Figure 3. Velocity spectra of u at $r/D=0$ and $Re=30'000$. (a) $x/D=1$, (b) $x/D=3$, (c) $x/D=5$, (d) $x/D=10$, (e) $x/D=15$, and (f) $x/D=20$. (Adopted from [8]).

In addition to statistical characterization, coherent structures have been studied as well over the last four decades to understand and describe free turbulent flows [10] [11]. Nevertheless, the research community has not yet come up with an accepted definition for coherent structures. To understand the coherent motion and analysis of the coherent structures in this report, Robinson's description [12] is adopted: "a coherent motion is defined as a three-dimensional region of the flow over which at least one fundamental flow variable (velocity components, density, temperature, etc.) exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest local scales of the flow."

Two-point correlations are used to identify those structures that give insight into the mass and momentum transports in large scale. The general form of a two-point correlation can be expressed as follows:

$$R_{a',b'} = \frac{\overline{a'_x b'_0}}{\sqrt{\overline{a'_0 b'_0} \cdot \overline{a'_x b'_x}}} \quad (5)$$

where $R_{a',b'}$ describes the spatially distributed influence of the variance of a component a'_x in the interrogation plane to the variance of a component b'_0 at a certain location of the plane as reference.

PART I – EXPERIMENTS AND COMPUTATIONS AT UM

UM's team has accomplished several significant developments of diagnostic and data analysis for this validation effort. In short they are:

- We have improved the design of the experimental facility originally provided by the GWU's team.
- To establish a stratified environment that could be studied at high-Reynolds number, a novel and systematic index matching strategy was developed, which enables the matching of the refractive index of fluids with density differences up to 9%. This is the highest density difference currently achieved in the field of fluid-dynamics. The methodology that we have developed in this project can be used to systematically identify fluids with even higher density differences.
- An additional modular experimental facility was designed and built to investigate scaling effects.
- Wire-mesh sensor were designed and built for high-resolution measurements of the time-dependent stratification in the tank(s).
- UM has conducted extensive refinement to the experimental protocol to improve repeatability and reproducibility of the experiments.
- A complete test matrix for jets in uniform environment, including measurements in the near and far field, has been carried out as reference data for measurements of jets in stratified environments.
- CFD RANS and CFD LES simulations using STAR-CCM+ and NEK5000 has been performed. Further analysis are currently on-going.
- One first publication in Experiments in Fluids (the premier journal for experimental methods developments) has been published, two more conference publications have been invited for publications in nuclear engineering archival journals. Additional publications are currently being drafted.
- One of our publications was selected for the best paper award (among more than 700 contributions) at the NURETH-17 conference, the top international conference in the field of nuclear engineering thermal-hydraulics.

1 HIGH RESOLUTION VELOCITY FIELD MEASUREMENT OF TURBULENT ROUND FREE JET IN UNIFORM ENVIRONMENTS

An experimental facility has been built to generate a round axisymmetric incompressible vertical jet. The original design was provided by the GWU's teams. Several modifications were made at UM to improve the design and eliminate some of the drawbacks of the original facility. A simplified schematic of the DESTROJER facility (DEnsity Stratified Turbulent ROund free Jet ExpeRiment) is shown in **Figure 4**. The axial jet flow is driven by a servo-engine-driven piston, so that possible fluctuations introduced by the motor are avoided, resulting in a precisely controllable and repeatable inlet velocity profile. A software was implemented using JAVA to control the servo motor. The graphical interface of the software developed to control the motor speed accurately is shown in **Figure 5**. After being pushed through a 200.7mm diameter cylindrical chamber, the fluid passes through a first contraction with an exit diameter of 50.8mm. Then the flow is finally directed out of a following contoured jet nozzle with a diameter of $D=12.7mm$ into a 1m×1m×1m cubic tank, which is made of acrylic glass for optical access. A detailed design of

the first and second nozzle contraction profile is provided in **Figure 6**. The ratio between the tank width and the nozzle diameter is equal to 78, which ensures that there is no direct interaction between the jet and the side walls.

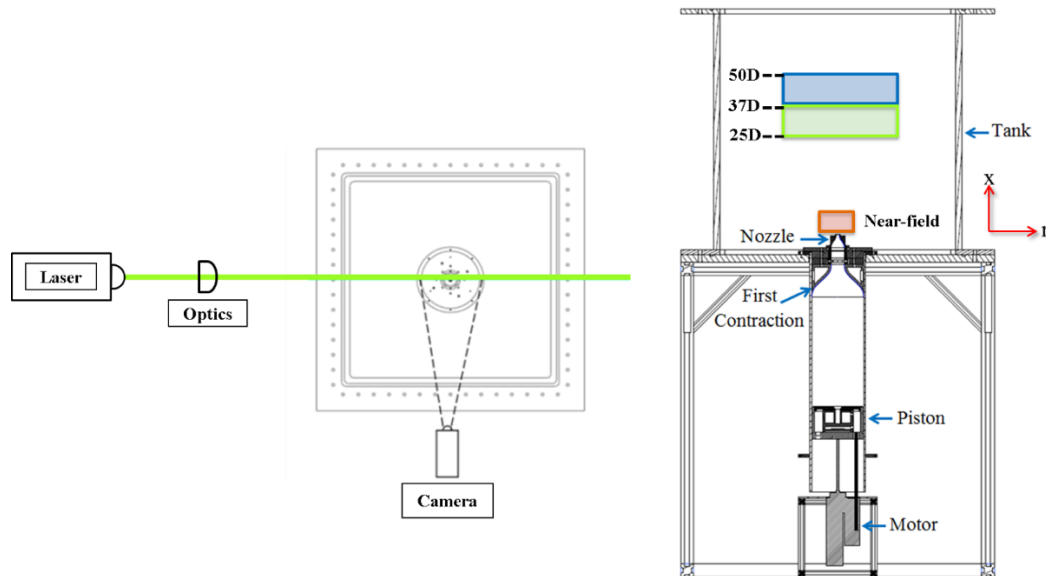


Figure 4. (right) Front view of DESTROJER facility with details shown on the right. PIV measurements are taken in the near-field region which is indicated by a red area. For the self-similar regions, measurements are separated into two regions of interest, green and blue area. (left) Shown on the left is the top view of the configurations of the imaging and laser systems.

To create a uniform environment, the DESTROJER tank is filled with water which is seeded with $10\mu\text{m}$ glass hollow sphere particles which have a similar density as water. A high-speed PIV system is implemented to visualize and quantify the velocity field. The PIV system includes two Phantom Miro LAB 340 high-speed cameras with $2'560 \times 1'600$ pixels, achieving 800Hz as the maximum frame rate at full resolution, with the illumination of a double-pulsed Nd:YLF Laser system having a maximum frequency of 10'000Hz at a wavelength of 527nm. The optics of the laser system include a combination of two spherical lenses to focus the original laser beam, and a third planar concave lens to form a light sheet which is aligned to the vertical mid-plane of the jet, as shown in **Figure 7**.

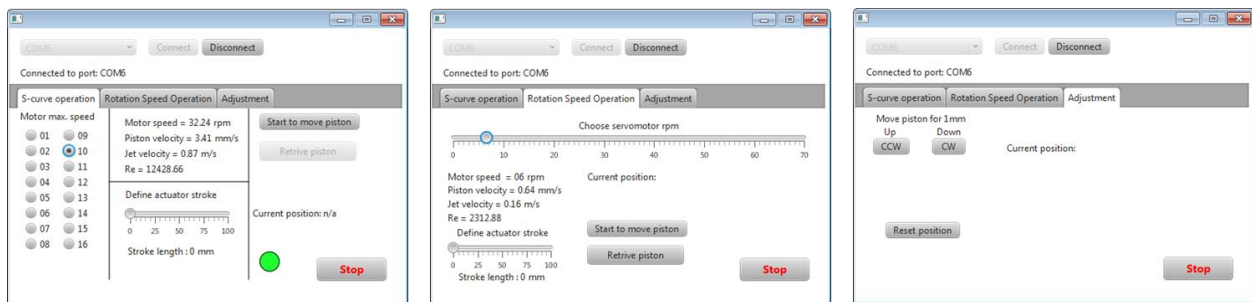


Figure 5. GUI to control servo-motor of jet injection system at UM.

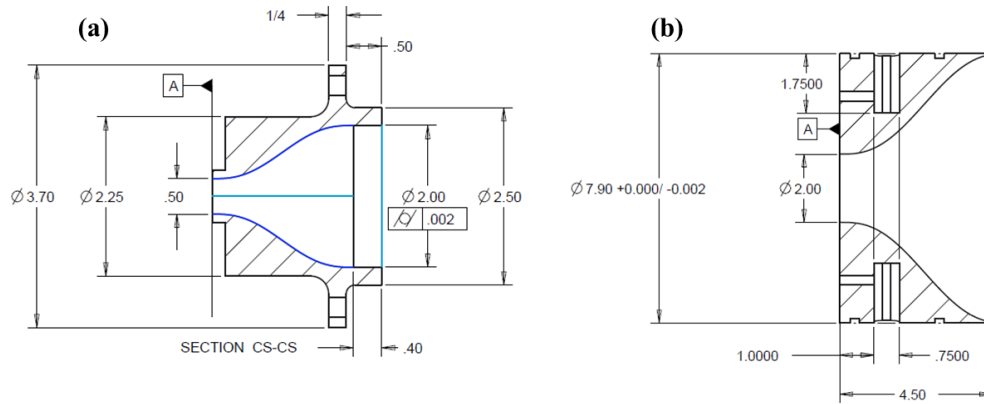


Figure 6. Contraction profiles for (a) the jet nozzle, and (b) the first contraction

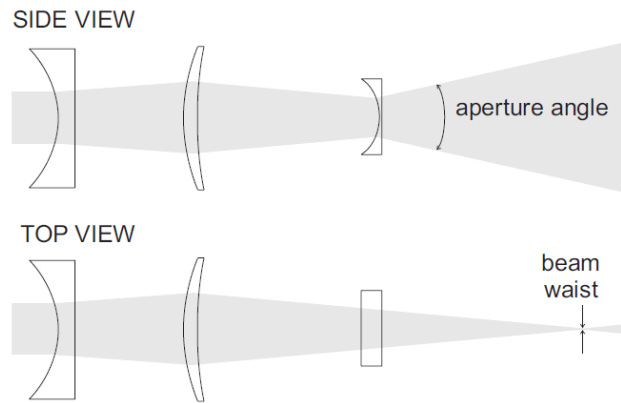


Figure 7. Lens configurations of the laser sheet formation.

The high-speed cameras are equipped with a Kenko Tokina AT-X M100 PRO D Macro lens (100mm f/2.8) combined with a Nikon TC-201 teleconverter to double the focus length and perform high-spatially resolved recordings for the near-field region of the jet ($1 < x/D < 5$). **Figure 8(a)** shows the small calibration target used for near-field measurements with a dimension of $5\text{cm} \times 5\text{cm}$ and overall 41×41 dots; each dot has a diameter of about 0.1 mm . Overall 8'048 recordings are taken at the near-field measurements with acquisition frequencies ranging from 2'000Hz to 10'000Hz to ensure sufficient particle movements within frames and achieving a spatial resolution for velocity vectors of $24 \times 24\text{ }\mu\text{m}^2$.

For the self-similar regions of the jet ($25 < x/D < 50$), a Nikon Nikkor AF 50mm f/1.8 lens alone is used for recording velocity fields at lower frequencies ranging from 125Hz to 460Hz. The calibration target used for the self-similar region is shown in **Figure 8(b)**, which has a dimension of $20\text{ cm} \times 20\text{ cm}$. About 50'000 images are taken for the self-similar regions to achieve good turbulent statistics, with a spatial resolution of $114 \times 114\text{ }\mu\text{m}^2$. The experimental test matrix for jets in uniform environment is shown in **Table I**, including the nominal jet velocities U_0 , the averaged fluid temperature in the tank and the corresponding Reynolds number.

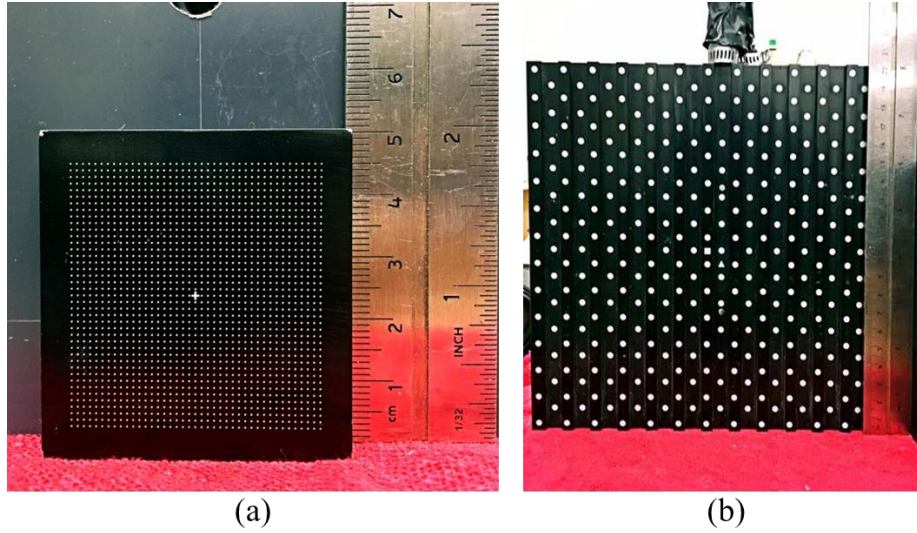


Figure 8. Calibration targets used in UM's (a) near-field regions and (b) self-similar regions.

Table I. Jet inlet velocity and fluid temperature of the experiments conducted.

Experiment Case	U_0 [m/s]	Temperature [°C]	Nominal Re [-]	Imaging Region Specification
T5k	0.38	19.21	5'000	Near-field
T10k	0.79	19.35	10'000	Near-field
T15k	1.19	19.21	15'000	Near-field and self-similar
T20k	1.60	19.21	20'000	Near-field and self-similar
T22k	1.87	18.46	22'500	Near-field and self-similar

For the self-similar region, a multi-pass approach is used with an initial interrogation window size of 64×64 pixels² with 50% overlap and a final interrogation window size of 32×32 pixels² with 75% overlap is applied, while for the near-field analysis a final interrogation window size of 48×48 pixels² with 75% overlap is chosen because of the limited seeding density in the flow. Since particle image diameters of about 4 pixels were found, Whittaker's interpolation method [13] is applied in Davis 8.3 to reconstruct the vector fields in the final pass to avoid a bias error introduced by peak locking.

1.1 Uncertainty Analysis

Uncertainty quantifications are crucial to assess the confidence in the results and evaluate the repeatability of the experiments. According to Moffat [14], to the user of the data, the statement of the range within which the experimental results might have fallen by chance alone is of great help in deciding whether the present data agree with theoretical results or differ from them. The detected sources of uncertainty within the conducted experiments can be categorized in manufacturer's specifications, limitations in the accuracy of the applied measurement systems, data processing, and statistical uncertainties. All possible uncertainty contributions are either explicitly computed within 95% interval of confidence or interpreted as such. This allows obtaining a

combined uncertainty associated with the best estimate of a particular variable X_i . According to Kline and McClintock [15], the uncertainty in a computed result preserves the odds and can be estimated with good accuracy using the root-sum-square (RSS) combination of the effects of each input, and the overall uncertainty in the result $\sigma(R)$ can be propagated by the RSS method including the uncertainties from each variable $\sigma(x_i)$ as shown in Eq. 6:

$$\sigma(R) = \sqrt{\sum_{i=1}^N \left[\frac{\partial R}{\partial x_i} \sigma(x_i) \right]^2} \quad . \quad (6)$$

For velocity fields measurements, the first uncertainty source is associated with the relative error due to the drag of seeding particles $\sigma_{drag}(u)$ in a Stokes flow, which can be estimated to be a maximum error of 1% with Stokes number much less than unity as suggested in Tropea et al. [16]. The second source originates from the method to compute the vector fields by using a direct normalized correlation on a graphics processing unit (GPU). During the experiments, the diameter of each particle on the raw images occupies between one to four pixels, and this could lead to a bias error called peak-locking. Van Doorne et al. [17] and Foucault et al. [18] have shown that using a sub-pixel interpolation scheme, suggested by Whittaker [13], increases the accuracy by shifting and deforming the second interrogation window and thus decreases the error due to peak-locking significantly. An optimization of the image particle density within each interrogation window, the in-plane loss of particle pairs and the out of plane loss of particle pairs, increases the probability of a valid detection of the particle displacement and thus the reliability of the resulting velocity field to more than 95% [19] and then the associated uncertainty can be formulated by $\sigma_{corr}(u) = 5\%$. The random error component $\sigma_{re}(x_i)$ for each of the variables is constructed with a 95% significance interval as shown in Eq. 7,

$$\sigma_{stat}(u_i) = \frac{t \cdot S(x_i)}{\sqrt{N}} \quad (7)$$

where t is the value computed by the inverse t-test of the Student's t-distribution for the total sample population N at the desired confidence level and $S(x_i)$ is the standard deviation of the quantity. However, for higher-order moments, such as the Reynolds stresses $(\overline{u'_i u'_j})$, which are computed by the statistics of multiple velocity samples, the distribution does not necessarily follow a normal distribution. Therefore, the Chi-square (χ^2) test is applied to construct the interval of confidence. Forlay-Frick et al. [20] have shown that the non-parametric test procedure is asymmetric in contrary to the Student's t distribution and therefore upper and lower bounds of the confidence interval need to be quantified. According to Sullivan [21], the statistical uncertainty on higher order moments depends on the amount of data used to estimate the variance and the defined significance level and can be estimated by Eq. 8 with The subscripts L and U in denoting the lower and upper bound:

$$\left[\frac{\sqrt{N-1}}{\chi_L} \cdot \overline{u' u'} \leq \overline{u' u'} \leq \frac{\sqrt{N-1}}{\chi_U} \cdot \overline{u' u'} \right] \quad (8)$$

Also, the signal to noise ratio (SNR) is included. The individual sources of uncertainty propagate into the estimate of the higher order moments and are combined by the method of RSS.

1.2 Calibration Systems for Laser Alignment

To achieve reliable quantitative measurements using PIV, image calibration is one of the most crucial procedures. Introducing a novel way to calibrate the laser sheet with the new calibration target holder system, random errors caused by human's judgments can be reduced, leading to more reliable and higher-resolved experimental results.

1.2.1 Small target for near-field experiments

Figure 9 shows the specially designed calibration target holder with a 12.7 mm pin that matches the diameter of the jet nozzle. When inserting the holder into the nozzle, the calibration target can fit tightly into the target holder, allowing for an accurate alignment of the front surface of the calibration target with the jet center, as indicated in **Figure 10**.

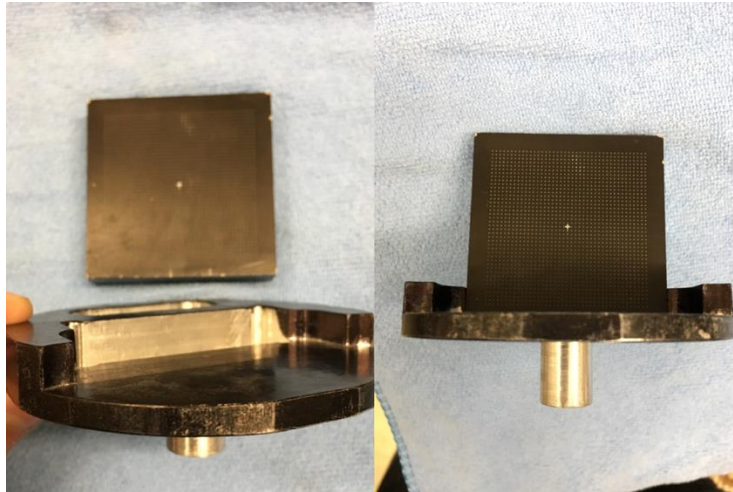


Figure 9. Calibration target and its holder which can fit in the 12.7 mm diameter nozzle.

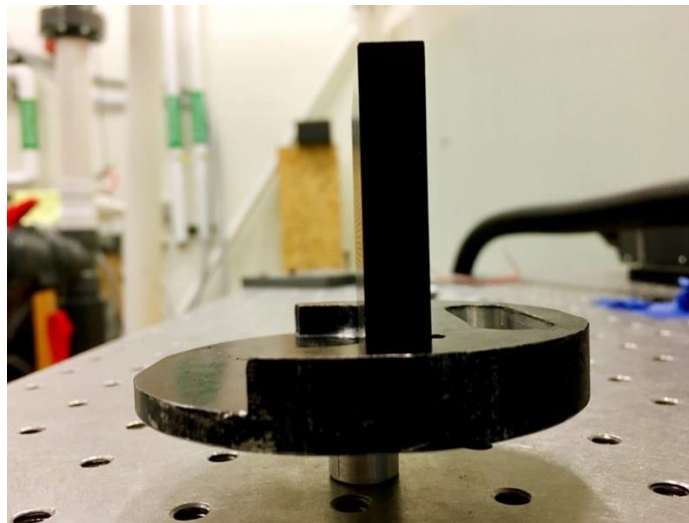


Figure 10. Side view of the calibration target and its holder.

As shown in **Figure 11**, there is a slot milled on the target holder which can be used to rotate the holder from a distance. Inserting an adjustable aluminum bar into the slot, the orientation of the calibration target can be well controlled outside the tank, as shown in **Figure 12**.

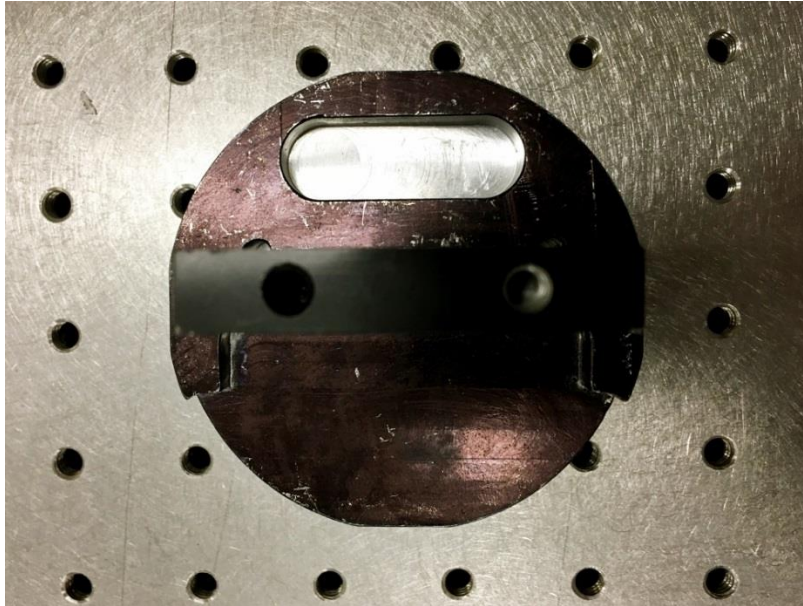


Figure 11. Top view of the system, showing the slot designed for rotation mechanism.

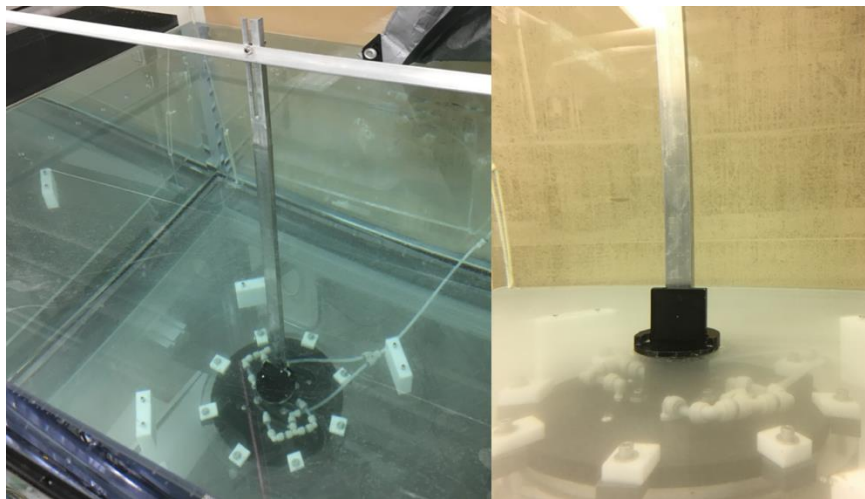


Figure 12. Rotation mechanisms to adjust the orientation of calibration target.

Confidently knowing that the center of the calibration target is indeed the center of the jet, the dots on the surface of the target can be used as guidance for aligning the laser sheet. With the target facing the laser sheet, as shown in **Figure 13**, the PIV laser can be aligned to the center of the jet when the center dots on the targets are illuminated. Later, by rotating the target and aligning the front surface with the laser sheet, the alignment is completed.

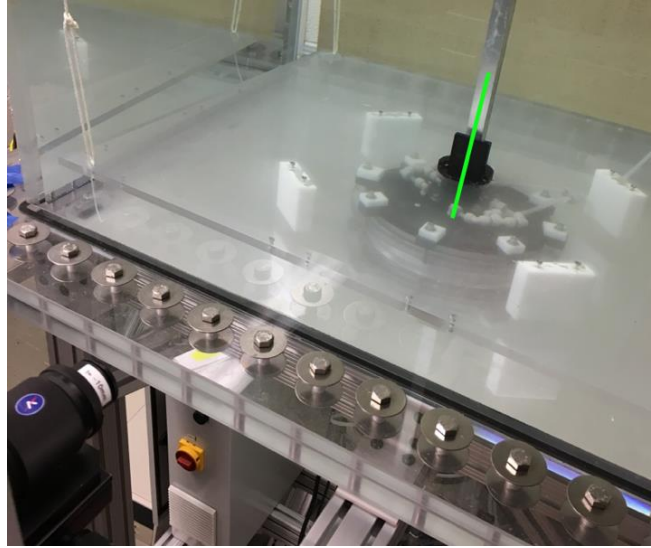


Figure 13. Illustration of laser light aligned in the center of the target.

1.2.2 TSI target for self-similar region experiments

The calibration target used in far-field experiments, as shown in **Figure 8(b)**, is a 20 cm $\times$ 20 cm TSI square target with 19 $\times$ 19 dots on the front surface. Each dot on the plate surface has a diameter of 2 mm, and the spacing between every two dots is 1 cm.

As shown in **Figure 14**, a conceptual calibration target holder design was made using SOLIDWORKS. With a bar to support the weight, the holder has two guide rails that can be used to accommodate for different fields of interest covering from at least 20D to 50D. Moreover, the holder is centered by inserting the pin into the jet nozzle on the bottom. However, the concern of this design is that it has the potential to damage the nozzle, which is hard and expensive to replace.

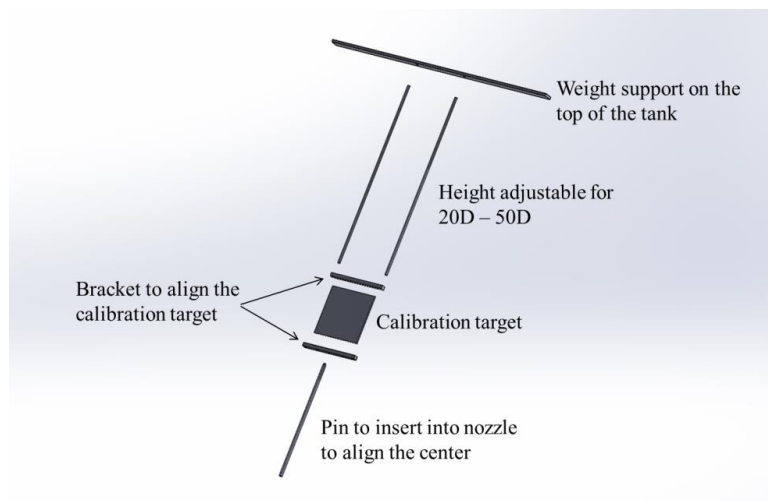


Figure 14. Conceptual design of calibration target holder for far-field experiments.

The final design of the T-shape holder was manufactured as shown in **Figure 15**. As illustrated in **Figure 16**, the calibration target is held by L brackets that can slide up and down along the slot of the aluminum structure material, giving a wide range of adjustments.

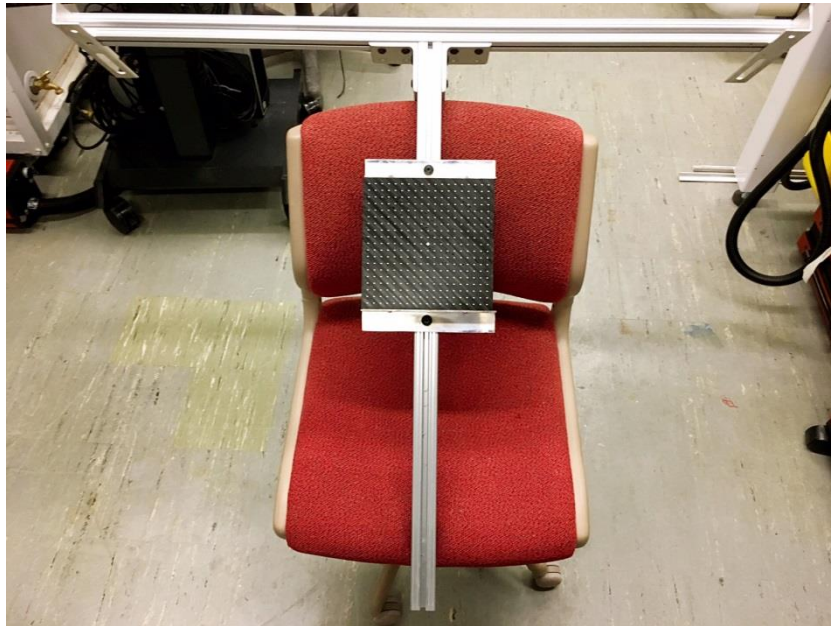


Figure 15. Finalized calibration system for far-field experiments.

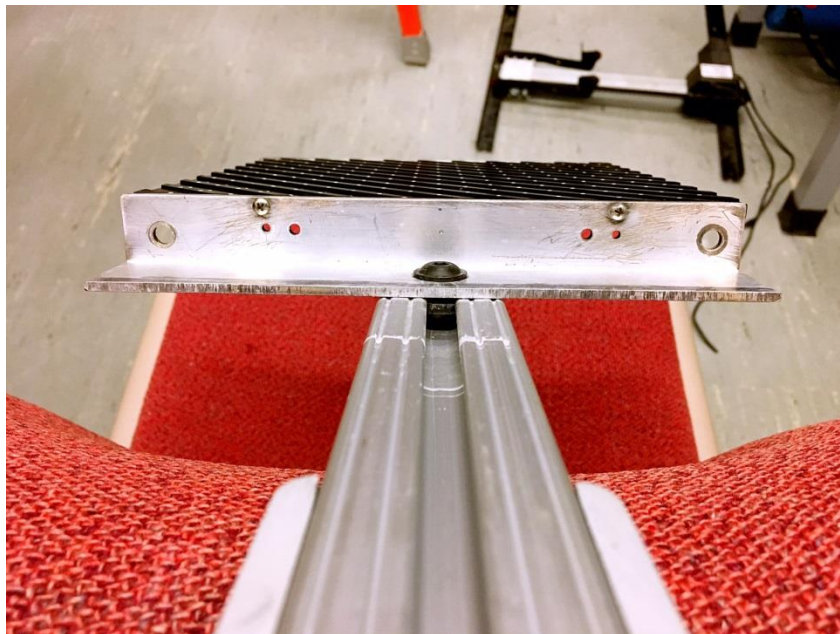


Figure 16. Top view of the calibration holder with TSI target attached.

There are slots pre-drilled on each shoulder piece of the T-shape beam, as shown in **Figure 17**, so that the calibration target holder can be fastened on the top edges of the square tank, adding the accuracy of laser sheet alignment as well. After placing the system into the tank filled with water, a pendulum and a 3D printed part can be utilized to align the target front surface with the center of the nozzle, as indicated in **Figure 18**.



Figure 17. Slots on the shoulders of the target holder.

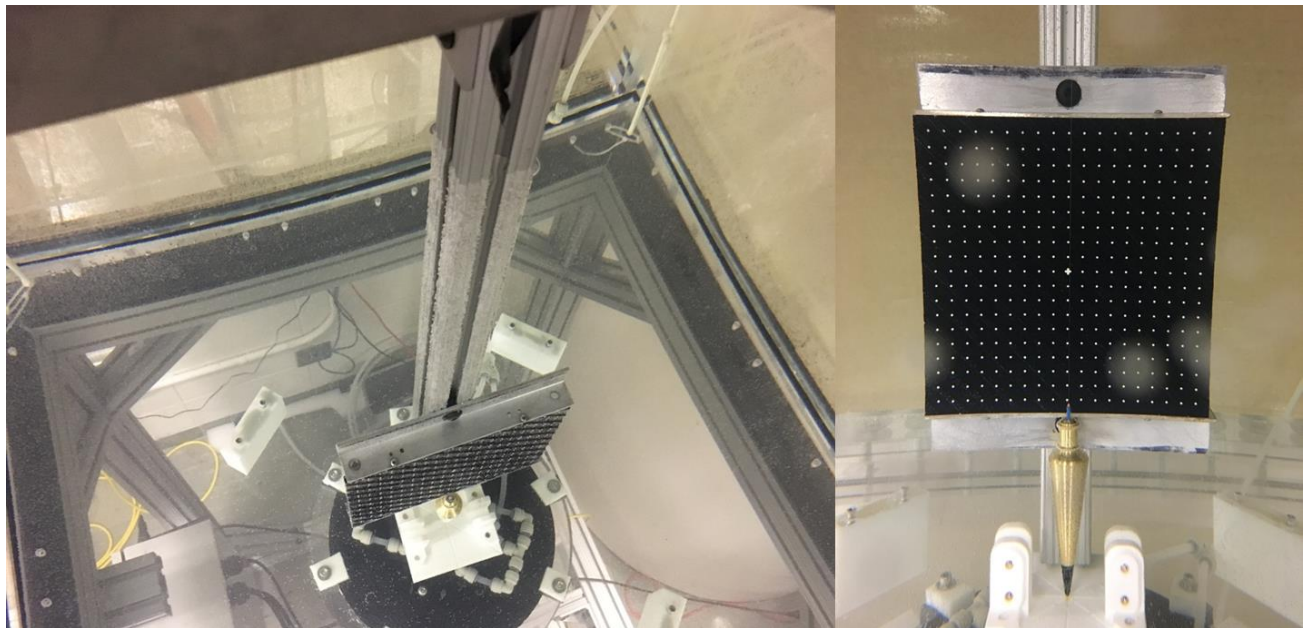


Figure 18. Alignment of the calibration system in the tank.

1.3 Wire-Mesh Sensor for the DESTROJER Facility

Wire-mesh sensors allow the measurement of the fluid conductivity field with high spatial and temporal resolution. For this project, wiremesh sensors are used at UM to characterize the density stratification in the experimental facility. The design of the wiremesh sensor PCB board is reported in **Figure 19**. The printed boards are shown in **Figure 20**. The sensor allows to measure the local fluid conductivity with a time resolution of up to 10,000 frames/s over a matrix of 128×8 , for a total of 1024 measuring points. The dimension of the PCB board is 795.5 mm $\times$ 73.5 mm. A spatial resolution of 3 mm is achieved for the central part of the sensor, where the stratified layer is

expected to be, while a spatial resolution of 10 mm is achieved in the top and bottom part of the sensor.

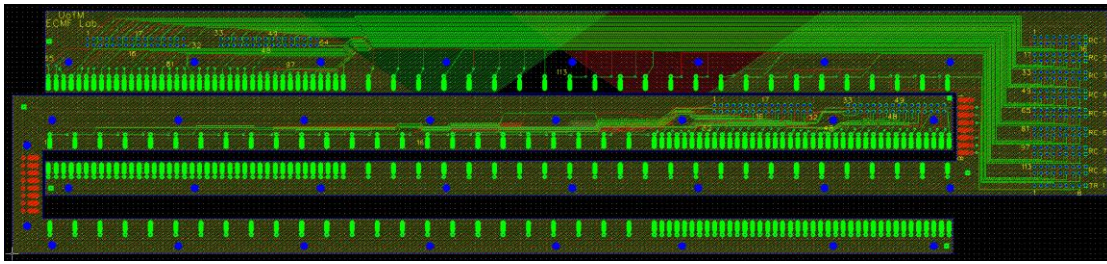


Figure 19. PCB board design using FreePCB software.

This wire-mesh sensor is also equipped with a metal frame, as shown in **Figure 21**, which has pre-drilled holes and allows to securely fix the PCB board. With the all-in-one design of the high-spatial-resolution wire-mesh sensor and the sensor frame, density and/or concentration fields can be measured without the need to disturb the stratified layer in the tank. The complete sensor is shown in **Figure 22**.

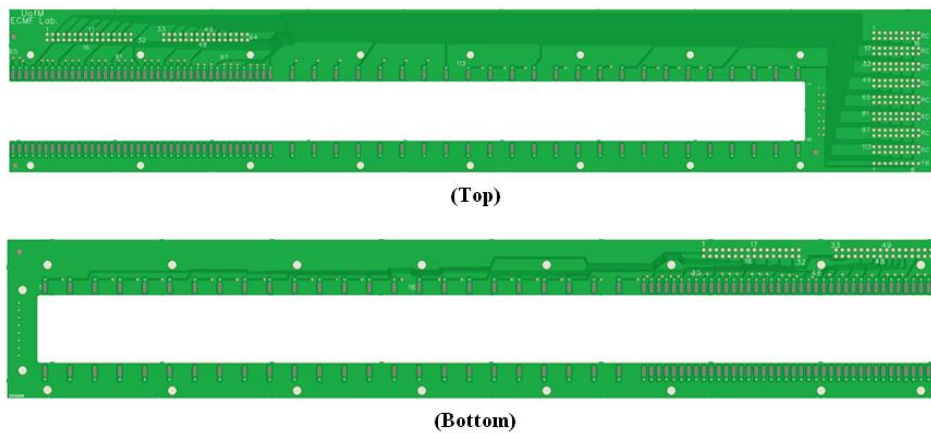


Figure 20. PCB board design (rendered).

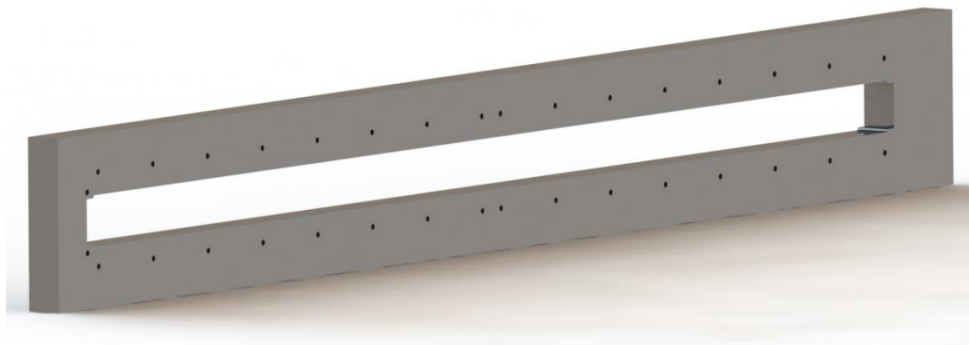


Figure 21. Wire-mesh sensor frame.



Figure 22. Wire-mesh sensor mounted on the frame in ECMFL.

More detailed features like the cable connections and the transition regions are shown in **Figure 23**.

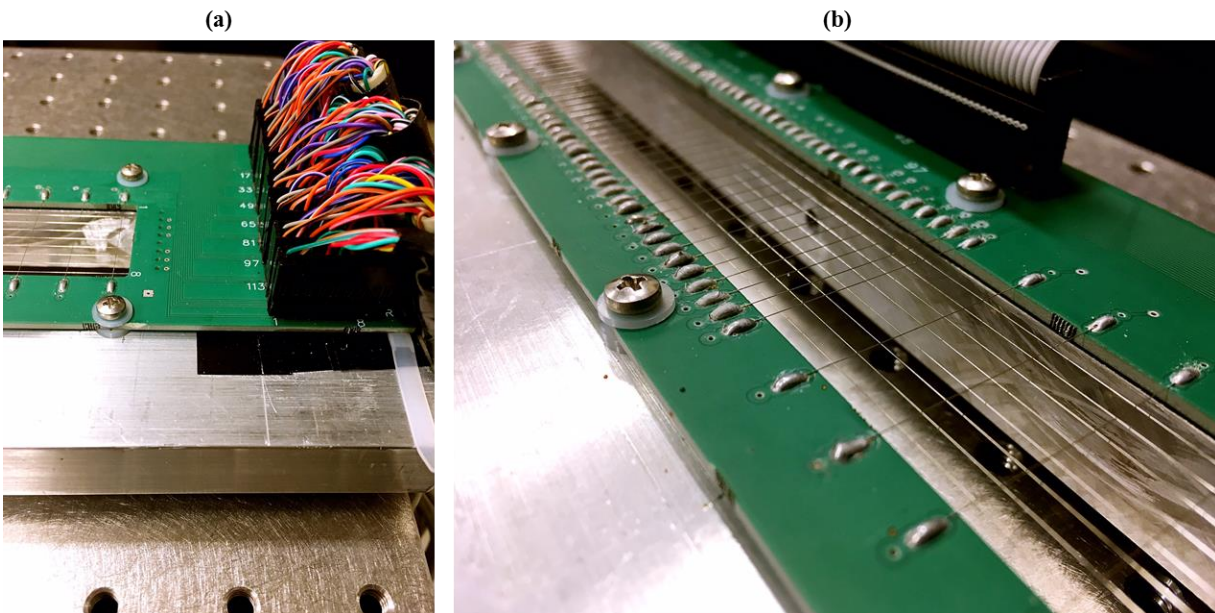


Figure 23. Close view of the wire-mesh sensor with (a) cable connections of eight channels, and (b) the transition from the coarse region (10 mm apart) to the fine region (3 mm apart).

1.4 Results and Discussion

1.4.1 Nozzle Symmetric Validation at Near-Field Regions

To verify whether the jet nozzle is perfectly symmetric and to ensure repeatability of the experiments, individual measurements were performed on two imaging planes perpendicular to each other and their average velocity fields, as well as Reynolds stresses, were compared and

discussed. The measurement setup is illustrated in **Figure 24**, where the two imaging planes are indicated together with the position of PIV laser and camera system (SE and SW indicated the laser pointing direction).

Detailed experimental parameters for the measurements carried out on the two perpendicular imaging planes at $Re = 10,000$ in near-field are summarized in **Table II**. A total of 9054 images captured over a 22-seconds measurement were sufficient to achieve converged near-field flow data.

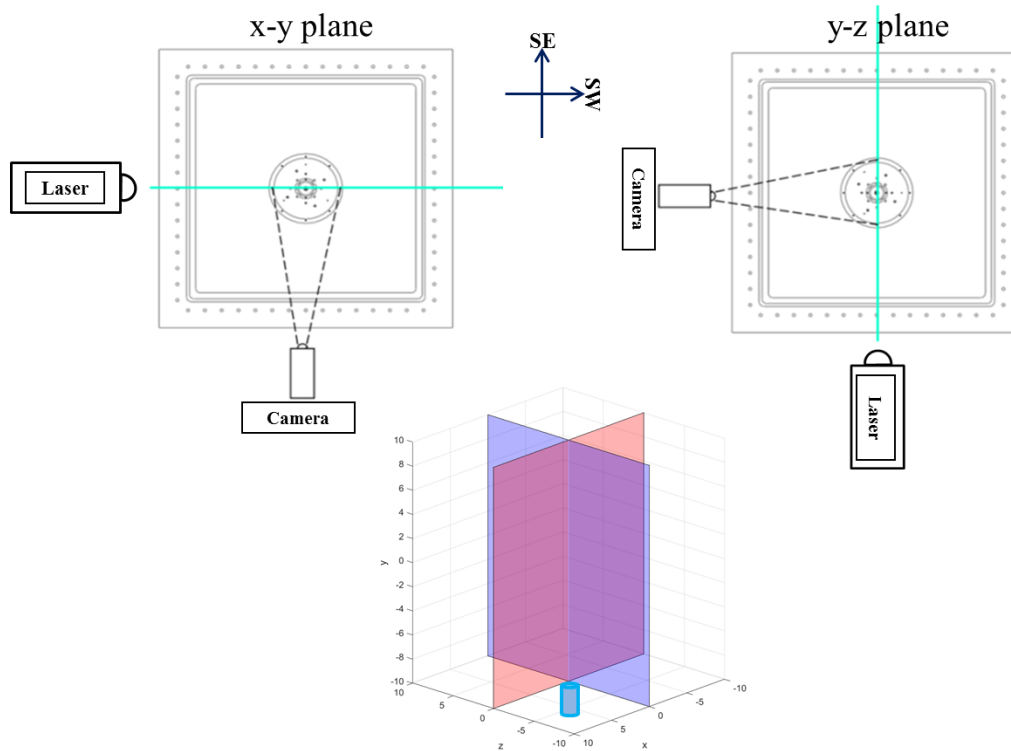


Figure 24. Illustration of laser and camera planes for the symmetric test, and for the different color planes plotted at the bottom; red indicates XY imaging plane and blue is YZ imaging plane.

Table II. Experimental parameters used in the symmetric test.

Laser Facing	Jet Velocity	Temp.	Δt	Acq. Rate	# of images	Measure Duration
--	m/s	$^{\circ}\text{C}$	μs	Hz	--	s
SW	0.79	19.35	260	400	9054	22.635
SE	0.79	20.58	230	400	9054	22.635

The axial time-average velocity profiles and Reynolds stresses obtained at $x/D = 1, 2$, and 3 for the two imaging planes are reported in **Figure 25**. Overall, good agreement between the two separate measurements is observed. Small differences are observed for the velocity field across the jet, but this is to expected as these velocities are rather small, most of the jet momentum being in the axial direction.

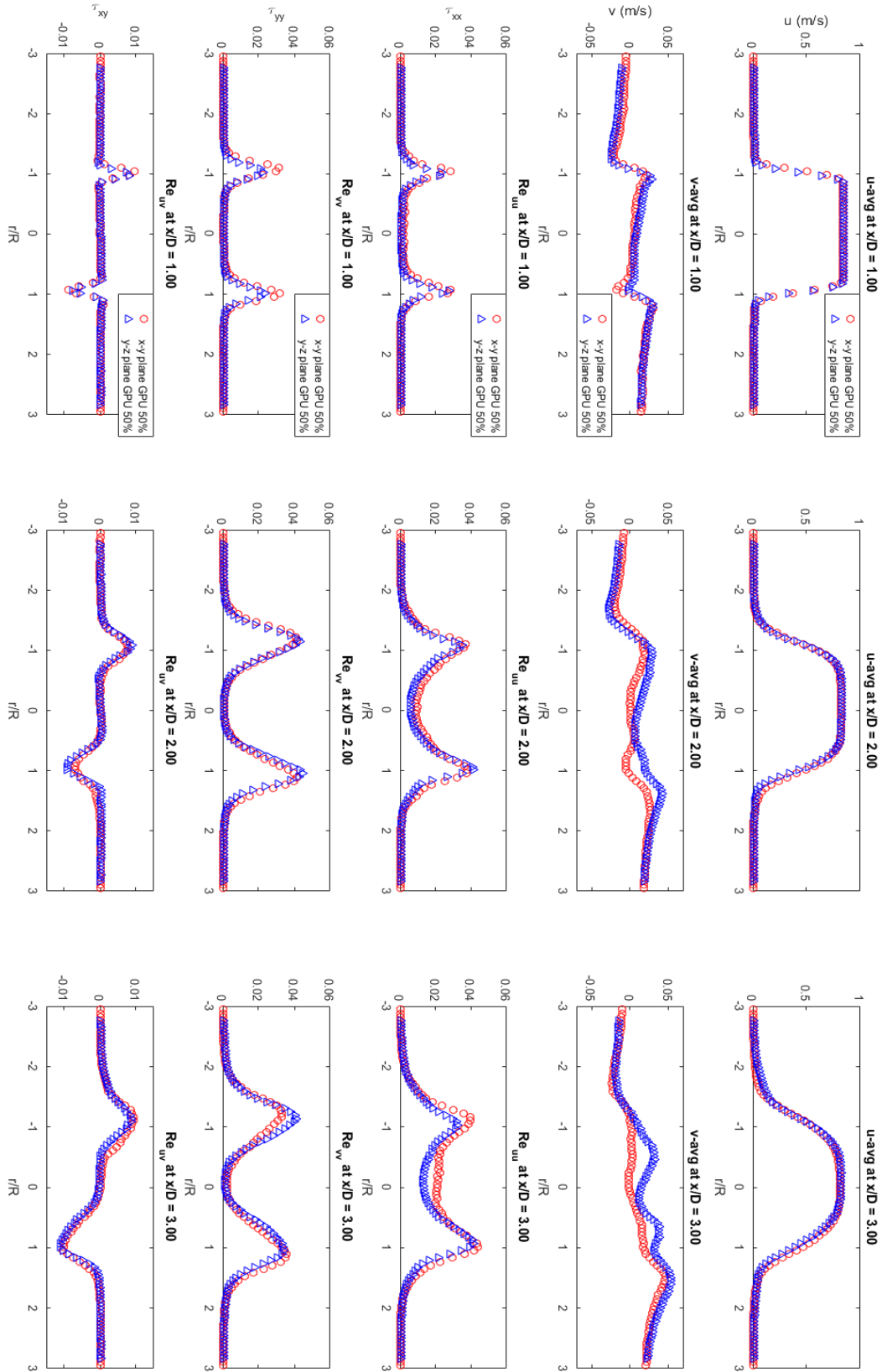


Figure 25. Average velocities and Reynolds stresses for XY and YZ imaging planes.

In conclusion, shown in **Figure 25**, the agreements in velocities and stresses profiles for two perpendicular planes across the nozzle indicated that the jet flow could be considered as symmetric. In this light, the image size of the PIV measurements for the near-field experiments can be reduced to achieve a higher acquisition rate for time-resolved PIV in the future.

1.4.2 Mean Velocity Profiles at Near-Field Region

Several measurements have been carried out to characterize the turbulent free jet in the DESTROJER facility. In this section turbulent statistics, coherent structures, and spectral analysis is reported for the experiment case T22k, characterized by a $Re = 22,500$. Both the near-field and the self-similar region are analyzed. Details about the imaging setup are reported in **Table III**.

Table III. Imaging parameters for PIV measurements for Experiment Case T22k.

Experiment Case	T22k ($Re = 22,500$)		
Region of Interest	Near-field for $1 < x/D < 5$	Self-similar for $25 < x/D < 36$	Self-similar for $37 < x/D < 50$
Acquisition Rate	10'000 Hz	460 Hz	260 Hz
Images Recorded	8,048	47,776	47,975
Cross-correlation Window Size	64×64 (50% overlap) 48×48 (75% overlap)	64×64 (50% overlap) 32×32 (75% overlap)	
Spatial Resolution	$24 \times 24 \mu m^2$	$114 \times 114 \mu m^2$	$115 \times 115 \mu m^2$

Figure 26 shows the jet evolution in the near-field region for Experiment Case T22k, while **Figure 27** shows the jet evolution in the near-field region for Experiment Case T5k, T15k, and T22k. Here the streamwise mean velocity profiles (left), turbulent kinetic energy (TKE) (middle), and the shear stresses (right) at axial positions $x/D = 1, 2, 3, 4$, and 5 are reported. Uncertainties for mean velocity profiles are presented by error bars which indicate the combined error at 95% confidence interval, while the two-sided uncertainty intervals are represented by the shaded green area between the upper and lower bounds of the measured TKE and shear stresses profiles which are plotted in blue dots.

At one jet-diameter away from the jet exit, a top-hat velocity profile can be observed as predicted in the potential core of the jet, and turbulence mixing happens in the shear layer regions, indicated by the maximum turbulent kinetic energy and shear stress at the jet boundary layers ($r = \pm 6.35mm$). As the downstream distance increases, the jet velocity develops, expanding from a top-hat shape to form a parabolic profile with a growing of the shear layer towards the center of the jet. As shown in **Figure 26** and **Figure 27**, beginning from two jet-diameters away from the jet exit, the turbulent intensity at the centerline begins to develop, and the peaks of the shear stresses increase further downstream as well. For $2 < x/D < 3$, there is a transition of TKE where the amplitude of the peaks increases from the beginning and starts to decay further downstream.

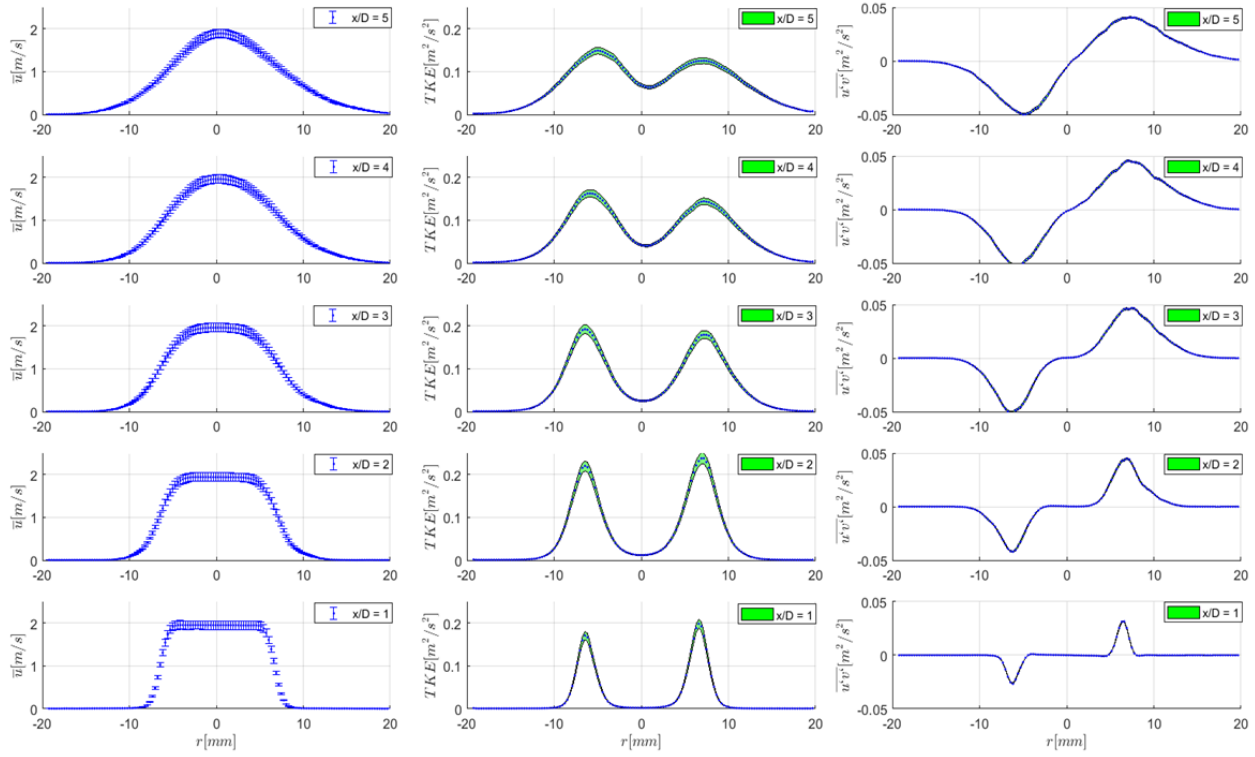


Figure 26. Streamwise mean velocity profiles (left), turbulent kinetic energy (middle) and shear stress (right) at different axial x/D distances for Experiment Case T22k.

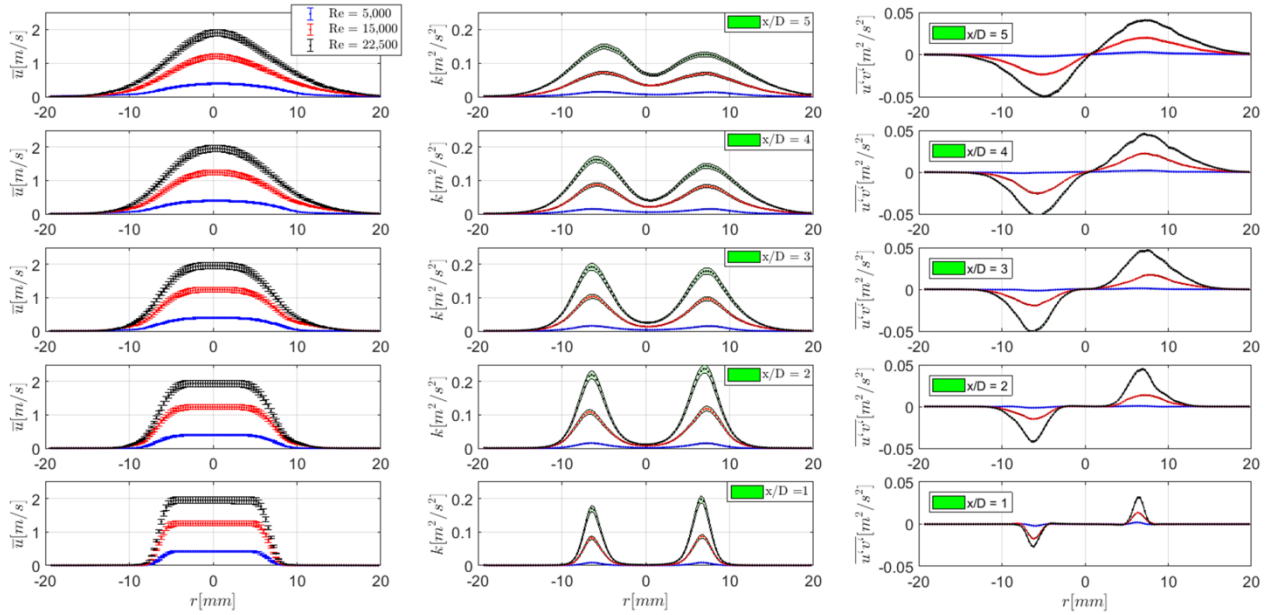


Figure 27. Streamwise mean velocity profiles (left), turbulent kinetic energy (middle) and shear stress (right) at different axial x/D distances for Experiment Case T5k, T15k, and T22k.

Figure 28 shows the normalized streamwise mean velocity, streamwise velocity fluctuations, and the TKE profiles in comparison to experimental results published in the open literature as obtained using hot-wire probes by Quinn and Militzer [22], Xu and Antonia [23], Romano [24], Iqbal and Thomas [25], and Boguslawski and Popiel [26]. Considering the experimental and statistical uncertainties, the streamwise mean velocity profiles of DESTROJER, as well as the axial velocity fluctuations are in remarkable agreements with the results found in the literature, indicating the high fidelity and high repeatability of the measurements performed at the DESTROJER facility.

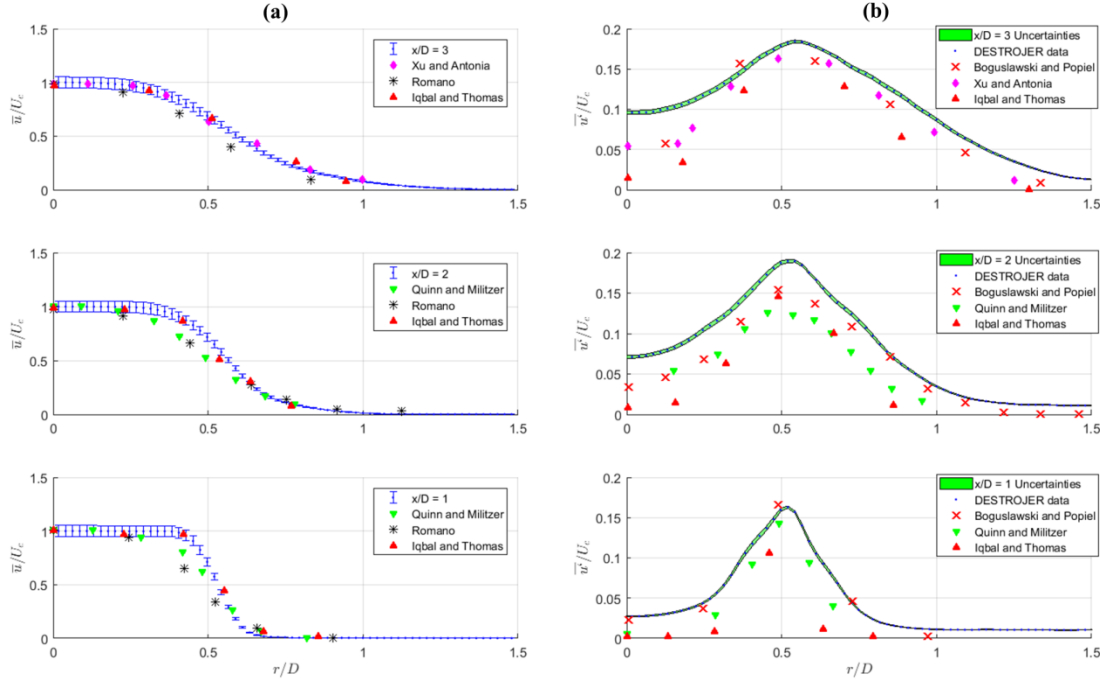


Figure 28. Comparisons with the published literature results of (a) streamwise mean velocity profiles, and (b) axial velocity fluctuations u' at $x/D = 1, 2$, and 3 for Experiment Case T22k. Legend: ▼ Quinn and Militzer [22]; ♦ Xu and Antonia [23]; * Romano [24]; ▲ Iqbal and Thomas [25]; × Boguslawski and Popiel [26].

1.4.3 Self-Similar Statistics

In **Figure 29** the measured decay of the jet centerline mean velocity in the jet self-similar region is reported for Experiment Case T22k, in the region ranging from $25D$ to $50D$ away from the jet. The data are shown as blue squares including uncertainty bars (uncertainty bars are too small to be seen in the plot). Good agreement is obtained when comparing to the published experimental results from Xu and Antonia [23], Wygnanski and Fiedler [27], Panchapakesan and Lumley [28] and Quinn [29]. A linear fit of the experimental results for case T22k gives a jet decay constant of 5.81 , and $x_0/D = 2.43$. **Table IV** presents the comparison for the centerline velocity decay parameters, demonstrating that the results from DESTROJER facility fall into the ranges of the values for jet virtual origin and decay constant observed by Xu and Antonia [23], Wygnanski and Fiedler [27], Panchapakesan and Lumley [28], Quinn [29], and Fellouah et al. [30], Hussein et al. [31]. The streamwise mean velocity normalized by the centerline velocity is plotted with error bars against the non-dimensional coordinates $r/(\frac{x}{D} - \frac{x_0}{D})$ from $25 < x/D < 50$ as shown in **Figure 30**. These normalized velocity profiles form several Gaussian-shape curves and collapse on each other, indicating that the jet flow from 25 jet-diameters away from the jet inlet has already entered the

self-similar region. Using the same non-dimensional coordinates, normal stresses and shear stress are also plotted at those downstream locations in Figure 30. According to Hussein [31], the normalized centerline values for the mean normal stresses $\overline{u'u'}$ and $\overline{v'v'}$ measured by Laser-Doppler Anemometry (LDA) were 0.076 and 0.047, and 0 for the mean shear stress $\overline{u'v'}$, which are close to the results we observe.

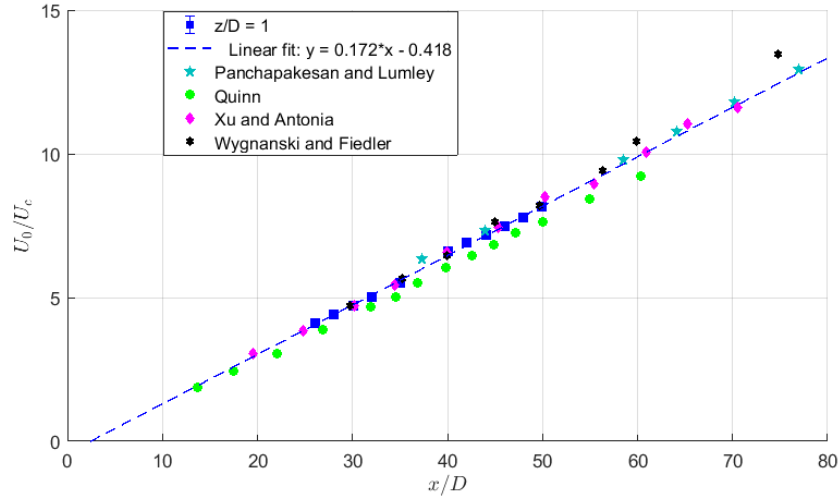


Figure 29. Axial decay of the centerline mean velocity for Experiment Case T22k and the linear fitting curve of DESTROJER data is $y = 0.172x - 0.418$. Experimental results of the previously published literature are plotted in superposition for comparison. Legend: ♦ Xu and Antonia [23]; ★ Wygnanski and Fiedler [27]; ★ Panchapakesan and Lumley [28]; ● Quinn [29].

Table IV. Centerline velocity decay parameters comparison for contraction jets.

Authors	x/D Region	x_0/D	B
Qin with DESTROJER results	25 - 50	2.43	5.81
Xu and Antonia [23]	20 - 75	3.7	5.6
Wygnanski and Fiedler [27]	<50	3	5.7
Panchapakesan and Lumley [28]	30 - 160	0	6.06
Quinn [29]	18 - 55	3.65	6.1
Fellouah et al. [30]	15 - 29	2.5	5.59
Hussein et al. [31]	30 - 120	4	5.8
Mi et al. [32]	0 - 64	3.5	4.48

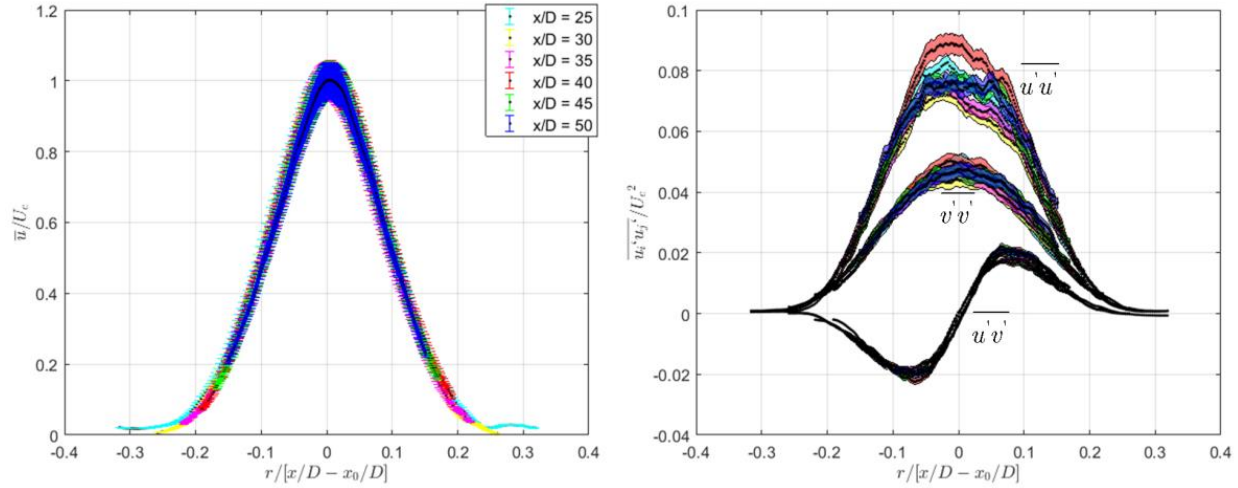


Figure 30. Scaled streamwise mean velocity profiles collapsing of several downstream locations (left) and Reynolds stresses collapsing at the same downstream location (right) of Experiment Case T22k with $Re = 22,500$ in the self-similar region.

1.4.4 Potential Core Length

The potential core extends from the nozzle and is the central portion of the flow in which the velocity remains constant and equal to the jet inlet velocity, formed as a result of turbulent mixing which originates near the jet inlet. The potential core length x_c , defined by $u_c(x_c) = 0.95U_0$ where u_c is the centerline mean axial velocity. **Figure 31** shows the potential core length normalized by the jet diameter (L/D) with respect to the jet inlet velocity for the experiment cases T5k, T10k, T15k, T20k, and T22k, illustrating that the potential core length is decreasing as the jet inlet velocity increases. This is in agreement with the studies conducted by Sivakumar et al. [36]. According to the linear-log plot in **Figure 31**, there is a relationship between the potential core length and the jet Reynolds number.

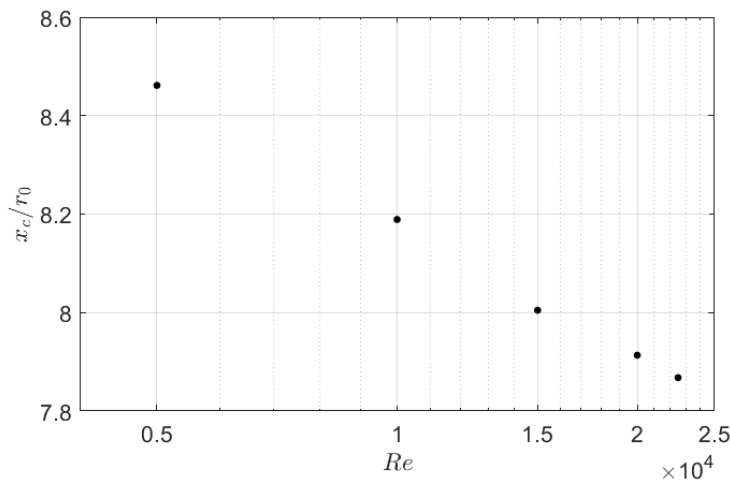


Figure 31. Linear-log plot for normalized potential core length of different Reynolds number cases $Re = 5'000, 10'000, 15'000, 20'000, \text{ and } 22'500$. Power fitting curve: $x_c/r_0 = 12.82Re^{-0.04874}$

1.4.5 Entrainment

Entrainment in a turbulent jet flow describes the engulfment of the ambient fluid surrounded the jet flow. This phenomenon contributes to the conservation of the jet momentum flow rate but leads to an increase in the jet mass flow rate with the increasing distance from the jet nozzle. Eq. 9 is used to generate a linear fit for the mean spread rate of the jet half-radius, $r_{1/2}$, beyond the potential core ($x/D \geq 15$) for each situation.

$$\frac{r_{1/2}}{D} = A \frac{x}{D} - B \quad (9)$$

Figure 32 shows the measurements of growth of $r_{1/2}$, with the jet downstream distance for three different experimental cases T5k, T15k, and T22k in comparison to the results observed by Quinn and Militzer [22], Xu and Antonia [23], Mi et al. [32], and Fellouah and Pollard [34]. Some investigators' published constants (A and B) are shown and compared with the DESTROJER experimental results in **Table V**. The slopes (the constant A) of the fitting curves for the experimental results are close to the constants observed by Panchapakesan and Lumley [28] and Fellouah and Pollard [34] with some discrepancies on the interceptions (the constant B).

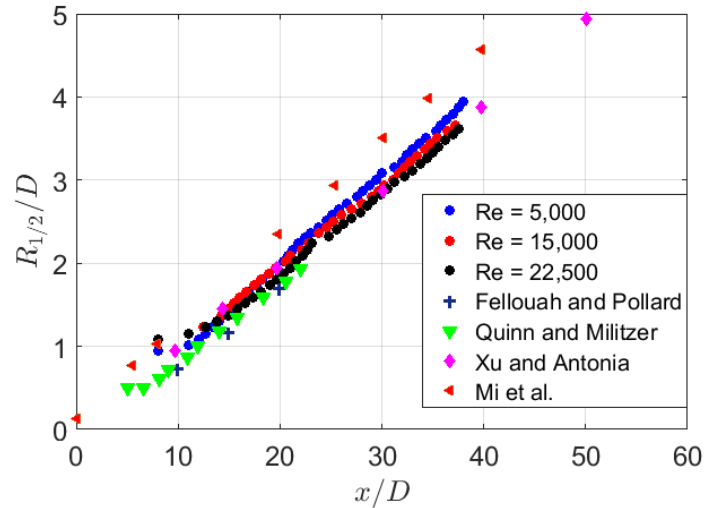


Figure 32. Axial evolution of the jet half-width for different Reynolds numbers. Results of the previously published literature are plotted in superposition for comparison. Legend: ▼ Quinn and Militzer [22]; ♦ Xu and Antonia [23]; ▲ Mi et al. [32]; + Fellouah and Pollard [34].

Table V. Linear fit constants for entrainment study.

Authors	A	B
Experiment T5k (Re = 5,000)	0.106	0.132
Experiment T15k (Re = 15,000)	0.097	0.126
Experiment T22k (Re = 22,500)	0.099	0.124
Panchapakesan and Lumley [28]	0.096	
Fellouah and Pollard [34]	0.097	

1.4.6 Lumley Triangle

The issue of realizability in turbulence is also essential because it illustrates whether the velocity field measurements guarantee positive normal Reynolds stresses and satisfy other appropriate constraints, such as the Schwarz inequality between Reynolds stress components. The anisotropic behavior of turbulence can be visualized by plotting the invariant map of Lumley and Newman [37], also called the Lumley triangle, which uses the second and third principal components of turbulent anisotropy defined as

$$II = a_{ij}a_{ji} / 2 = l_1^2 + l_1l_2 + l_2^2 \quad (10)$$

$$III = a_{ij}a_{jn}a_{ni} / 3 = -l_1l_2(l_1 + l_2) \quad (11)$$

to create the coordinate system $(III, -II)$ as shown in **Figure 33**.

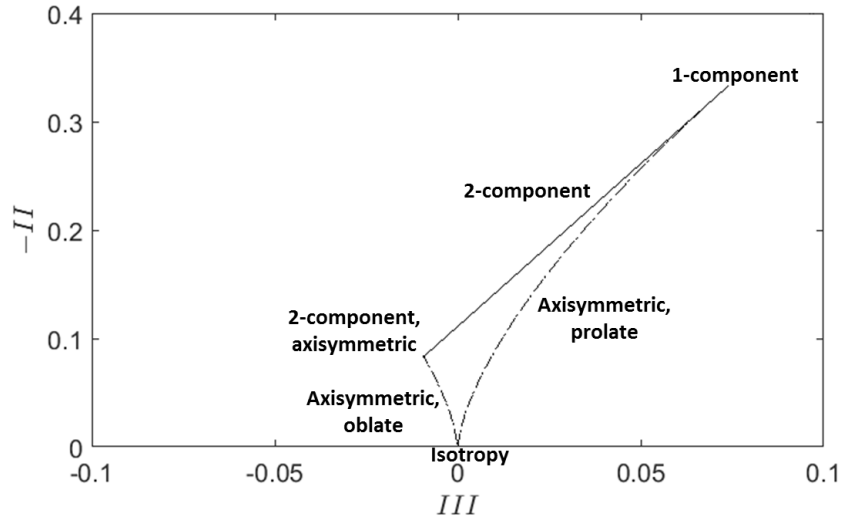


Figure 33. Demonstration of Lumley triangle with the second and third principal components of turbulent anisotropy with characteristic shapes for each boundary locations.

As mentioned, the DESTROJER facility has been tested to ensure that the jet flow is axisymmetric in the radial and spanwise directions, and 2D PIV measurements were conducted for the data mention in this report. Therefore, when calculating the anisotropic tensor, azimuthal symmetry is assumed.

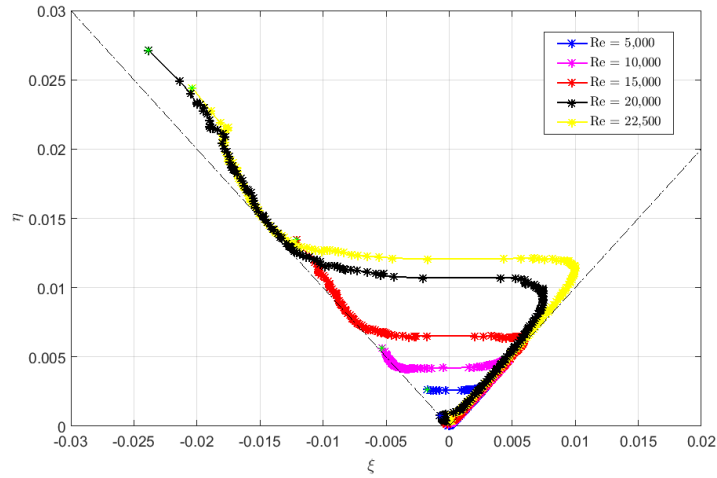


Figure 34. Lumley triangle plot for different Reynolds number cases from 5'000 to 22'500 in the near-field regions ($1 < x/D < 5$).

Figure 34 shows the measurements of the near-field flow region ($1 < x/D < 5$) in the Lumley triangle plot for Reynolds numbers ranging from 5'000 to 22'500. Similar behavior is obtained for all cases, with turbulence state decaying from a 3D axisymmetric pattern (left side of Lumley's triangle) to isotropic turbulence (origin of the Lumley's triangle). According to **Figure 34**, this illustrates that the jet turbulence begins as an axisymmetric oblate shape and then transforms into an axisymmetric prolate case as flow travels downstream until it reaches isotropy.

1.4.7 Spectral Dynamics

The Power Spectral Density (PSD) was computed at several downstream locations along the jet center line. The spectra of the near field results are shown in **Figure 35**, normalized by the Kolmogorov length- and velocity scale.

The length scale is defined as:

$$\eta_K = \left(\frac{\nu^3 D}{\bar{u}} \right)^{1/4}. \quad (12)$$

The Kolmogorov velocity scale is defined as:

$$u_K = \left(\frac{\nu \bar{u}^3}{D} \right)^{1/4}. \quad (13)$$

Here $\bar{u}$ is the stream wise component of the mean velocity at the location where the PSD is computed, ν is the kinematic viscosity and D is the hydraulic diameter. Figure 35 shows the resulting spectra for different downstream distances along the centerline of the jet (left) and for different radial locations across the jet at $x/D=2$ (right). Within the potential core of the jet ($1 < x/D < 3$), we observe a departure from the $-5/3$ slope of the energy cascade, that is associated with the range of frequencies in which the energy cascade is dominated by inertial transfer, while the -7 slope characterizes the dissipative range where viscous forces dominate. The spatial development of the spectra clearly indicates that the near field is dominated by shear-layer vortex roll-up that eventually evolves to a broad frequency distribution.

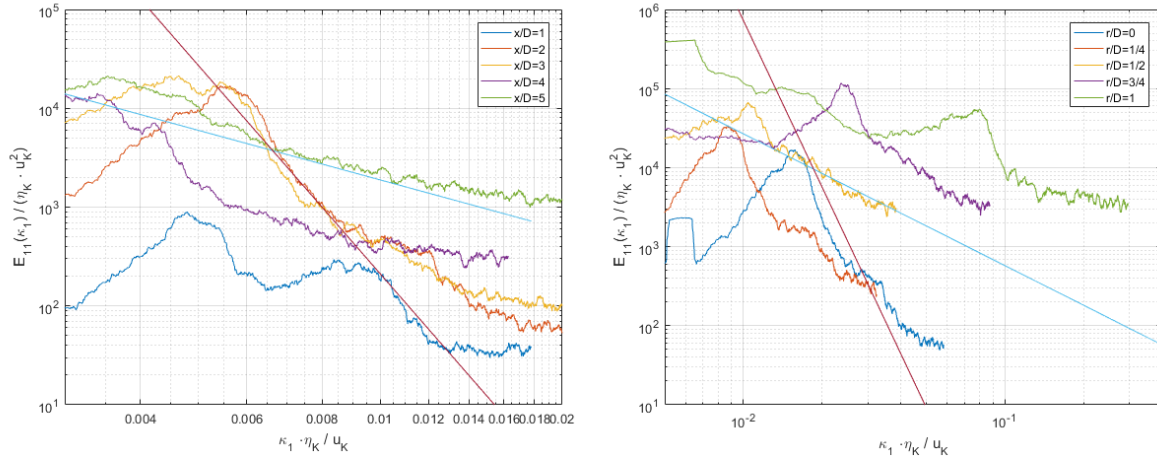


Figure 35. Power spectral density (PSD) for experiment T15k. Left: at the jet center line for different downstream distances x/D . Right: at $x/D=2$ for different radial distances r/D . The light blue straight line represents the $\kappa^{-5/3}$ slope of the inertial sub range, the red straight line represents the dissipative range with κ^{-7} .

At $x/D = 3$, the velocity spectra evolve to display a turbulence cascade with one peak remaining at a Strouhal number $St = 0.512$, which was close to $St=0.485$ found by Jung et al.[33] ($x/D = 4$ and $Re = 117\,600$) and $St = 0.4$ found by Mi et al. [12] ($x/D = 3$ and $Re = 16\,000$) and $St = 0.479$ found by Fellouah and Pollard in 2009 [34] ($x/D = 3$ and $Re = 30\,000$). At these positions, the formation of coherent structures is apparent with the increased energy content at these peak frequencies. The vortex roll-up frequency remains consistent along r/D until the center of the shear layer. With increased distance from the core, deceleration due to friction with fluid in rest occurs to shift the rollup frequency towards the right in the spectra (shown in Fig. 5(right) for $r/D=3/4$ & 1).

Coherent structures of the flow in the near field region are obtained by spatial correlations of variance and covariance of velocities to identify structures that give insight into the momentum transports at large scales. The understanding of coherent motion defined by Robinson [35] is adapted: “a coherent motion is defined as a three-dimensional region of the flow over which at least one fundamental flow variable (velocity components, density, temperature, etc.) exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest local scales of the flow.” Here the focus lies on two-point autocorrelations of normal stresses and the shear stress. The correlation is defined by:

$$R_{f',f'} = \frac{\overline{f'_x f'_0}}{(\overline{f'_x f'_x} \cdot \overline{f'_0 f'_0})^{1/2}}. \quad (14)$$

Subscripts in Eq. 14 indicate the variance of the reference point (denoted “0”) and in the whole flow field (denoted “x”). The variances itself are defined for the streamwise component as:

$$f' \equiv u'u' - \overline{u'u'}. \quad (15)$$

Similar equations apply for the radial- and the shear stress component. **Figure 36** shows the resulting structures for reference points at the same locations where the spectral analysis in Figure 35 (left) was performed. On the left column of **Figure 36**, the spatial autocorrelation of $R_{u'u'}$ is shown for various downstream distances in the near field of the jet. Within the potential core of the flow ($1 < x/D < 3$) we observe a paired structure that spans radially across the jet. The secondary structure reflects the potential core confined by the vortex ring which evolves due to shear on the

boundaries of the jet. At a location of $x/D=2$, we observe two secondary maxima in stream wise direction. They indicate how alternating vortex ring pairs are formed around the core. It is at this location, where, on the outer boundary of the shear layer, the stream wise fluctuations show coherence to the core structure exactly half a period behind, due to entraining fluid. Further downstream at $x/D=4$, the core of the vortex ring collapses as shown by a more and more circular structure, which is no more correlated to the outer region of the jet.

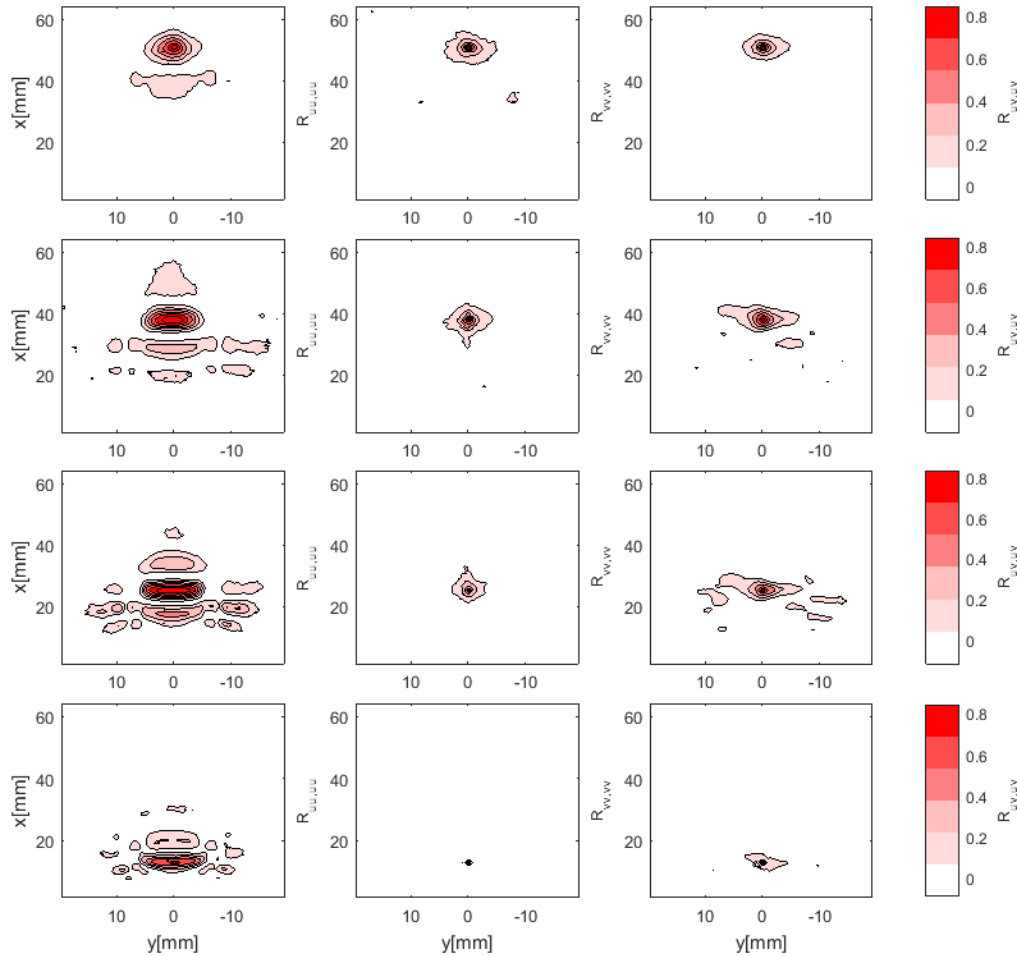


Figure 36. Two point autocorrelations of variances of velocities for experiment T15k. The reference points are along the jet centerline for various downstream distances (bottom to top row: $x/D=1, 2, 3$ & 4) Left column: $R_{u'u',u'u'}$. Middle column: $R_{v'v',v'v'}$. Right column: $R_{u'v',u'v'}$.

The correlation depth of the cross stream spatial autocorrelation at $x/D=1$ is found to be extremely small within 1 mm. At this point, the flow is extremely anisotropic, and momentum fluctuations are strongly stream-wise oriented within the potential core. This dynamic is also reflected by the coherent field of shear (right column). While internal cross stream friction develops with the development of vortex rings, also shear within the core occurs. Beyond the tip of the core downstream, local shear, and both fluctuating components of velocity span an almost circular penetration depth that defines the starting point of the intermediate field of the jet. It is this ‘lack’ of friction within the core that leads to a dissipative transport of eddy scales within the energy spectrum, and as friction develops, small neighboring structures begin to interact, merge and form

larger structures, which in turn change the distribution of scales in the spectrum. This can be observed in **Figure 35** (left) where the slope of the spectrum departs from -7 (illustrated by the straight red line) across the boundaries of the potential core towards the -5/3 slope (illustrated by the straight blue line).

Figure 37 shows two point autocorrelations of variances of velocities for experiment T15k. The reference points are at $x/D=2$ for various radial distances (bottom to top row: $r/D=0, 1/4, 1/2$ & $3/4$). The left column shows the streamwise variance autocorrelation $R_{u'u',u'u'}$, the middle column shows the cross stream variance autocorrelation $R_{v'v',v'v'}$ and the right column shows the shear stress autocorrelation $R_{u'v',u'v'}$. We observe a symmetric correlation of both sides of the jet. While the correlation depth of the core and the inner side of the shear layer at $r/D=1/4$ shows similar structures as the jet centerline (at $r/D=0$) for streamwise autocorrelations, the cross stream structure spans considerably deeper into the shear region, which leads to more internal friction and thus larger structures to form. The situation aggravates in the core of the shear layer at $r/D=1/2$, where the cross stream structure dominates the streamwise in size. This inflection is evident in the spectrum of **Figure 35** (right). Here the spectrum already slopes at -5/3. Focussing on the correlation at the outer region of the jet shear layer ($r/D=3/4$), large structures dominate, and at this point are fully infused by viscous effects. At $r/D=1/2$ the shear stress correlation field reflects the complex structure of three vortex rings, by paired co- and anticorrelated regions that are alternating antisymmetric across the layer.

Figure 38 shows the spectral analysis for various streamwise distances at the centerline (left) and various radial distances at $x/D=16$ (right) in the mixing transition of the jet. The analysis of the potential core revealed a viscous transfer of scales within the energy spectra beyond the core. **Figure 38** supports this theory. We also observe decay in large-scale structures towards the outer limits of the jet (visible in the primary peaks of the spectra). While the transport of scales follows a -5/3 slope towards the whole intermediate field, the change in penetration depth of coherent structures shows a minimum. **Figure 39** shows this phenomenon where two-point autocorrelations of variances of velocities for experiment T15k are given. The reference points are at $r/D=0$ for various downstream distances (bottom to top row: $x/D=10, 14, 18$ & 22). The left column shows the streamwise variance autocorrelation $R_{u'u',u'u'}$, the middle column shows the cross stream variance autocorrelation $R_{v'v',v'v'}$ and the right column shows the shear stress autocorrelation $R_{u'v',u'v'}$. At $x/D=14$ all three autocorrelations show a minimum in penetration depth, which increases further downstream, concluding that the mixing transition ends with this minimum since all structures keep growing further within the self-similar region. With focus on the inflection at $x/D=14$, **Figure 40** shows two-point autocorrelations for various radial distances (bottom to top row: $r/D=0, 1, 2$ & 3). From the core of the jet towards radially away from the core, we observe a vertically elongated streamwise structure that is growing in size, in conjunction with a spanwise elongated structure of radial variances, while shear covariant structures remain symmetric and circular.

The phenomenology is illustrated in **Figure 41**. It appears that the initially formed vortex ring pairs, which surround, and thus limit the potential core of the jet in the near field, roll up and merge further downstream. The transported friction within the vortices towards the potential core of the jet, affect the rate at which energy is transported across different scales from a dissipative to a viscous behavior. Once the structural extent of the vortex pairs (illustrated in red and blue) overcome the ‘singularity’ of the core – here the potential core – a disc-like momentum structure evolves. This coherent momentum structure collapses towards an energetically more favorable symmetry, a sphere; where we detected the minimum extent of penetration depth across the core

(shown in Figure 39). The shear field structure within the core of the collapsing vortex ring pair structures is found to be symmetric, which confirms that the detected disc structure shears towards the centerline to form a sphere.

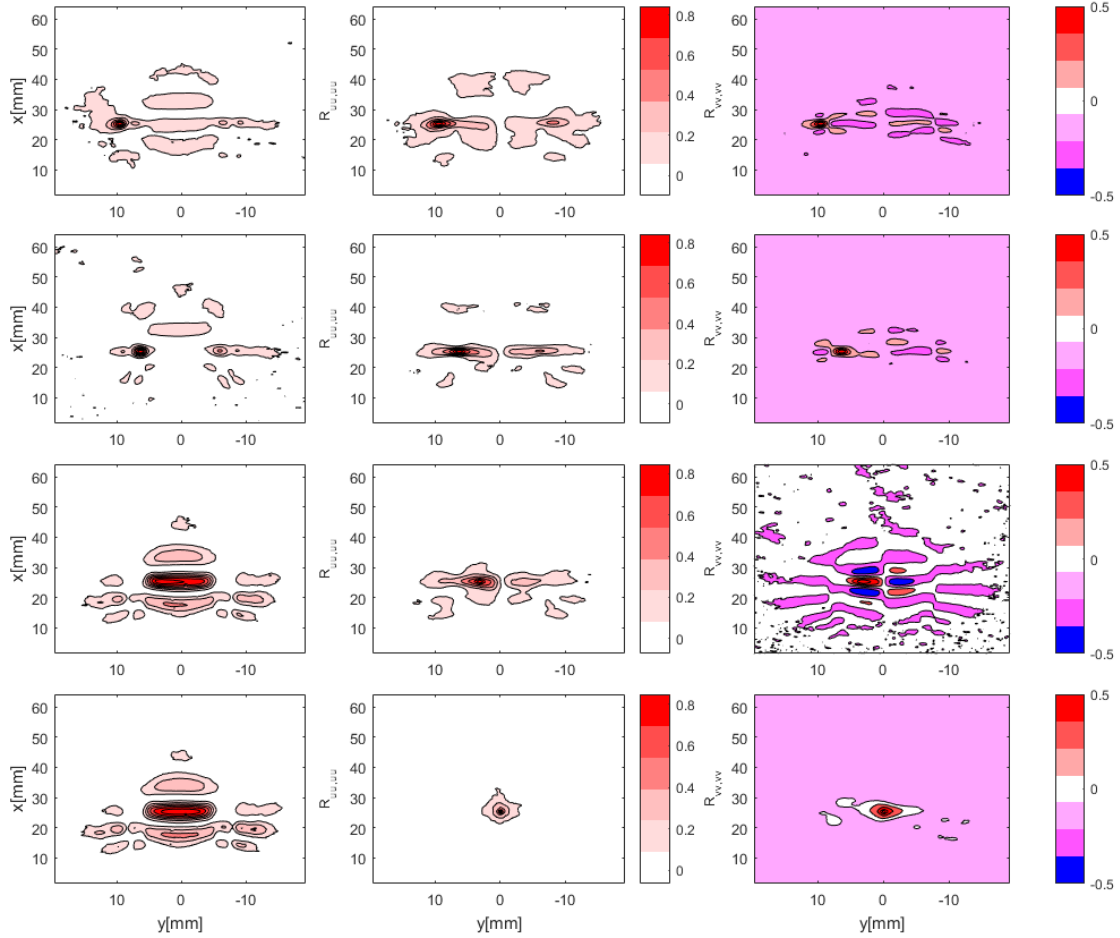


Figure 37. Two point autocorrelations of variances of velocities for experiment T15k. The reference points are at $x/D=2$ for various radial distances (bottom to top row: $r/D=0, 1/4, 1/2$ & $3/4$) Left column: $Ru'u',u'u'$. Middle column: $Rv'v',v'v'$. Right column: $Ru'v',u'v'$.

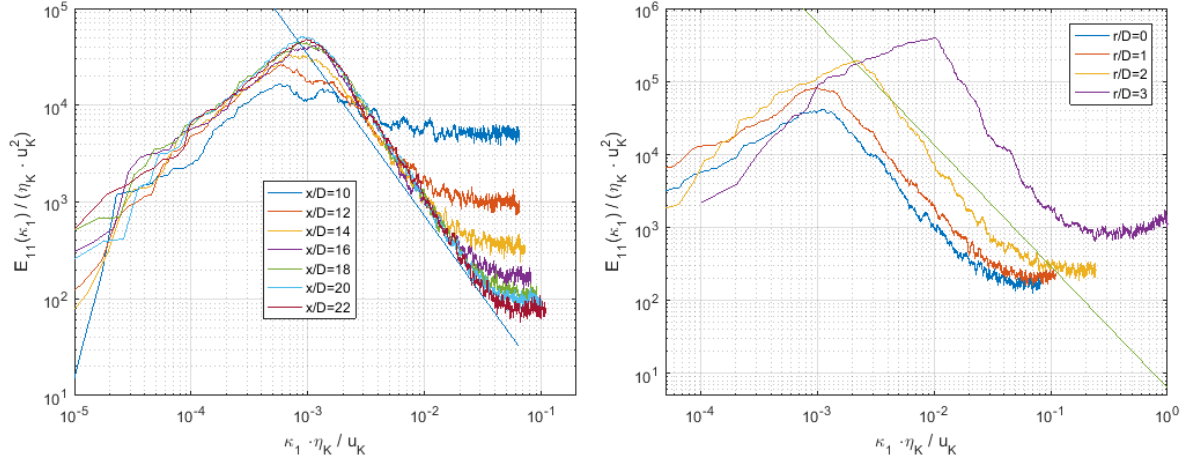


Figure 38. Power spectral density (PSD) for experiment T15k. Left: at the jet centerline for different downstream distances x/D . Right: at $x/D=16$ for different radial distances r/D . The light blue straight line represents the $\kappa^{-5/3}$ slope of the inertial subrange.

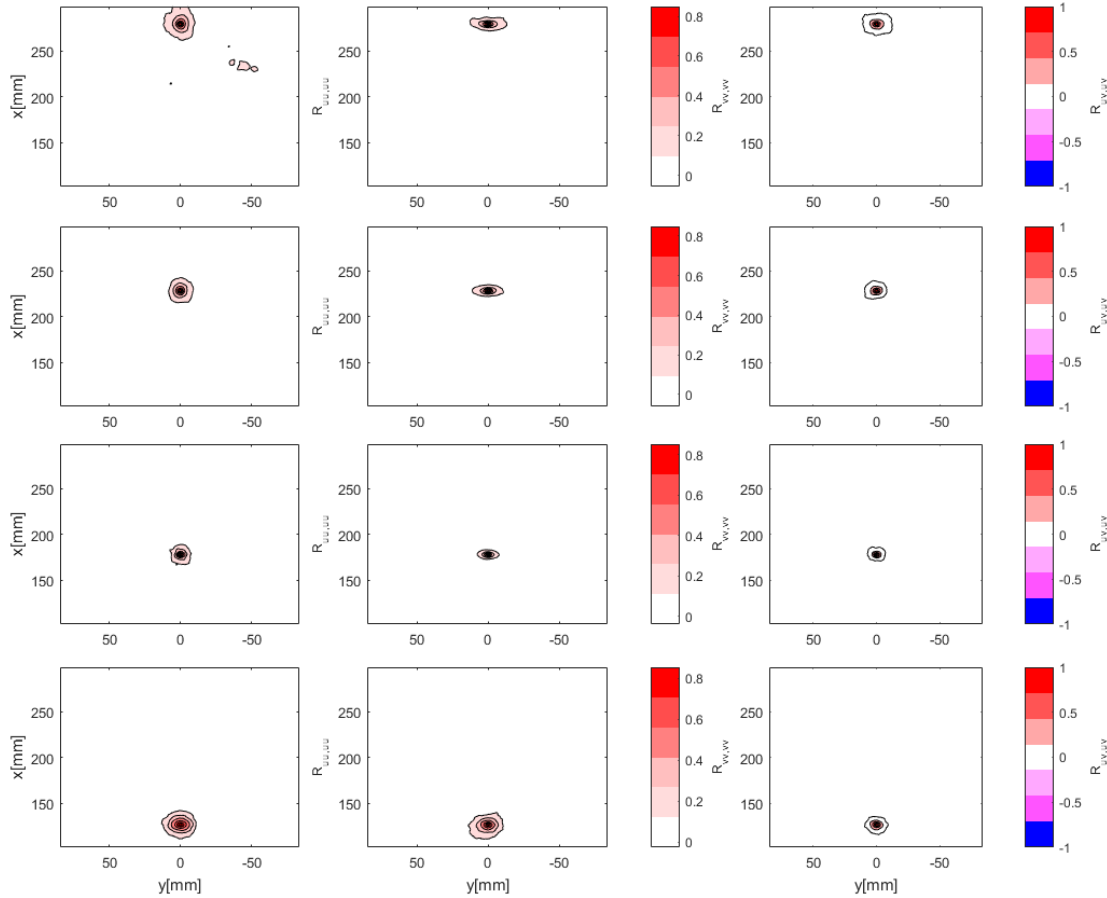


Figure 39. Two point autocorrelations of variances of velocities for experiment T15k. The reference points are along the jet centerline for various downstream distances (bottom to top row: $x/D=10, 14, 18$ & 22) Left column: $R_{u'u',u'u'}$. Middle column: $R_{v'v',v'v'}$. Right column: $R_{u'v',u'v'}$.

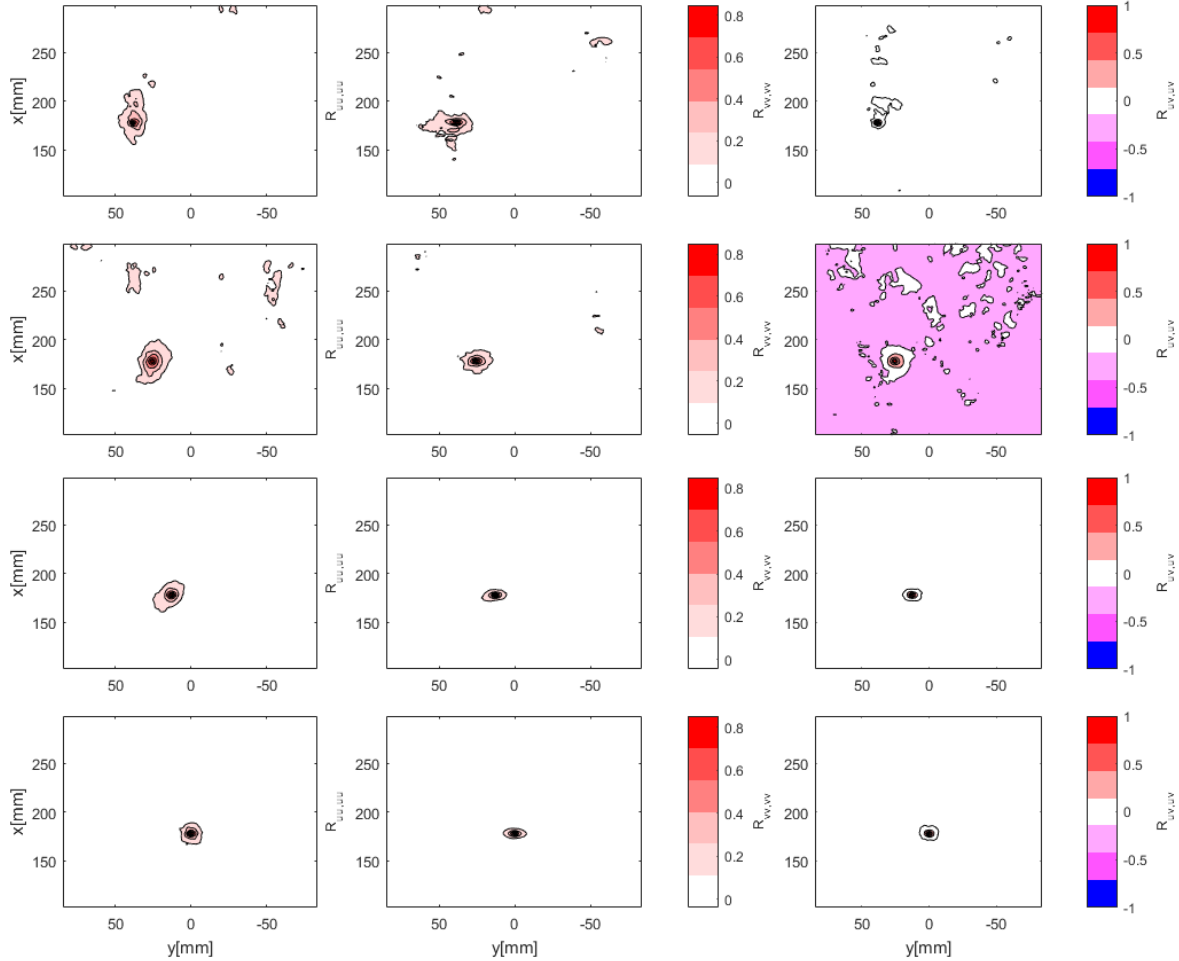


Figure 40. Two point autocorrelations of variances of velocities for experiment T15k. The reference points are at $x/D=14$ for various radial distances (bottom to top row: $r/D=0, 1, 2$ & 3) Left column: $Ru'u', u'u'$. Middle column: $Rv'v', v'v'$. Right column: $Ru'v', u'v'$.

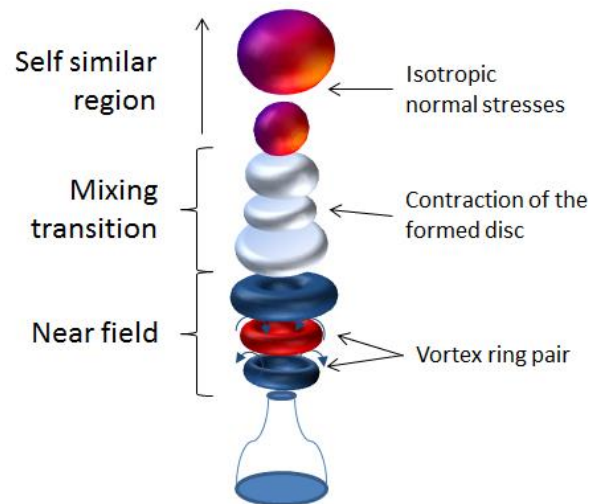


Figure 41. Illustration of the dynamics towards the transition region of a turbulent round free jet at an outer scale Reynolds number of $Re=15\,000$.

2 REFRACTIVE INDEX MATCHING (RIM)STUDY

In order to perform PIV measurements of fluids with different density, it is necessary to first ensure that the two fluids have the same refractive index. To perform the refractive index matching (RIM) experiment, a database is utilized to obtain the properties of aqueous solutions of 66 chemicals as a function of concentration at 20 °C [38].

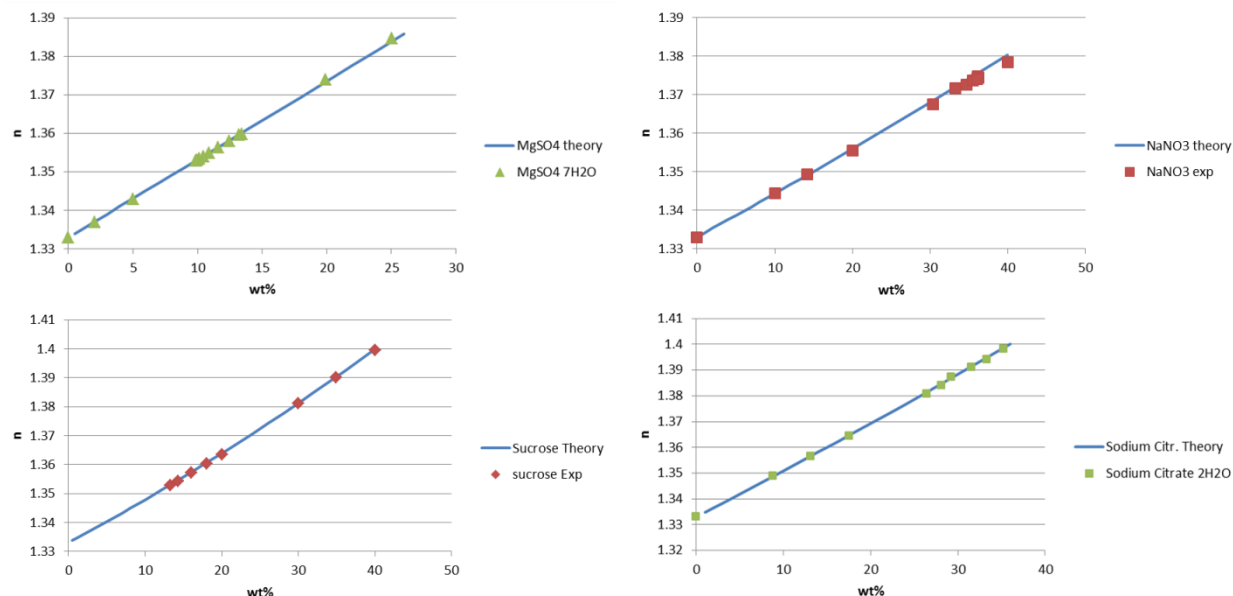


Figure 42. Verification of the refractive index vs. concentration for four potential chemicals in the database.

Figure 42 shows the plots of the refractive index with the weight percentage for the four potential candidates identified to perform RIM at 20.8 °C. All of the experimental data points show good consistencies with the theoretical curves, indicating the experiments we performed were valid. Therefore, by linearly fitting the curves, the data points measured can be used as our database to accommodate for the environment properties variations in the lab, for example, the room temperature fluctuations and pressure changes.

2.1 Stratified Experiments in a Scaled Replica

As mentioned previously, due to the cost of the chemicals and potentially hazardous waste, a scaled replica ($11 \times 11 \times 11 \text{ cm}^3$) of the original DESTROJER facility was designed and manufactured as reported in **Figure 43**. The jet inlet diameter is scaled to 1.1 mm. This small scale facility has been used to test and verify the achievement of refractive-index matching, before performing experiments on larger setups.

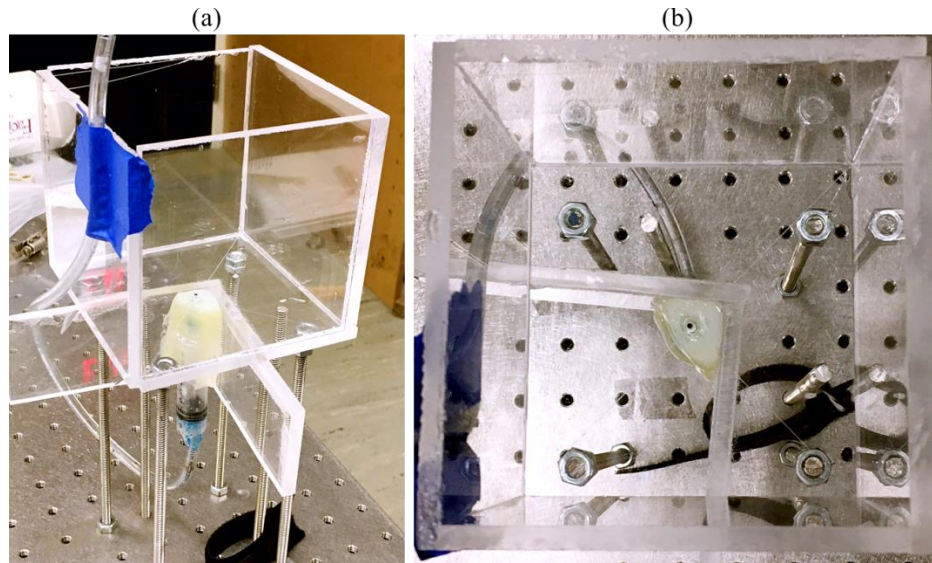


Figure 43. A scaled replica ($11 \times 11 \times 11 \text{ cm}^3$) of the square tank (a) leveled on the optics table, and (b) its top view with the scaled jet nozzle on the bottom.

The jet is powered by a syringe pump which provides a maximum inlet jet velocity of 0.5 m/s, corresponding to a Reynolds number of 547. Even though this is classified as a laminar flow, the PIV raw particle images can still be used to judge whether RIM can be achieved for the stratified environment tests.

Sodium chloride (NaCl) and isopropanol solutions are used to create the stratified layer in the tank, with both fluids having a refractive index of 1.3424 at 20.5 °C. After seeding the solutions with fluorescent glass hollow particles and forming the stratified layer in the small replica tank, PIV images are recorded. In **Figure 44** raw particle images are presented. In particular, in **Figure 44(a)** a raw image obtained for the case in which the refractive index of NaCl solution located at the bottom matches the refractive index of the isopropanol solution located at the top. In **Figure 44(b)**, instead, a raw image is presented which has been obtained in absence of refractive index matching, with a NaCl solution at the bottom of the tank and deionized water at the top. The red line indicates the separation of the stratified layers due to the density differences. For the well-matched refractive index case (a), the raw PIV images exhibit particles with sharp contrast and pixel occupations similar to images obtained in case of uniform environments. For the case where the refractive index is not matched (b) the light scattered by the seeding particles gets bent due to the refractive index mismatch, resulting in blurred PIV images.

Matching of refractive index is crucial for valid PIV measurements. **Figure 45** shows the raw and processed images when the jet with the same NaCl solution as present in the bottom part of the tank is impacting the stratified layers. In case RIM is achieved, as in **Figure 45(a)**, good contrast for particles and background is obtained, resulting in a continuous velocity field. When no RIM is achieved, as for the case in **Figure 45(b)**, blurred regions are observed due to the mismatched refractive index, leading to many empty spaces in the computed velocity vector field, and inaccurate velocity magnitude.

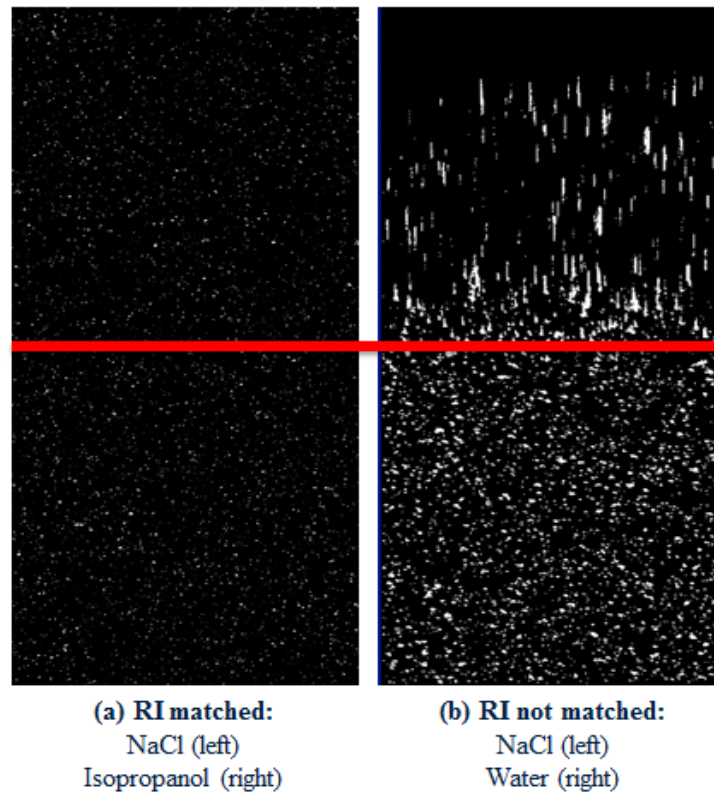


Figure 44. Stratified layers with (a) matched refractive index at 1.3424 for NaCl and isopropanol solutions and (b) unmatched refractive index for NaCl solution and pure water.

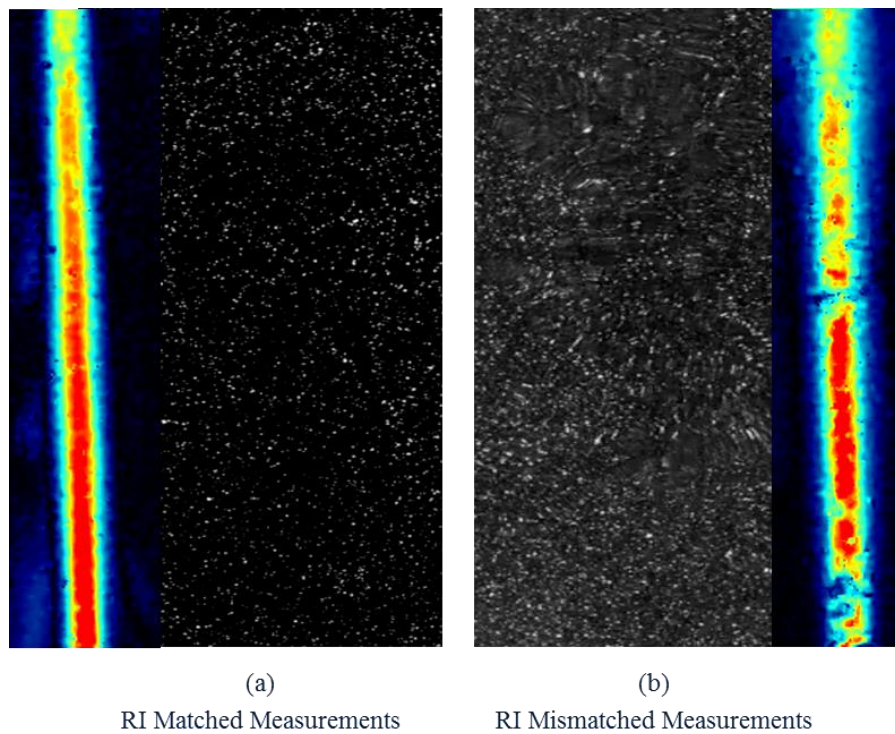


Figure 45. PIV measurements of (a) matched refractive case and (b) unmatched refractive index case. The processed instantaneous velocity fields are shown for the corresponding raw images.

2.2 Establishing RIM for High-Density Ratios

We chose to use a combination of two aqueous solutions, in particular, a mixture of H₂O, 1-Isopropyl alcohol (CH₃CHOHCH₃) and Glycerol (H₂O-CH₂OHCHOHCH₂OH). All three liquids are fully miscible among each other and exhibit a large density difference. Generally, the partial molar property of a component in a real mixture differs from that of an ideal mixture, due to molecular interactions between the component molecules and the resulting mean free path (or average molecular radii) of the mixtures [39]. This deviation is called the excess property and is defined about those of pure substances [40, 41]. As we deal with a system of three components and the excess RI n^E is then defined as:

$$n^E = n_D - \sum_{i=1}^3 x_i \cdot n_{D,i} \quad (16)$$

where n_D is the refractive index of the real mixture, x_i and $n_{D,i}$ are the mass fraction and the refractive index of the pure component i respectively. A similar definition applies for the excess density ρ^E (or excess specific volume). Measurements of the refractive index and the density have been performed at 298.15 K and atmospheric pressure over the whole composition diagram. For measuring the RI, a Sper Scientific 300037 Digital Refractometer with a range of $1.3330 < n_D < 1.5318$ and an accuracy of 0.1% at a resolution of 0.0001 was used. The density was measured using a 50 ml volumetric flask, class A in combination with a Zieis Z136EZ Precision digital scale, that has an accuracy of 0.5g, which translates to an uncertainty of ~1% in density measurements.

2.3 RIM Results and Discussion

Figure 46 shows the resulting excess properties relative to their ideal behavior (left: relative excess density, right: relative excess refractive index). The fundamental principle was to relate optical distortion to the specific excess volume within a mixture. This assumption may hold for weak polar molecules, as they are of interest in the petrol chemistry, but for our purpose, this relation is no longer applicable. Considering light to be of electro-magnetic nature, the interaction of molecules with a strong differing dipole moment, like water and 1-isopropyl alcohol, leads to more complex structural properties when mixed, shown in **Figure 46**.

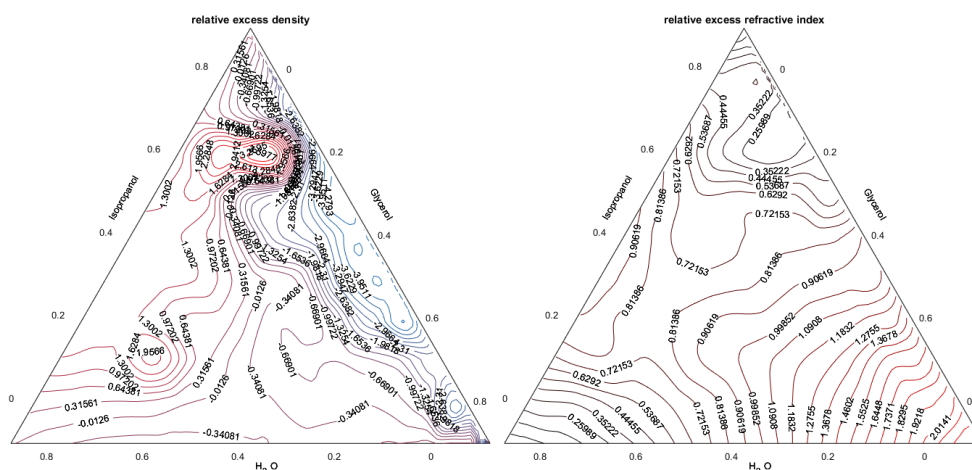


Figure 46. For the ternary system H₂O - Glycerol - Isopropyl alcohol left: contours of constant relative excess density, right: contours of the constant relative excess refractive index.

Figure 47 shows contours of constant RI in superposition to the density of the ternary system. The color code for the density is chosen to be white at the density corresponding to pure water; blue represents lower density and red higher density. The chosen combination of two liquids with matching RI towards the intermixed region of two liquids is illustrated by the yellow line. Mixing in ternary plots is represented by a linear connection between the two points in the diagram. To measure flow dynamics towards the mixing region, it is, therefore, crucial to detect a region in which the RI is not changing along the connecting line. The green line in figure 4 represents a combination of two aqueous solutions with identical refractive index (here $n_D=1.3762$). Theoretically, the possible density difference would be even larger ($\sim 22.6\%$), but when both liquids begin to intermix, the refractive index changes and light scattered by seeding particles get deflected while traveling towards the camera and consequently the measurements will be biased. The mass fractions of the chosen combination of liquids (yellow line in **Figure 47**) together with their density at an RI of $n_D=1.3708$ are given in **Table VI**. With this combination, it is possible to realize a density difference of 8.6% while keeping the RI constant towards the mixing range. The kinematic viscosity of both ternary solutions was measured by a Cannon-Fenske Routine Viscometer and found to be 4.187cP for solution (I) and 4.464cP for solution (II).

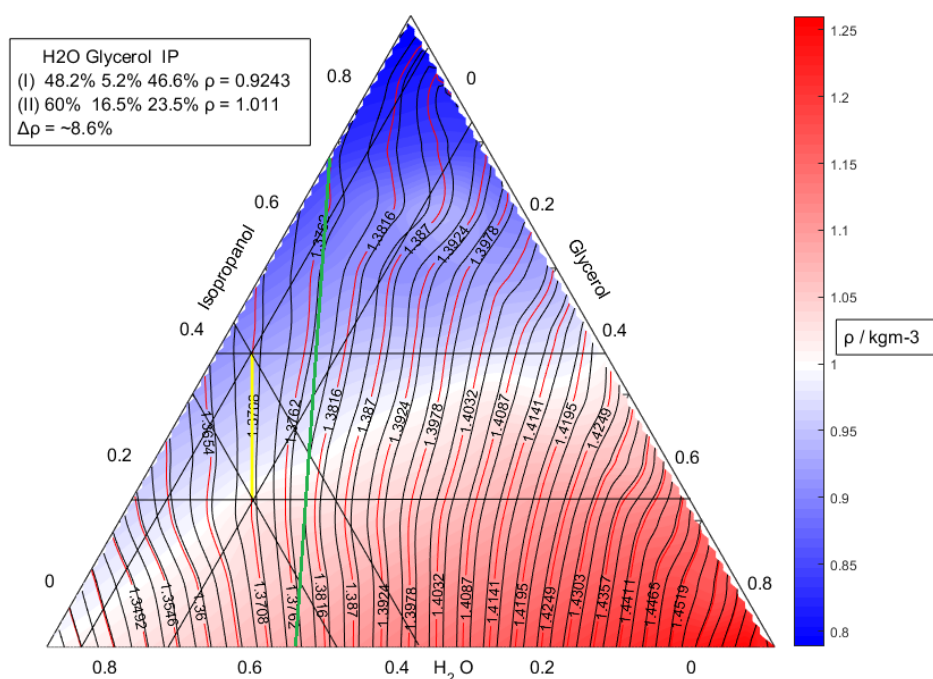


Figure 47. Contours of the constant refractive index in a superposition of the density (colormap) for the ternary system H₂O - Glycerol – Isopropyl alcohol.

Table VI. Nominal Parameters of the two liquids with 8.6% density difference

Mixture.	H ₂ O	Glycerol	Isopropanol	ρ g/cm ³
(I)	0.482	0.052	0.466	0.9243
(II)	0.600	0.165	0.235	1.0110

2.3.1 Proof of principle

To verify the proposed chemicals combinations, the scaled replica tank is equipped with a high speed PIV system that comprises a Phantom Miro LAB 340 camera with 2560×1600 pixels, a pixel size of $10 \times 10 \mu\text{m}^2$, 12 bit digital output and a maximum recording frequency of 800Hz at full scale, as well as a high speed double pulsed Nd:YLF Laser with a maximum recording frequency of 10kHz at a wavelength of 527nm and 70mJ energy/pulse. A Kenko Tokina AT-X M100 PRO D macro lens in combination with two Nikon TC-201 Teleconverters is used to perform high spatially resolved recordings in the vertical mid-plane of the jet. The syringe is driven by an electric engine to inject liquid at a constant flow rate of 25ml/min into the tank. The walls of the tank are made of acrylic glass to gain optical access in the entire jet domain. Only qualitative measurements without spatial calibration were performed. The tank was filled with the heavier liquid (II), and the lighter liquid was injected into the syringe. The flow field was qualitatively measured with PIV in the vertical mid-plane of the jet. Overall three experiments have been conducted:

- A reference case with pure water injecting into pure water
- A stratified case with the lighter liquid being injected to the heavier at 8.6% density difference with RIM
- A stratified case without RIM and a density difference of 7.3% (here the lighter liquid (I) was injected into the tank filled with pure water

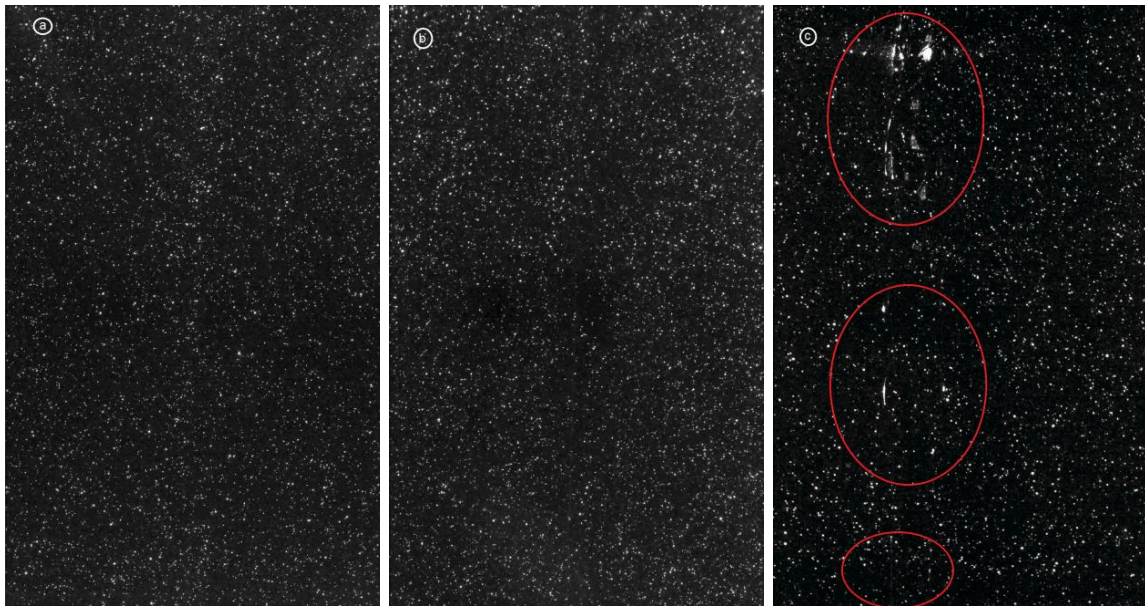


Figure 48. Raw PIV images for the three test cases. (a) reference experiment with pure water, (b) Index matched with a density ratio of 8.6% (c) not index matched with density difference of 7.3%

Figure 48 shows raw images from PIV recordings for the three cases. The jet injects from the bottom and progresses to the top. In image (c) of **Figure 48** particle images are deflected by the mixing interface (marked by red circles), especially in the upper part of the image where mixing is more pronounced. The situation exacerbates after a stratified layer built up in the upper part of the facility, shown in **Figure 49**. This effect is not visible in image (b) of **Figure 48** where the RI

is matched and neither in the reference experiment (a), where identical substances are present. The light traveling towards the mixing region of the vertically established density stratification without RIM is heavily deflected.

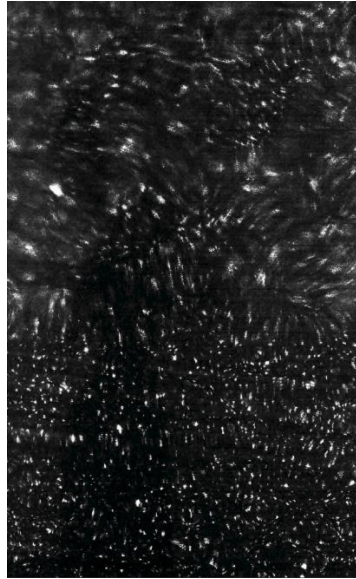


Figure 49. Raw PIV image of the stratified layer without RIM.

2.3.2 Primary test with 8.6% density ratio

Figure 50 shows the stream-wise mean velocity of the reference experiment (left) and the index matched experiment with 8.6% density ratio (right), with the jet coming from bottom to top.

While the centerline shows a significantly stronger decay rate for the density stratified case, the spreading rate with increasing downstream distance is considerably more pronounced. Due to the higher kinematic viscosity, the outer scale Reynolds number is about four times lower in the stratified case, and viscous forces within the liquid are overcome the inertia of the jet more pronounced than in the reference case. This viscous effect dominates the buoyancy effect of an accelerated flow behavior; unlike it would have been expected. However, when comparing the turbulence level, this effect is only apparent at the beginning of the jet close to the nozzle which is visible in **Figure 51**. Here the streamwise velocity fluctuations of the reference experiment (left) and the density stratified case (right) are shown. A strong decay of turbulence is observed, that is likely to be originated by suppression of turbulent transport across the density gradient since entrainment is far more pronounced in the stratified case.

In this light, we present a method to create a combination of two aqueous solutions with a large density difference and identical refractive indices, suitable to be used in turbulence research with optical measurement techniques applied. The method is based on the change of excess properties when three components are intermixing. We successfully achieved a density difference of 8.6% by using the ternary system H₂O – Isopropanol – Glycerol. To our knowledge, this has not been reported in the scientific literature yet. The principle has been proven by a qualitative test with a small scale turbulent free jet facility, equipped with high temporally and spatially resolved PIV. Although only qualitative measurements were performed, we observe a significant influence of density gradients on turbulence dynamics. While the mean velocity field seems to be affected

mostly by viscous effects, we observe a strong suppression of velocity fluctuations with evolving downstream distance that is likely originated by a dampened momentum transport across the density gradient.

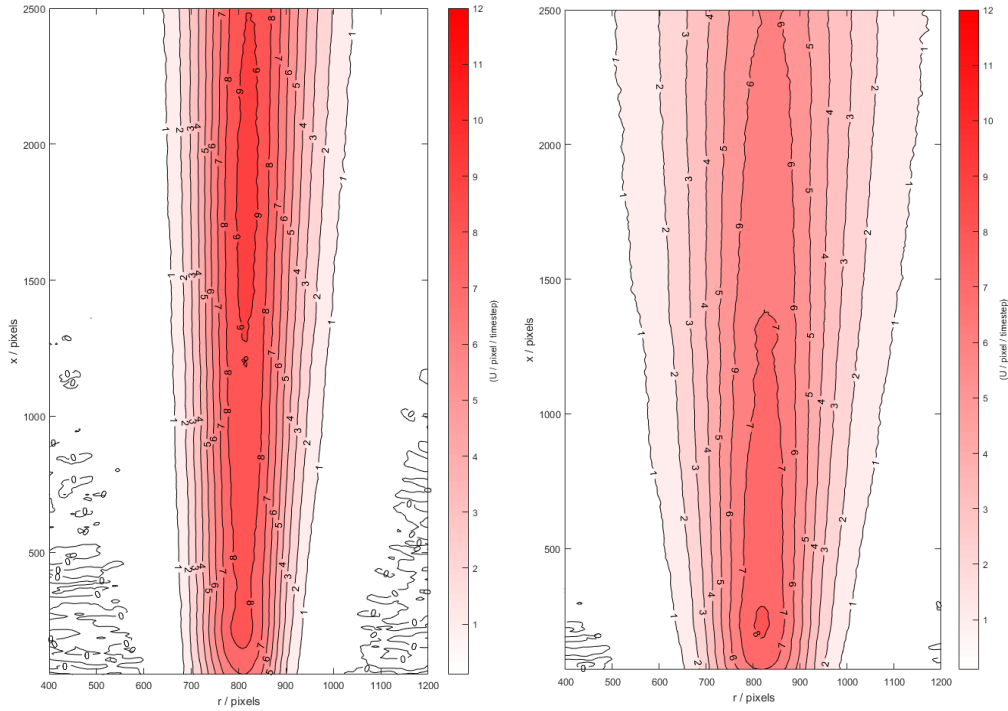


Figure 50. Streamwise mean velocity field (left), reference experiment with pure water (right). Index matched with a density ratio of 8.6%.

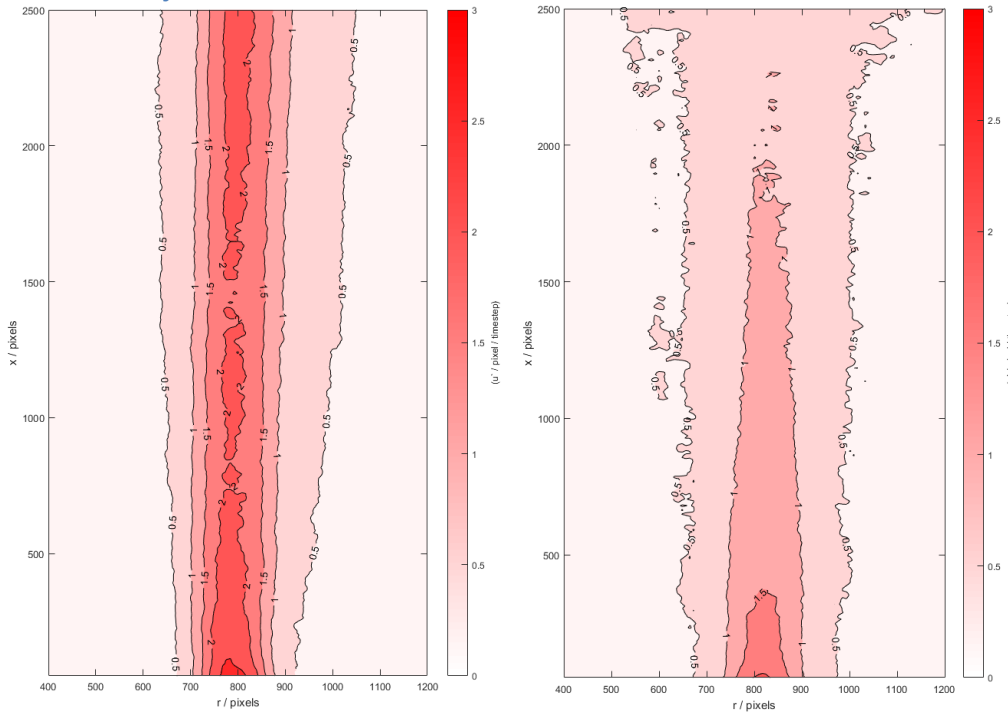
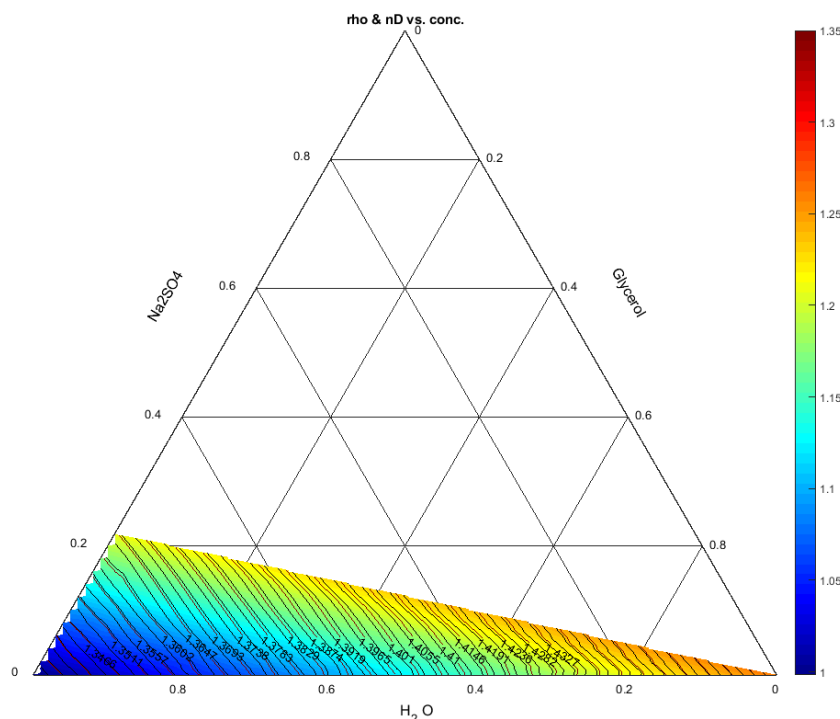


Figure 51. Turbulence kinetic energy (left), reference experiment with pure water (right). Index matched with a density ratio of 8.6%.

2.3.3 RIM study for water- Na_2SO_4 -glycerol solutions

Utilizing the ternary plot techniques, we conducted the refractive index matching study for solutions with water, sodium sulfate (Na_2SO_4) and glycerol shown in **Figure 52**. The reason that the plot is not fully extended to the whole region is due to the solubility of Na_2SO_4 in water. Theoretically, the possible density difference would be able to achieve about 12%, but Na_2SO_4 will tend to participate and fall out since the solutions will inevitably have some impurities where the Na_2SO_4 crystals will start to grow on overnight. **Table VII** provides two solutions pairs with density differences of 7.62% and 3.54% we found using the ternary plot.



3 CFD MODELLING WITH DESTROJER FACILITY FOR STEADY-STATE RANS MODEL

A CAD geometry is built for the DESTROJER facility, and initial benchmark of RANS models has been carried out using the experimental data recorded within this project.

3.1 CFD Geometry and Mesh Generation

The CFD model includes a $1 \times 1 \times 0.76 \text{ m}^3$ tank filled with water at the standard conditions. At the center of the bottom section, the inlet of a round jet with a diameter of 12.7 mm is modeled. To correctly capture the jet formation, a finer mesh is needed in the central part of the tank domain. An axisymmetric CAD geometry is created, with a width of 6.35 mm for the jet inlet and 0.76 m in length for the whole tank, as shown in **Figure 53**. The jet inlet length is 2 cm long.

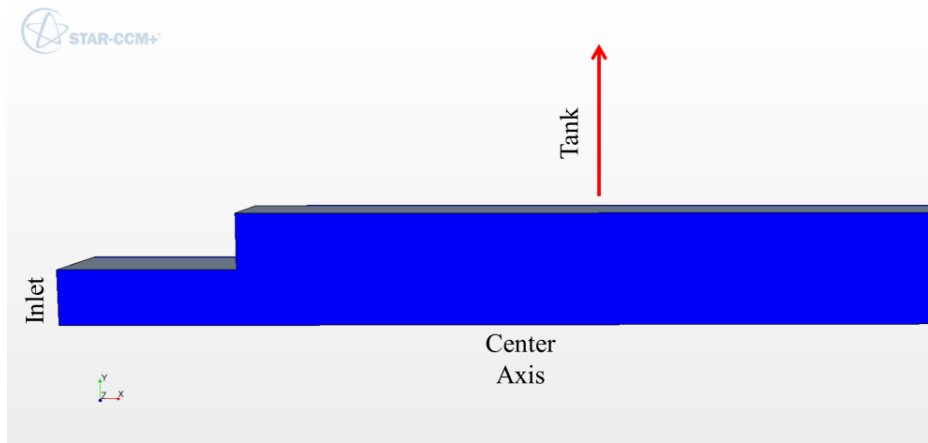


Figure 53. CAD geometry model before meshing.

After meshing the CAD geometry of **Figure 53**, the tank mesh is extruded radially for 50 cm with a specified number of layer and stretching ratio. In this way, the fine mesh will cover the jet evolution through the tank vertical axis. A zoom of the 2D axial mesh model is illustrated in **Figure 54**.

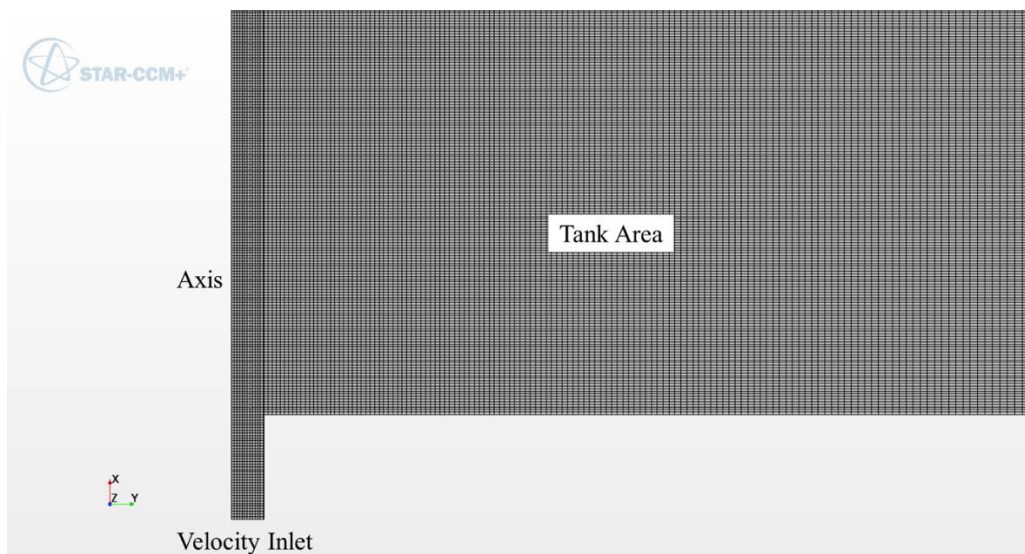


Figure 54. Meshing for the 2D axial model with 50 cm extrusion from the center.

Based on the CAD model shown above, the actual inlet geometry is implemented to replace the tube-shape inlet with the actual jet contraction profiles, as illustrated in **Figure 55** with a 2D mesh of 597,297 cells.

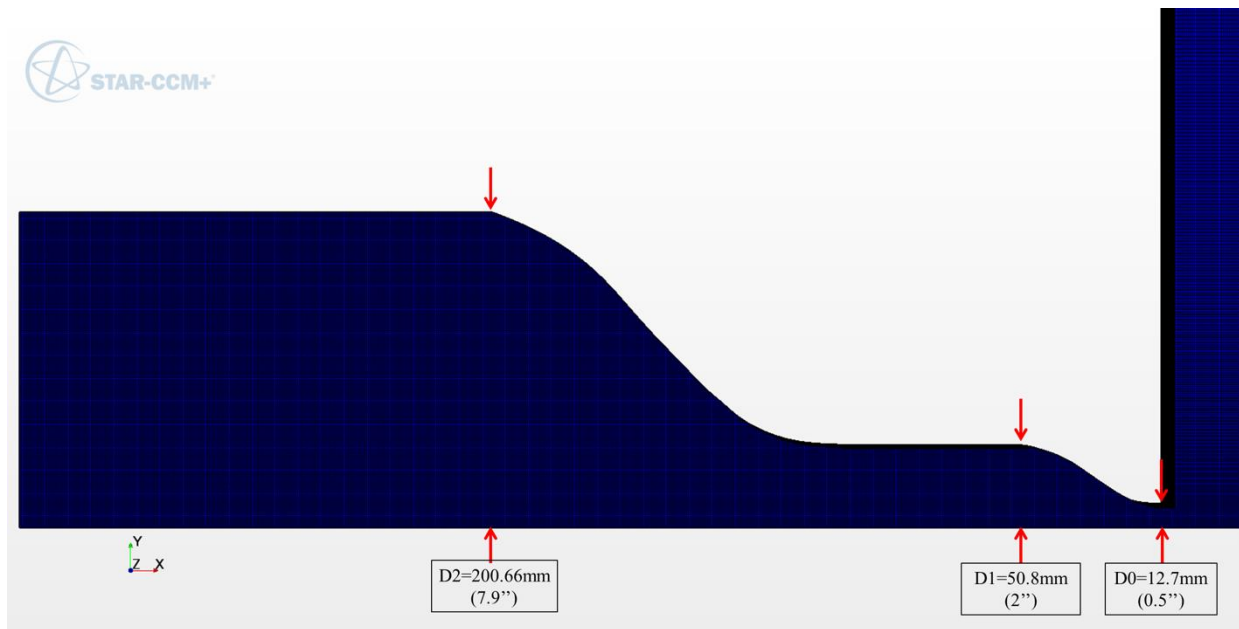


Figure 55. CAD model for with the actual jet geometry.

To ensure that the smallest cross-sectional area has at least ten layers of mesh cells, the mesh base size is selected to be 0.5 mm. It is then extruded for the tank domain by 0.5 m with 300 layers and five stretching. As shown in **Figure 56**, having 13 meshing layers together with five prism layers, the flow inside the jet can be well captured as well as the near-wall flow. The 2D axial CAD model can be visualized in Figure 57, with the centerline as the symmetric boundary.

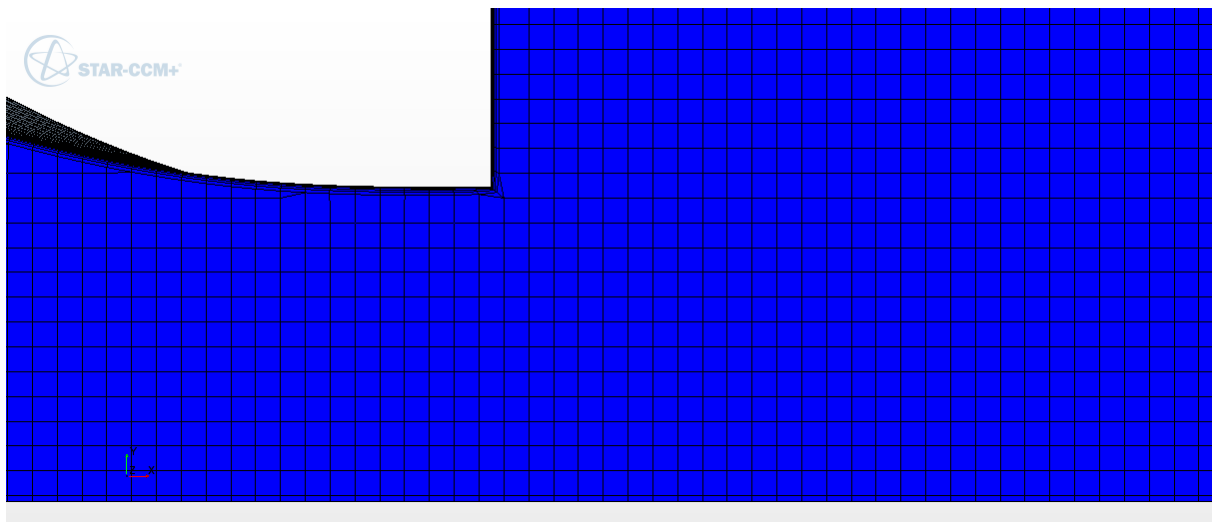


Figure 56. Zoom-in view of the jet outlet into the tank.

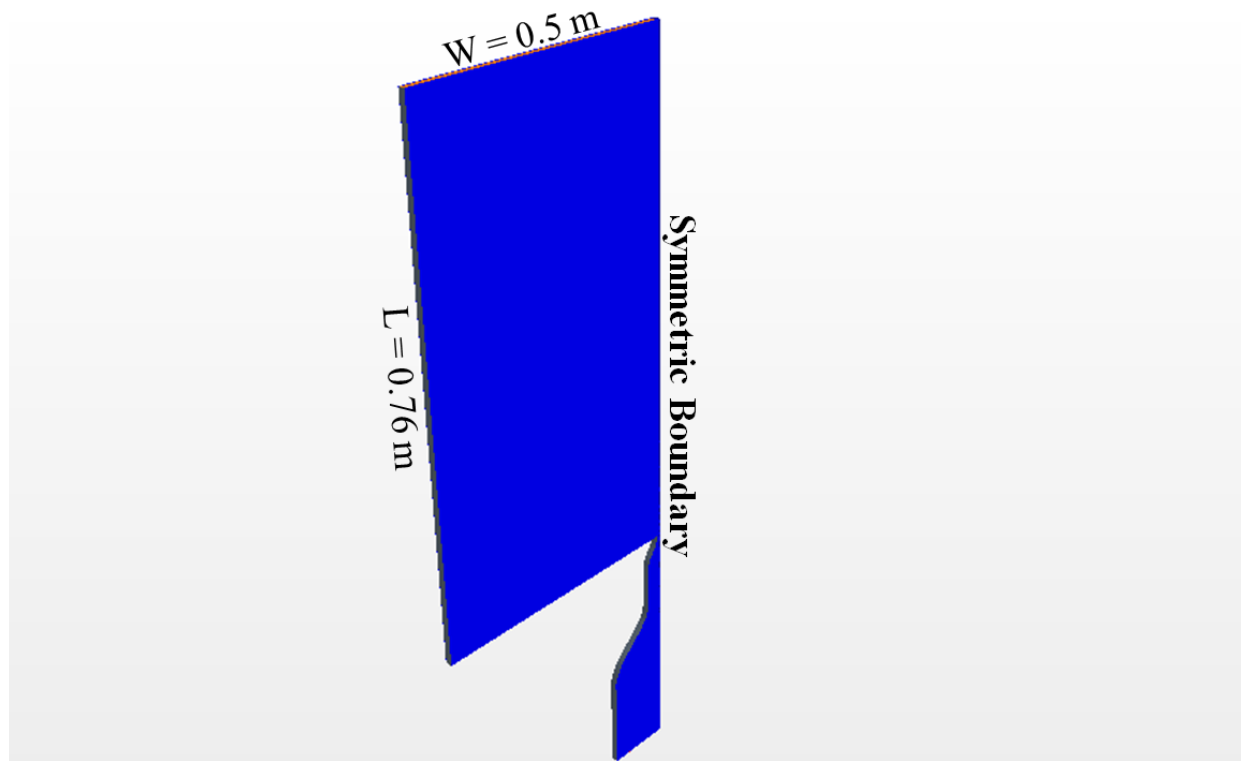


Figure 57. CAD model for CFD simulations.

3.2 Convergence Test

To perform the CFD simulations, the physics models used for a 2D axial model for the simulation are listed as follows:

- Axisymmetric
- Constant Density
- Gradients
- Gravity
- k- ϵ Turbulence
- Liquid
- Realizable k- ϵ Two-layer
- Reynolds-averaged Navier-Stokes Turbulence
- Segregated Flow
- Steady
- Turbulent
- Two-Layer All y^+ Wall Treatment

The simulation is run for 20,000 iterations with jet inlet velocity of 1.60 m/s, corresponding to a Reynolds number of 20,000. The residuals plot reported in **Figure 58** indicates good convergence.

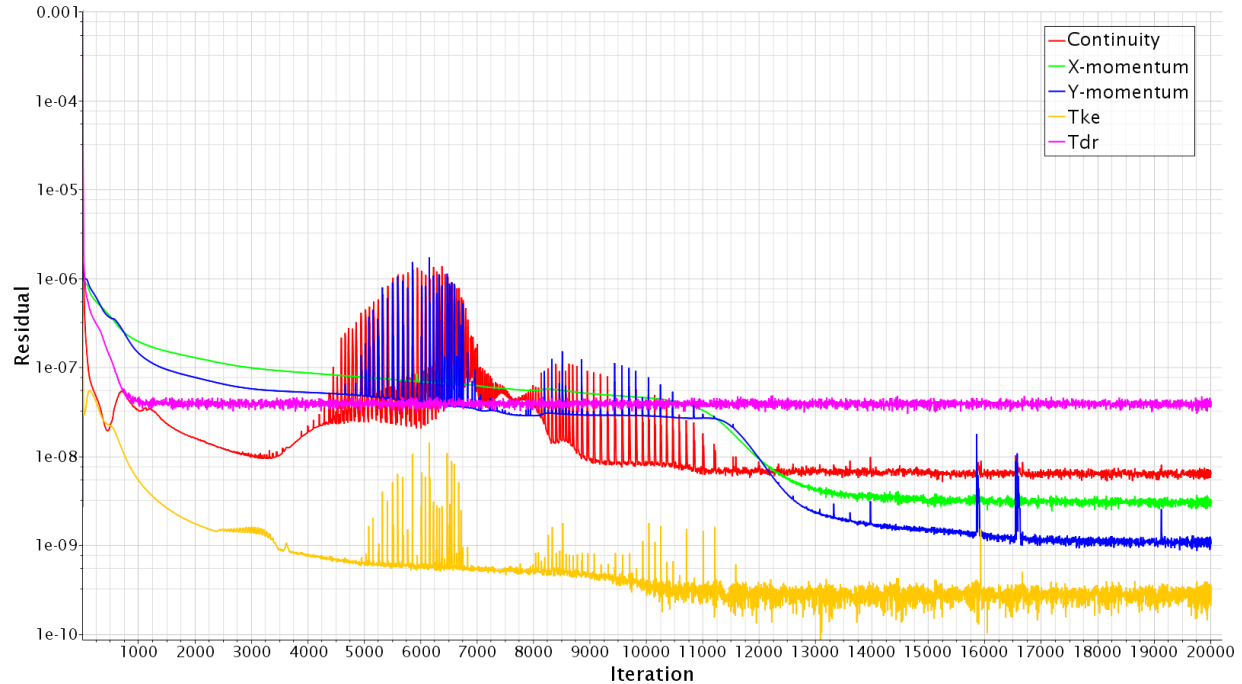


Figure 58. Residuals after 20,000 iterations for 0.5 mm meshing base size.

Convergence is demonstrated by also plotting the turbulent kinetic energy (TKE) as function of iteration numbers at different locations along the jet (see **Figure 59**) indicated with coordinates pairs (x,y), where x is the distance in mm from the jet inlet, and y is the radial distance in mm from the centerline of the jet. Good convergence is obtained in less than 10,000 iterations.

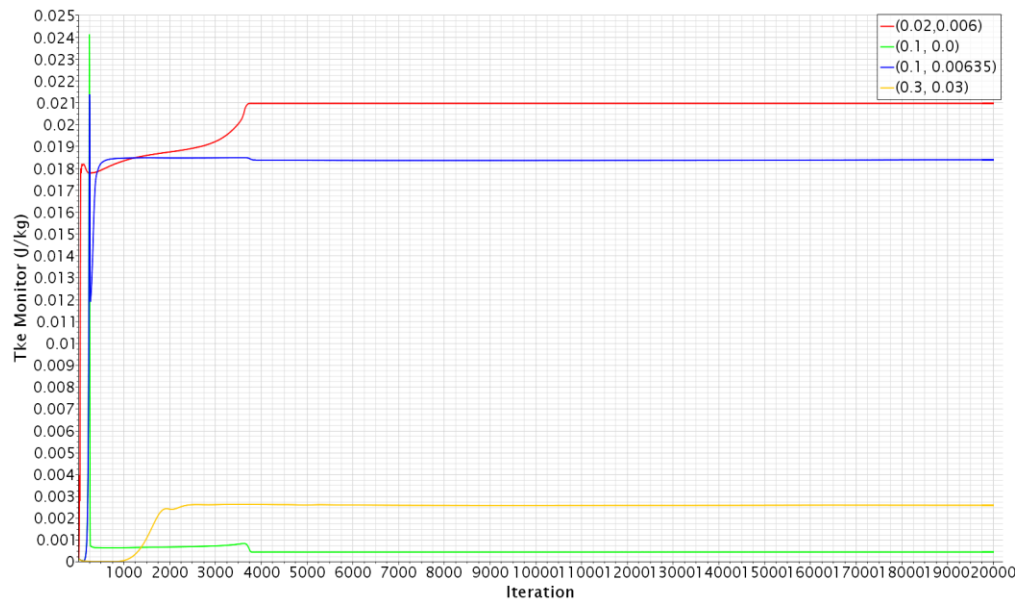


Figure 59. TKE monitor after 20,000 iterations for 0.5 mm meshing base size.

The comparison of the computed streamwise velocity profile and the DESTROJER experimental data at $Re = 20,000$ and $x/D = 1$ is reported in **Figure 60**. The experimental data are shown together with the estimated uncertainty bars. The simulation results are obtained using STAR-CCM+ with the realizable $k-\epsilon$ models. The comparison for the streamwise velocity gradients are shown in

Figure 61. Excellent agreements between the CFD RANS simulations and the experimental results is observed. Work is currently on-going for an extensive comparison between different RANS models and the experimental results for both near- and far-field.

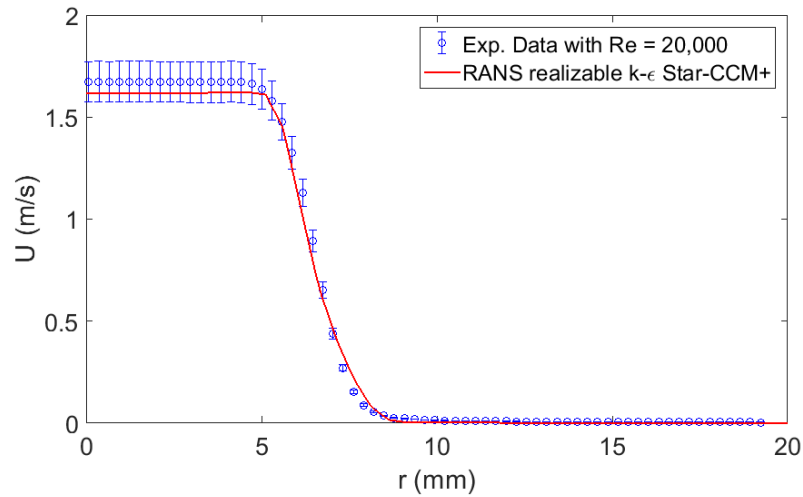


Figure 60. Streamwise velocity comparison at $x/D = 1$ for experimental data and Star-CCM+ simulations at $Re = 20,000$.

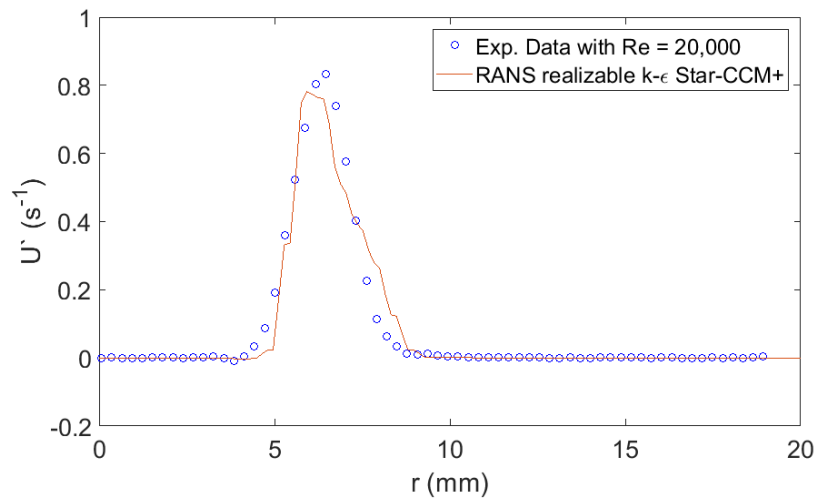


Figure 61. Streamwise velocity gradient comparison at $x/D = 1$ for experimental data and Star-CCM+ simulations at $Re = 20,000$.

4 SCALED FACILITY FOR DENSITY DIFFERENCE MEASUREMENT

A scaled, modular version of the DESTROJER facility has been designed and built at the University of Michigan to perform experiments of jets in stratified environments and investigate scaling effects by comparing with the experimental results obtained by the GWU team. **Figure 62** shows the CAD drawing of the scaled facility, with a tank size of $30 \times 30 \times 30 \text{ cm}^3$. Tank cross-sections of $10 \times 10 \text{ cm}^2$ and $20 \times 20 \text{ cm}^2$ have been fabricated as well. The servo-engine is connected to an actuator to drive a cylinder pump which can be charged with a certain fluid. A two-direction valve is mounted at the bottom, which allows to either inject fluid in the tank or discharge the tank fluid into the disposal vessel underneath the tank.

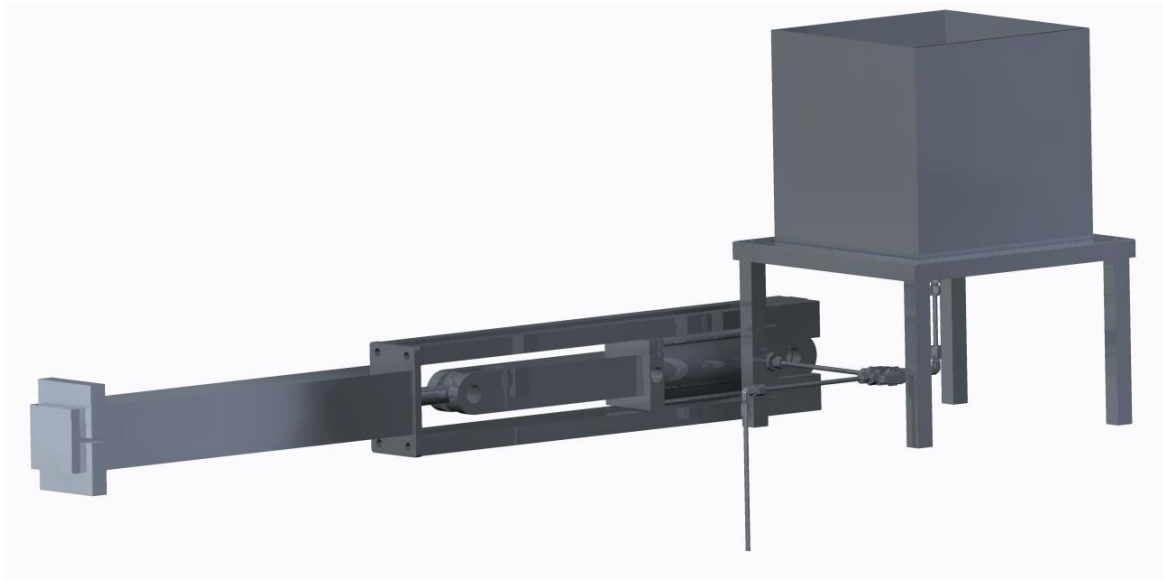


Figure 62. CAD drawing for the scaled facility with a tank size of $30 \times 30 \times 30 \text{ cm}^3$.

With a jet size of 2mm, the three tank size selections result in a tank-to-nozzle ratio of 50, 100, and 150 respectively. **Figure 63** shows the experimental facility setup, with the laser and imaging systems and the three tank sizes.

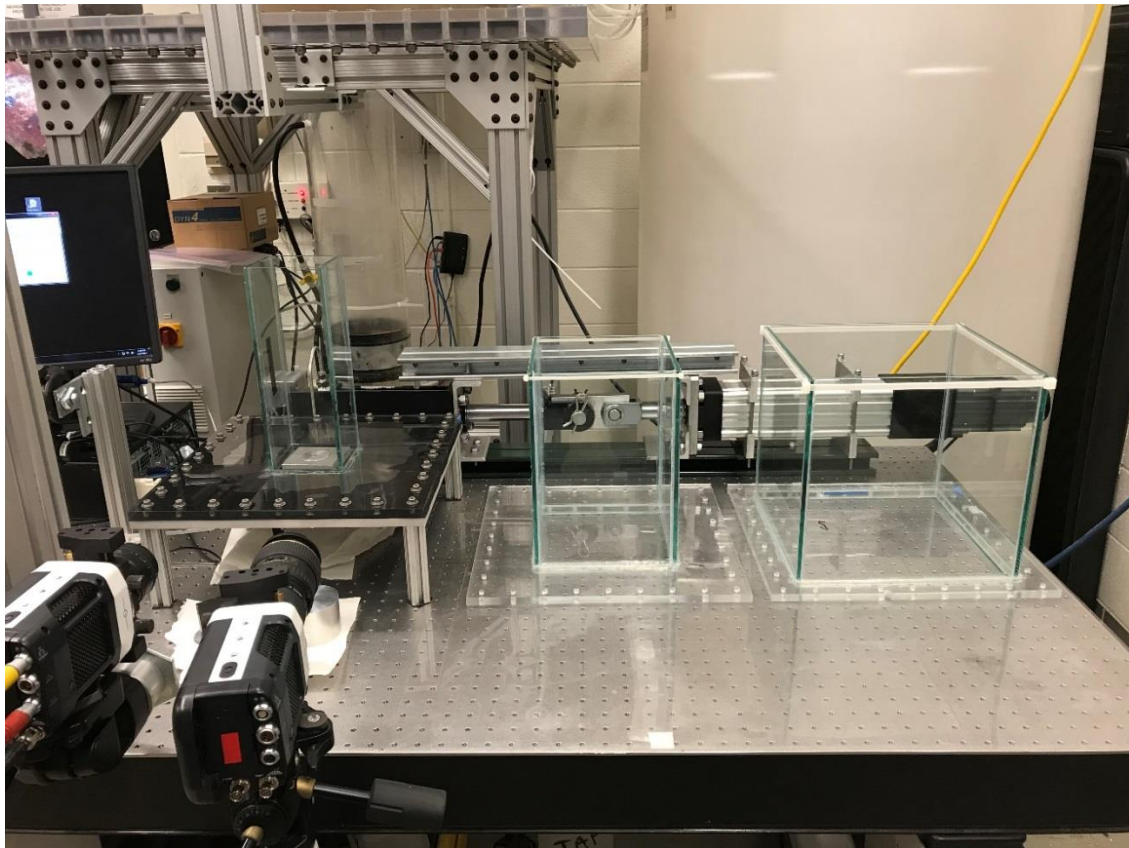


Figure 63. Experimental setup with the $10 \times 10 \times 30$, $20 \times 20 \times 30$, $30 \times 30 \times 30 \text{ cm}^3$ tanks, servo-engine and actuator driven piston and two cameras set up for both PIV and LIF.

4.1 Test Matrix for Stratified Environments

Figure 64 illustrates three conceptual experimental setups for the stratified environment, using red to represent the lower density fluid and blue for the higher density fluid. For the configuration in **Figure 64(a)** a jet impacts a uniform environment of different density (either lower or higher than the jet density) to investigate jet penetration and acceleration/deceleration inside the tank. For the configuration in **Figure 64(b)**, a jet enters in an environment where a sharp stratification layer is present, resulting in a stratification layer mixing phenomenon. Finally, in the configuration shown in **Figure 64(c)**, the jet enters an environment where a linear stratification is present. This latter configuration is a more realistic representation for what occurs in nuclear reactors (e.g. thermal stratification in the upper plenum of the hot pool in sodium-fast reactors).

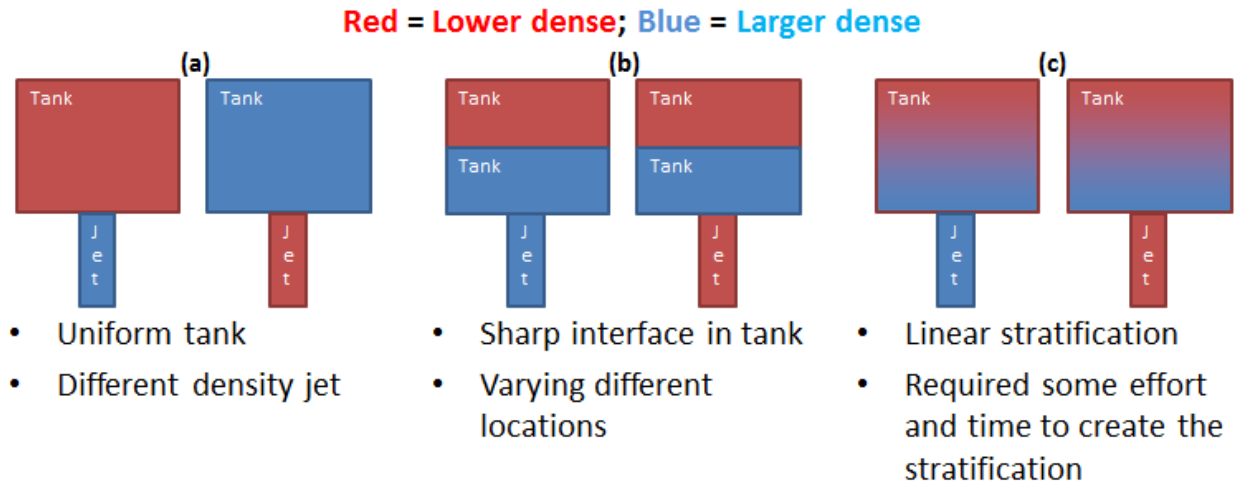


Figure 64. Illustration of the stratification experimental setup.

4.2 Wiremesh Sensor for Scaled Facility

A wire-mesh sensor was designed for the scaled tank setup. The sensor PCB board design is presented in **Figure 65**, with a size of 359 mm × 75 mm, and a 120×4 matrix of measurement locations, for a total of 480 measuring locations for a single measurement. For each horizontal wire crossing the board (transmitter wires) and vertical nodes along the board (receiver), the spacing is set to be consistently 2.5 mm apart.

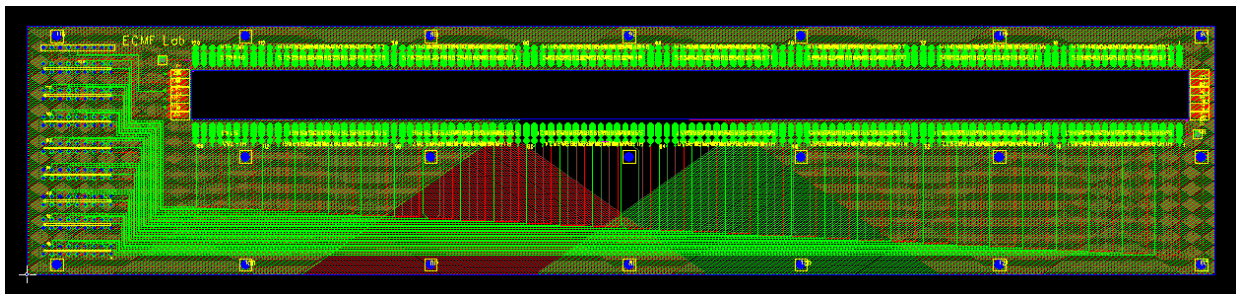


Figure 65. PCB board design with 120 pins connections.

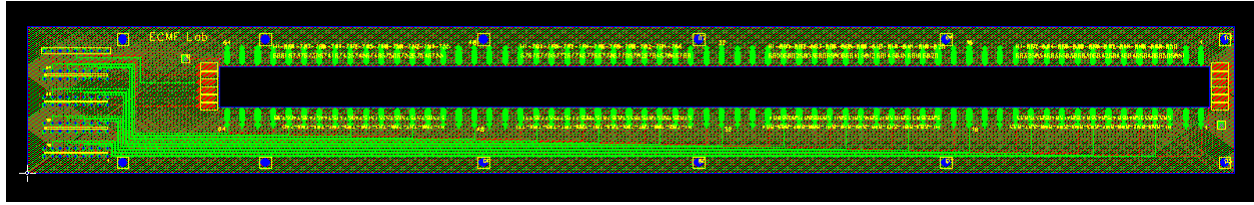


Figure 66. PCB board design with 64 pins connections.

Figure 66 shows the PCB board design with a size of 390 mm × 47 mm and 64×4 measuring locations (256 measuring nodes) for a single measurement. For each horizontal wire crossing the board (transmitter wires), the spacing is set to be consistently 2.5 mm apart, while the spacing for vertical nodes along the board (receiver) is designed to be 5 mm. This design is used in the 20×20 and 30×30 cm² cross-section tanks but with a tilted geometry setup as shown in **Figure 67**. With an inclined angle of 26.5°, we will be able to achieve a uniform spacing of 1.115 mm along the vertical directions with the combined readings of each node.

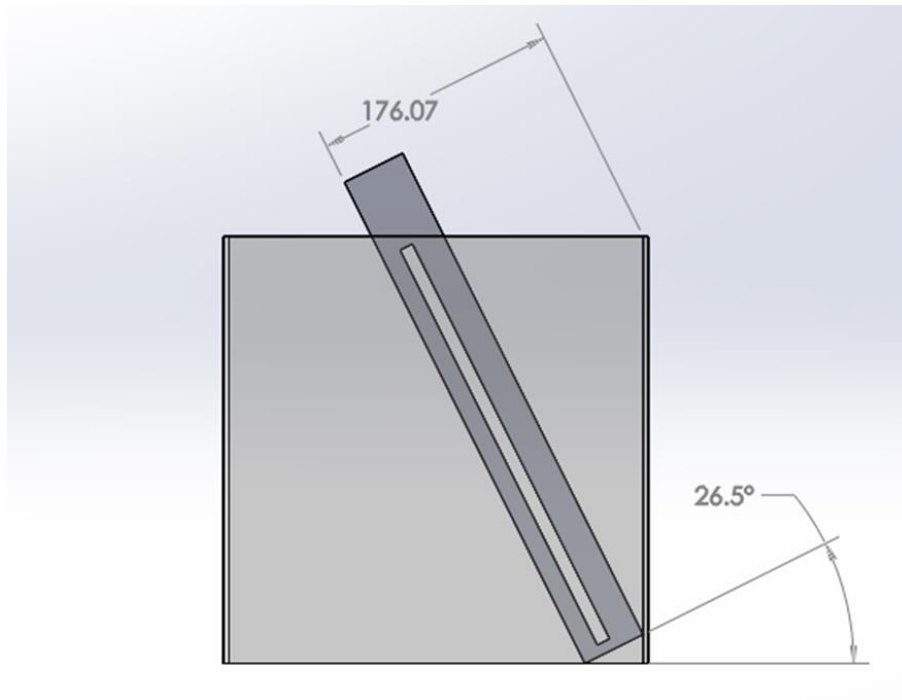


Figure 67. Tilted design for the 64-pin PCB board.

Figure 68 shows the completed 120-pin wiremesh sensor after the electrodes have been soldered on the PCB board on the left (**Figure 68, left**), and how the wiremesh sensor is mounted on the experimental setup of the 30×30×30 cm³ tank (**Figure 68, right**).

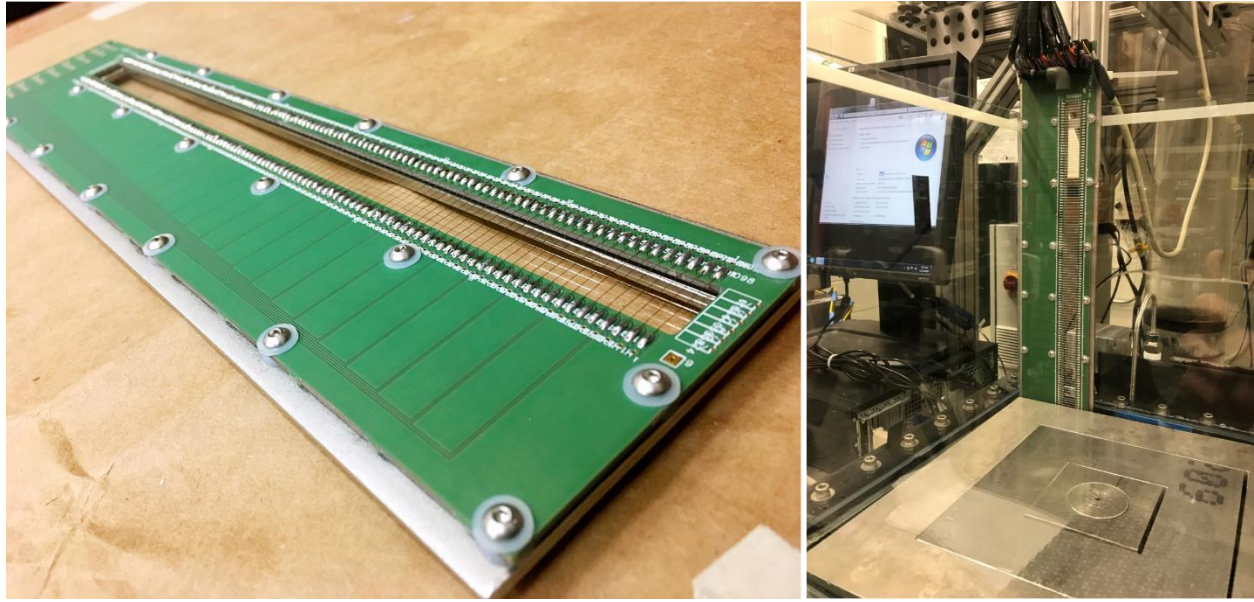


Figure 68. (left) 120-pin wiremesh sensor after soldering. (right) The experimental setup with the 120-pin wiremesh sensor mounted in the $30 \times 30 \times 30 \text{ cm}^3$ tank.

4.3 Collapsing Jet Experiments with LIF Imaging

In order to investigate the jet mixing mechanism in the presence of density differences, it is beneficial to have measurements of the concentration field, together with the velocity field. Therefore, LIF is implemented together with the PIV system. As shown in the bottom left corner of **Figure 63**, we are able to film LIF images simultaneously with raw particle images using the two-camera and laser setup.

Using the scaled facility, the jet is created by a piston that is driven by a linear actuator attached to a servo engine into the $10 \times 10 \times 30 \text{ cm}^3$ tank contained with heavier liquid (Mixture II mention in **Table VI**). The lighter liquid (Mixture I in **Table VI**) is injected vertically to through the nozzle at a constant nominal inlet velocity of 4.22 m/s to the tank. LIF measurements were performed with a density difference of 8.6% and the corresponding nominal jet Reynolds number of 2,100. The jet will collapse into itself after certain period as shown in **Figure 69**. The periodical collapsing of the jet is observed only at relatively low Reynolds numbers when buoyancy dominates on momentum. At higher Reynolds numbers (beyond 5,300 in the current setup) stable jets are observed even in presence of density differences.

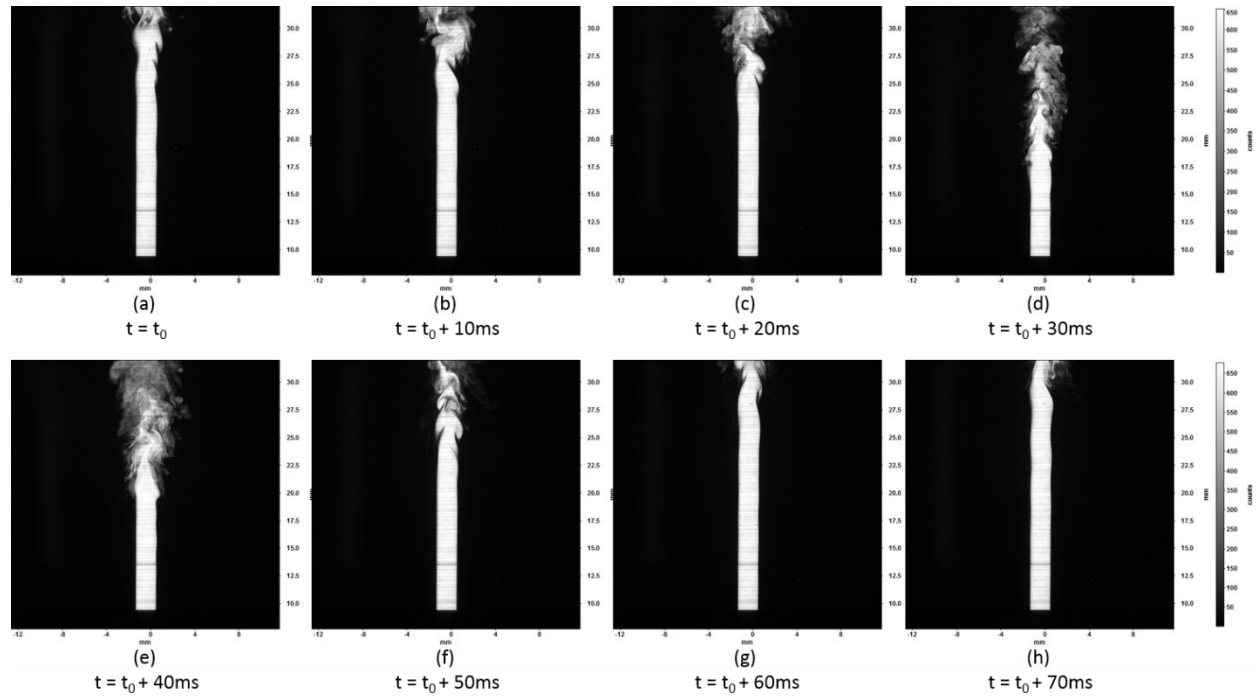


Figure 69. Collapsing jet with a Reynolds number of 8,400 after different time stamps.

4.4 Comparison Between Uniform Jet and Buoyant Jet

The jet is created by a piston that is driven by a linear actuator attached to a servo engine into the $10 \times 10 \times 30 \text{ cm}^3$ tank contained with heavier liquid (Mixture II mention in **Table VI**). The lighter liquid (Mixture I in **Table VI**) is injected vertically to through the nozzle at a constant nominal inlet velocity of 10.58 m/s to the tank. This corresponds to a Jet Reynolds number of $Re=5300$. A high-speed PIV system is used to measure the flow field in the vertical mid-plane of the jet. It comprises a Phantom Miro LAB 340 camera with a spatial resolution of $2560 \times 1600 \text{ pixels}$, a pixel size of $10 \times 10 \mu\text{m}^2$, 12 bit digital output and a maximum recording frequency of 800 Hz at full scale, as well as a high speed double pulsed Nd:YLF Laser with a maximum recording frequency of 10 kHz at a wavelength of 527 nm and 70 mJ energy/pulse. A combination of two spherical lenses, to focus the laser beam, and a third planar concave lens are used to create a light sheet. A total of 1613 Image pairs were recorded with the high-speed camera and laser system.

Figure 70 shows the streamwise mean velocity of the reference case (left), the stratified case with RIM at 8.6% density ratio (middle) and the stratified case without RIM (right). The jet progresses from bottom to top. When comparing the mean streamwise velocity field of the reference case and the Stratified case with RIM, only slightly different centerline velocity decay is observed, where buoyancy causes a slight acceleration of the jet with increased downstream distance. The velocity field without RIM shows a significant difference. This difference originates by the strong deflection of light when it travels through a region with varying refractive index. Not only the light that is scattered by seeding particles gets deflected on its way towards the camera sensor, but also the laser light sheet itself gets deflected.

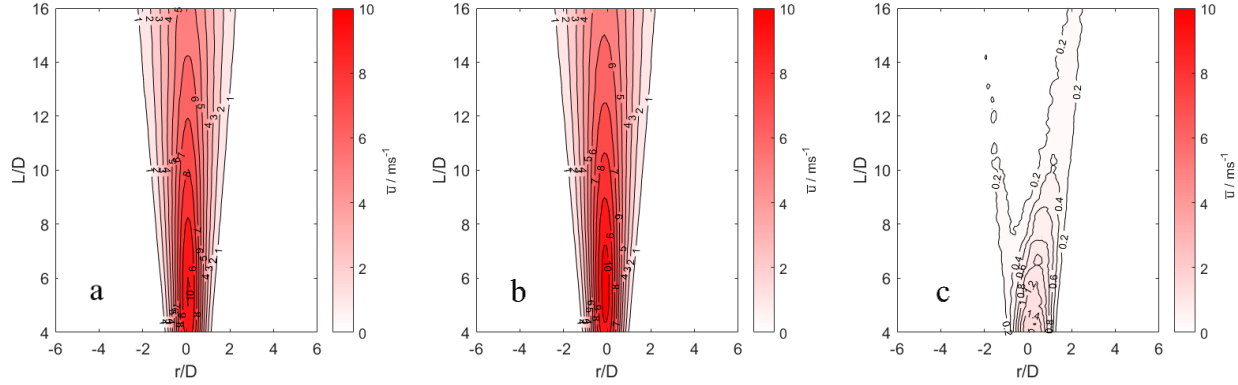


Figure 70. Streamwise mean velocity fields. (a) reference case with solution I being injected to solution I (no differences in density and RI), (b) stratified case with the lighter liquid (solution I) being injected to the heavier liquid (solution II) at 8.6% density difference with RIM (c) stratified case without RIM and a density difference of 8% (here both solutions were slightly altered with a refractive index of $n_D=1.3712$ for solution I and $n_D=1.3538$ for solution II).

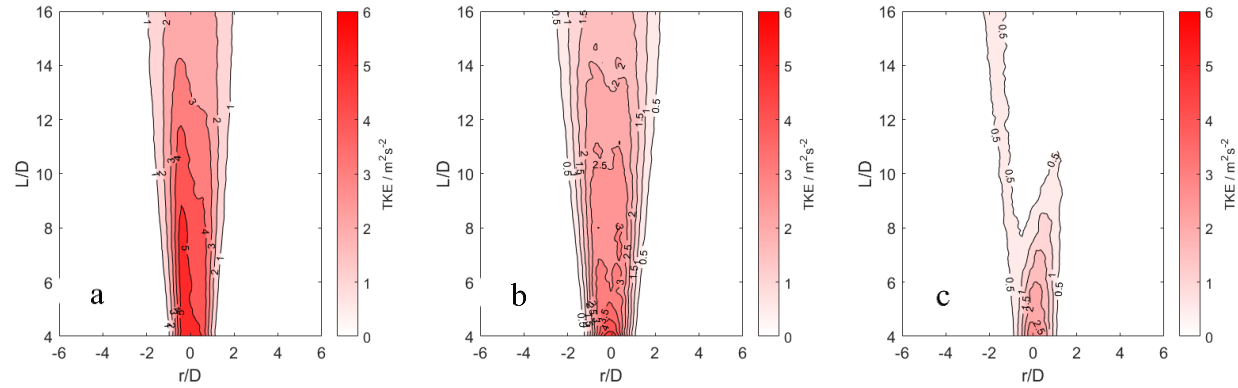


Figure 71. Turbulence kinetic energy. (a) reference case with solution I being injected to solution I (no differences in density and RI), (b) stratified case with the lighter liquid (solution I) being injected to the heavier liquid (solution II) at 8.6% density difference with RIM (c) stratified case without RIM and a density difference of 8% (here both solutions were slightly altered with a refractive index of $n_D=1.3712$ for solution I and $n_D=1.3538$ for solution II).

However, when comparing the turbulence level, lower TKE is found in the stratified RIM case, compared to the reference case without stratification, which is visible in **Figure 71**. Here the TKE of the reference experiment (left) and the RIM density stratified case (middle) are shown aside of the not index matched case (right). A strong decay of turbulence with increasing downstream distance is observed, that is likely to be originated by suppression of momentum transport normal to the density gradient. The results are strongly biased for the not index matched case, where TKE shows much lower levels compared to the RIM case.

A quantitative comparison of the RIM results with the reference case is done by a comparison of the volumetric flow rate. The nominal volumetric flow rate is given by the cross-sectional area of the nozzle and the nominal velocity u_n by:

$$Q_n = \frac{\pi}{4} D^2 \cdot u_n . \quad (17)$$

We then integrated the stream wise mean velocity by:

$$Q_i = \iint_{-r}^r \bar{u} dA . \quad (18)$$

Figure 72 shows the ratio of the integrated volumetric flow rate and the nominal volumetric flow rate for all three cases as a function of the downstream distance.

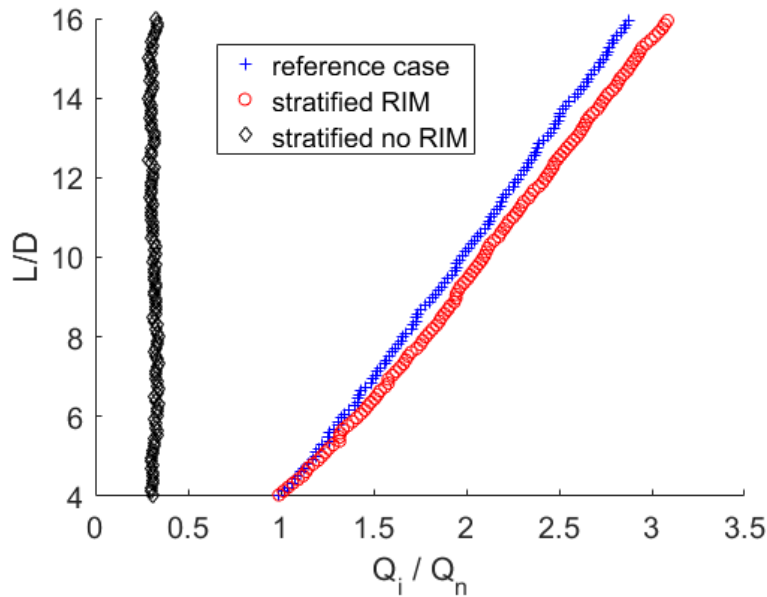


Figure 72. Integrated volumetric flow rate of the three cases, normalized by the nominal volumetric flow rate.

At 4 hydraulic diameters downstream the jet inlet, the integrated volumetric flow rate of the reference case and the stratified RIM case are almost identical to the nominal volumetric flow rate. This indicates extremely small entrainment to the jet at this point and demonstrates the applicability of RIM. In contrast, the integrated volumetric flow rate without RIM deviates significantly from the nominal flow rate, confirming that PIV measurements without RIM results in highly inaccurate velocity fields.

4.5 Sharp Density Interface with 3.16% Density Difference

Using the scaled facility, the jet is created by a piston that is driven by a linear actuator attached to a servo engine into the $30 \times 30 \times 30 \text{ cm}^3$ tank contained with heavier liquid (Mixture II mention in **Table VIII**) at the bottom half of the tank and the lighter liquid (Mixture I in **Table VIII**, dyed with Rhodamine 6G) on the top half, shown in the LIF reference image **Figure 73**. The sharp interface locates at 114 mm (57 jet diameter) away from the jet outlet. Then the lighter liquid is injected vertically into the tank through the nozzle at a constant nominal inlet velocity of 10.58 m/s to the tank. This corresponds to a jet Reynolds number of $Re = 17,000$.

Table VIII. Nominal Parameters of the two liquids with 3.16% density difference.

Mixture.	H ₂ O	Glycerol	Na ₂ SO ₄	ρ g/cm ³	μ N s/m ²
(I)	0.9343	0.0657	/	1.012	0.001248
(II)	0.9492	/	0.0508	1.044	0.001143

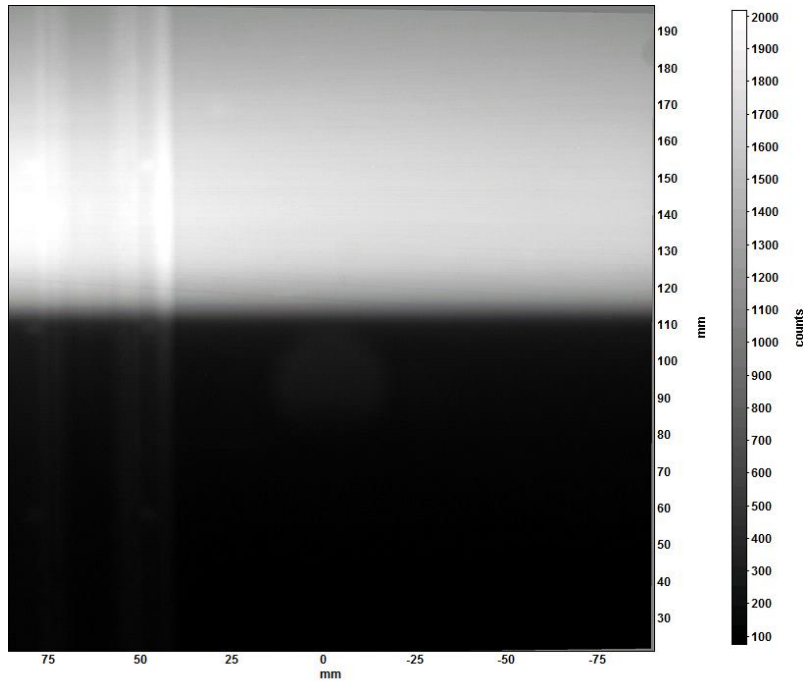


Figure 73. LIF reference measurement for sharp density difference interface with dyed lighter fluid on the top and non-dyed heavier liquid at the bottom.

The high-speed PIV and PLIF system is used to measure the flow field and concentration field in the vertical mid-plane of the jet. Two experimental sets, with a total of 3000 image pairs, were recorded with the high-speed camera and laser system to ensure the repeatability of the experimental setup and visualize the transient flow structures. **Figure 74** shows three successive images of particle images are in superposition with the corresponding concentration fields measured by LIF techniques when the lighter fluid jet is impacting with the sharp interface from $t = t_1$ to $t = t_1 + 40\text{ms}$, define t_1 as an arbitrary time after the jet impaction. From the crispy clear PIV and LIF images, we can tell the refractive indexes of these two solutions have been successfully matched without any sign of Schlieren.

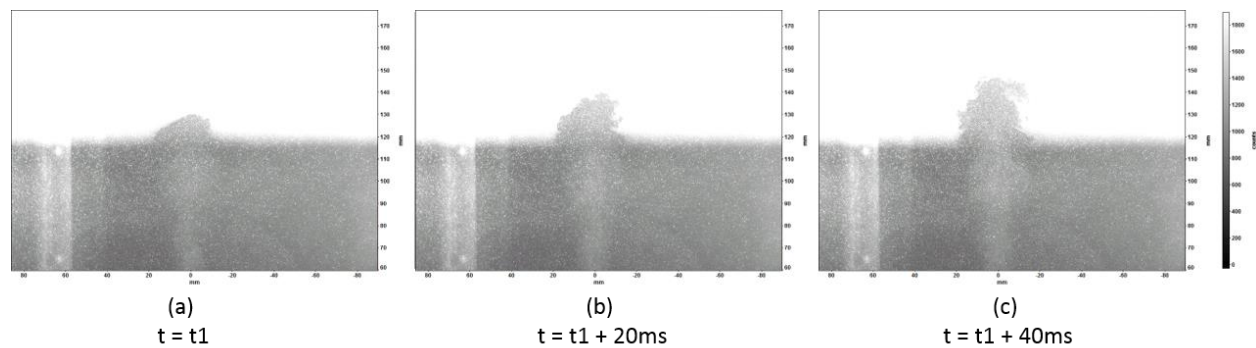


Figure 74. For the sharp interface experiment with a density difference of 3.16%, the raw particle images are superpositioned with LIF images at (a) $t = t_1$, (b) $t = t_1 + 20\text{ms}$, and (c) $t = t_1 + 40\text{ms}$

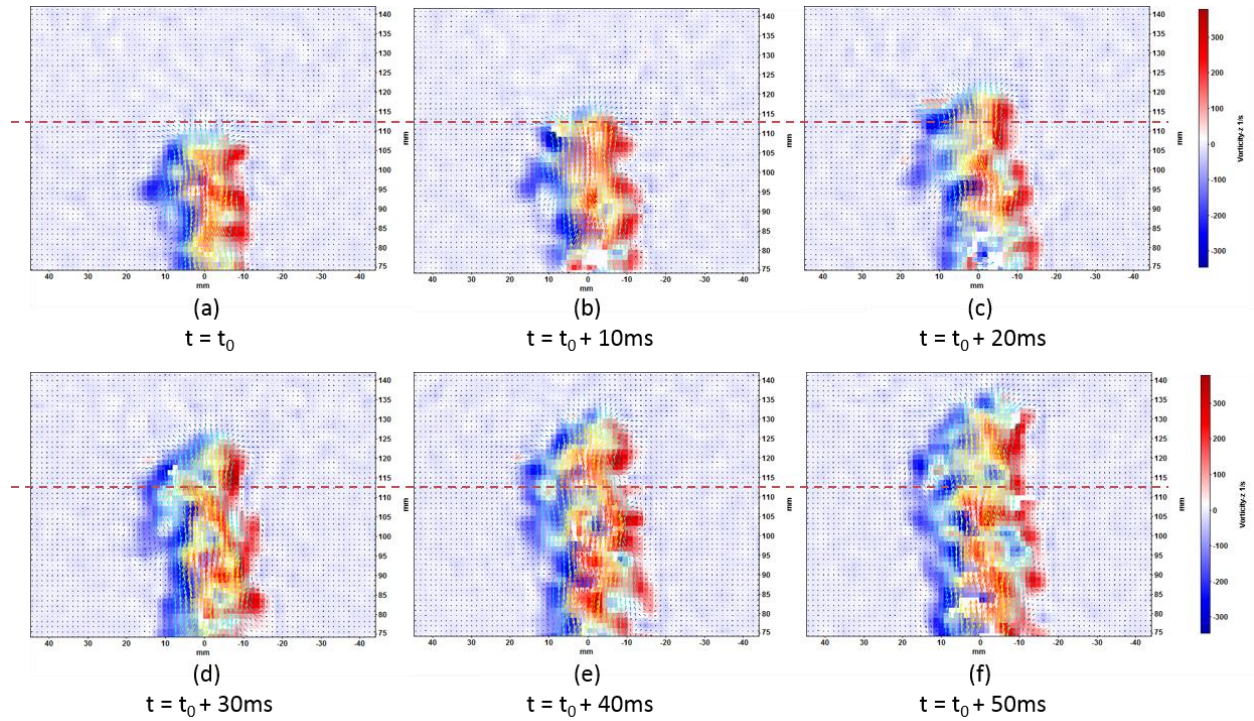


Figure 75. For the sharp interface (indicated with the red dashed line) with a density difference of 3.16%, define t_0 is right before the jet starts to impact the layer, velocity vectors plotted in superposition with vorticity fields at (a) $t = t_0$, (b) $t = t_0 + 10\text{ms}$, (c) $t = t_0 + 20\text{ms}$, (d) $t = t_0 + 30\text{ms}$, (e) $t = t_0 + 40\text{ms}$, and (f) $t = t_0 + 50\text{ms}$.

The raw particle images are analyzed using Davis 8.3 GPU processing, with an initial interrogation window size of 64×64 pixels² with 50% overlap for two passes and a final interrogation window size of 48×48 pixels² with 75% overlap for three passes. With sharp interface indicated by red dashed lines, **Figure 75** shows the velocity vector plots in superposition with the vorticity fields when the jet starts to impact the sharp interface at several different time points. Since **Figure 75** has the x-axis from positive to negative and the vorticity plot is mostly positive when x-axis is negative, this means that the vortices are rotating counter-clockwise where the x-axis values are negative, vice versa. Strong velocity fluctuations and anisotropy can be observed from the jet-interface impactions. It can be noticed that, due to the abrupt instabilities, probably there are some new vortices formed after the jet passing the interface, and this will be studied in the future to verify.

To analyze the mixing transition, we pick one-pixel area at the intersection of the initial sharp interface and the jet centerline and plot the LIF signal intensity counts from the beginning to the end of the experiment as shown in **Figure 76**. It is obvious that there are three stages involved in the mixing process: define t_0 is right before the impaction, the first stage is from $t_0 + 120\text{ms}$ to $t_0 + 3800\text{ms}$ with an increasing of intensity signals, the second one from $t_0 + 3800\text{ms}$ to $t_0 + 6500\text{ms}$ with a decreasing of LIF counts, and the last one till the end with an increasing signal again. By having a looking the real-time LIF images during the mixing process as shown in **Figure 77**, we can correlate the images what we have seen and concluded here.

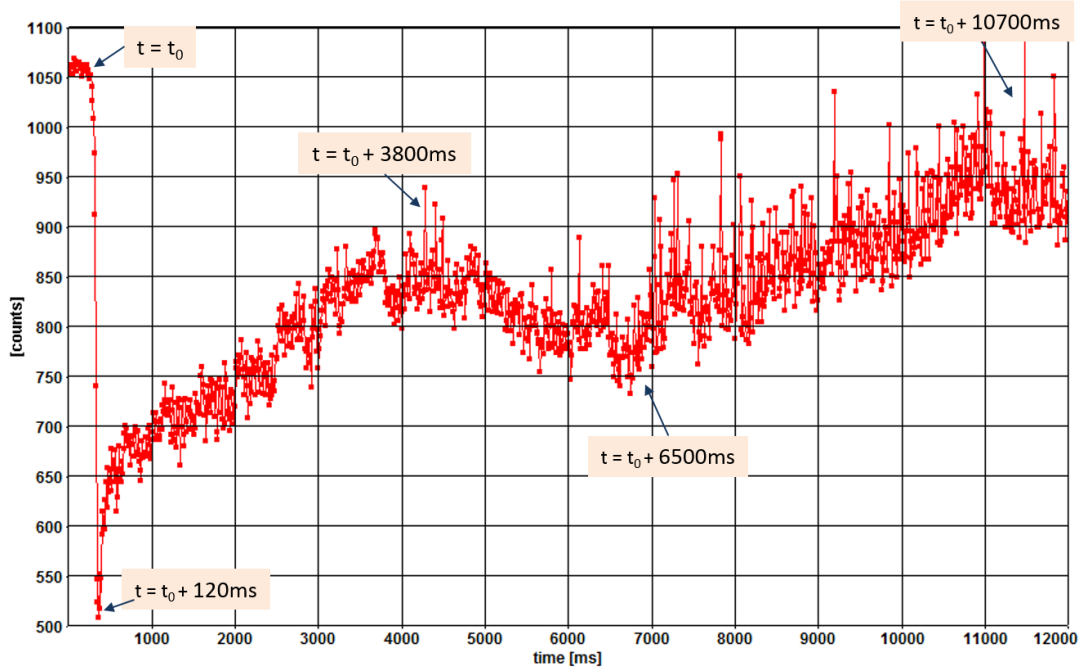


Figure 76. LIF signal intensity plot for the one-pixel area on the sharp initial interface at the jet centerline

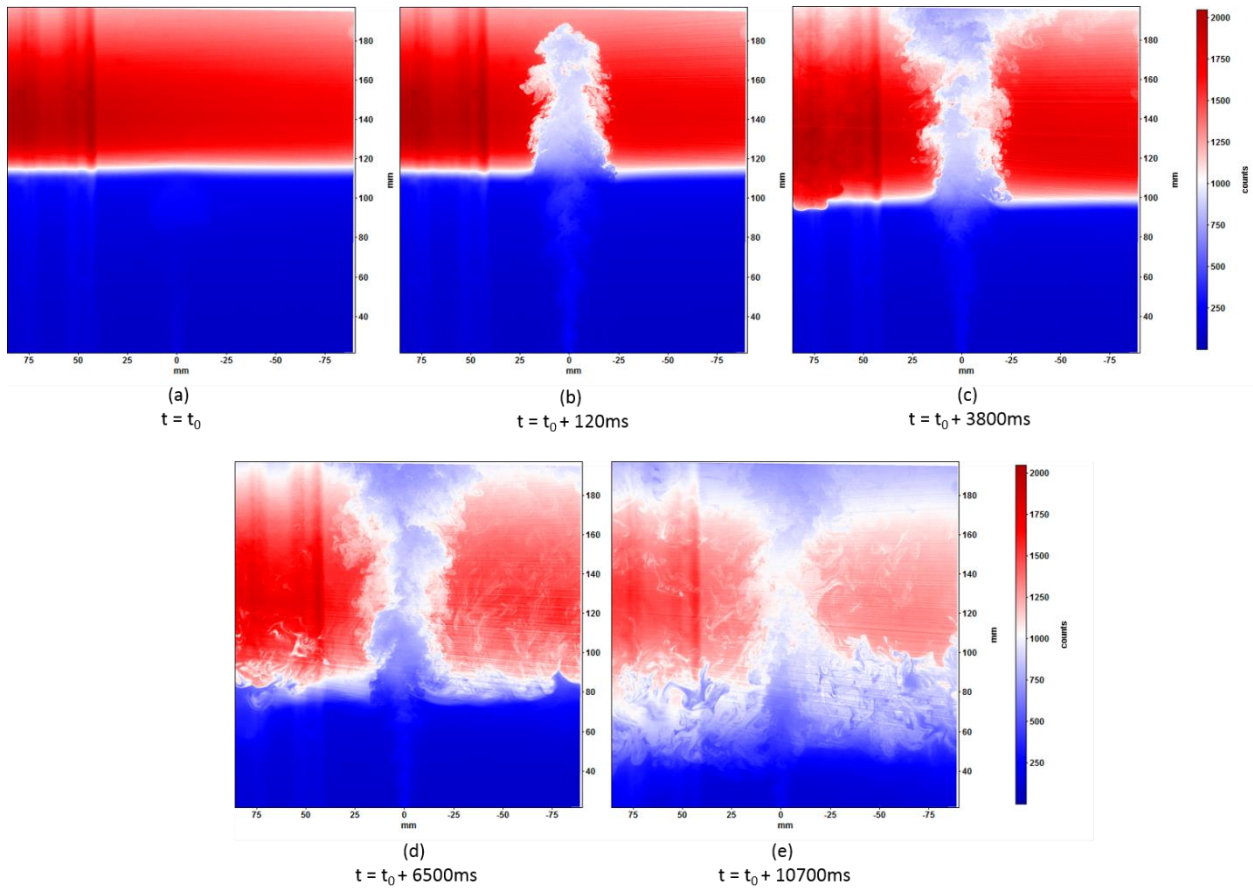


Figure 77. LIF images during the mixing process at several different time stamps.

Figure 77(a) shows the initial boundary condition of the sharp density difference interface, and at $t = t_0 + 120ms$ shown in **Figure 77(b)**, the sharp interface is still there after the lighter fluid jet starts impacting the layer. The LIF signal at the investigation point is increasing because of the mixing process between the dyed lighter fluid jet and the surrounding heavier liquid, and the interface slowly lowers but remains distinguishable until $t = t_0 + 3800ms$ when we start to see some fluid coming down from the side. That is the point where the transition starts, and the layer begins to be more and more turbulent. When the mixing gets more and more violent, and the jet gets more and more entrainments from the heavier liquid at the bottom, the LIF counts at the investigation point starts decreasing a little from $t = t_0 + 3800ms$ to $t = t_0 + 6500ms$. Due to the continuous down coming mixtures from the top, the sharp interface gets eroded. As shown in **Figure 77(c)**, we cannot tell the sharp layer at this point anymore. After that, since the momentum carried by jet keeps the mixing process going, the investigation point continues collecting LIF signals till the end of the jet shown in **Figure 77(d)**.

In addition, we also notice that there is inflection of cross-wise momentum after 40 jet diameters away from the nozzle shown in **Figure 78** when plotting the average cross-wise velocity over the time domain. This will be studied further together with the analysis of the vorticity formation during the whole experiment process.

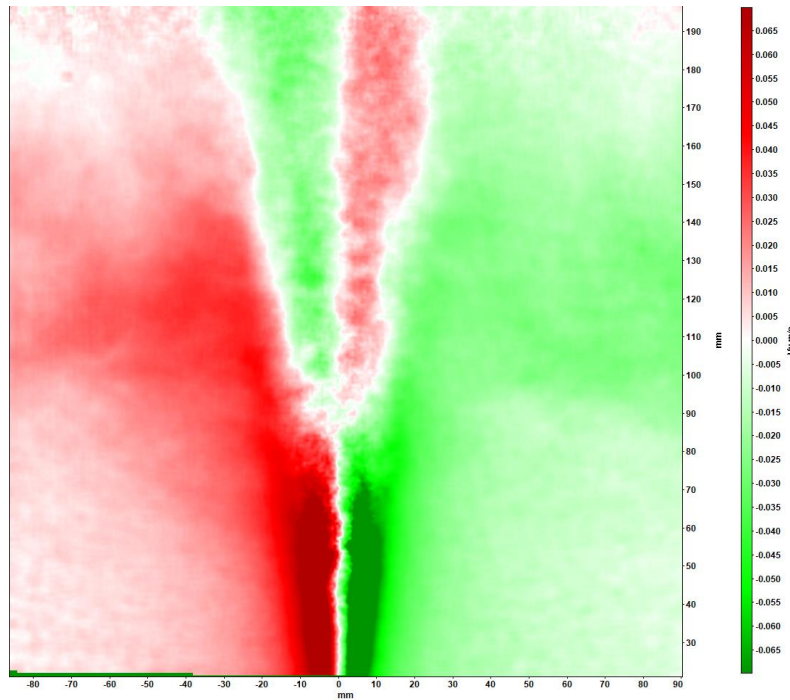


Figure 78. Average cross-wise velocity for the sharp density interface with 3% density difference.

4.6 Preliminary Experiment with Linear Density Stratification

Besides the sharp interface, we also conduct the experiment with a linear density stratification using the same liquid pairs mentioned in **Table VIII**. We filled the bottom 1.25cm of the tank using the heavier liquid S2 (Mixture II mention in **Table VIII**). By decreasing sequentially 5% of the heavier liquid and increasing sequentially 5% of the lighter liquid S1 (Mixture I mention in **Table VIII**), we prepare and well-mixed the intermediate solution and then pour into the tank

slowly to create a linear stratification environment with in total 21 intermediate layers shown in **Figure 79**, each layer having a thickness of 1.25cm.

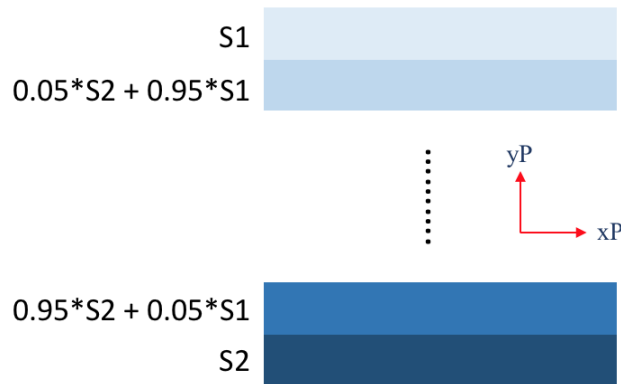


Figure 79. Schematic of the linear stratification setup.

We only dye the lighter liquid with Rhodamine 6G and the heavier liquid will not have fluorescent signal on the LIF images. **Figure 80** shows the raw LIF reference image for the linear stratification after we filled up the scaled tank, and the linear gradient can be observed clearly. Detailed analyses will be addressed later with the processed wire-mesh sensor signals.

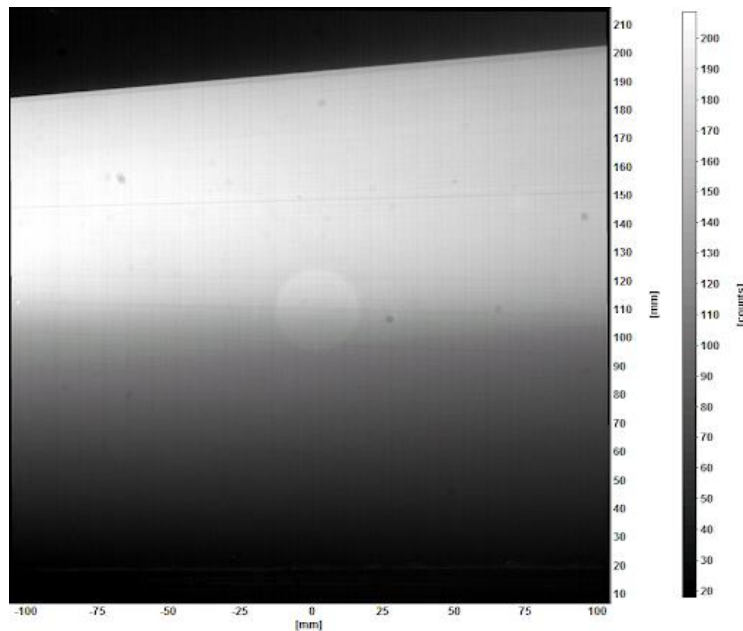


Figure 80. LIF reference image for linear stratification environment.

The lighter liquid is injected vertically into the tank through the nozzle at a constant nominal inlet velocity of 6.59m/s to the tank. This corresponds to a jet Reynolds number of $Re=10,000$. The high-speed PIV and PLIF system is used to measure the flow field and concentration field in the vertical mid-plane of the jet. One experimental sets, with a total of 1613 image pairs, were recorded with the high-speed camera and laser system with a measurement duration of 22 sec. The

raw particle images are analyzed using Davis 8.3 CPU processing, with an initial interrogation window size of 64×64 pixels² with 50% overlap for two passes and a final interrogation window size of 48×48 pixels² with 75% overlap for three passes.

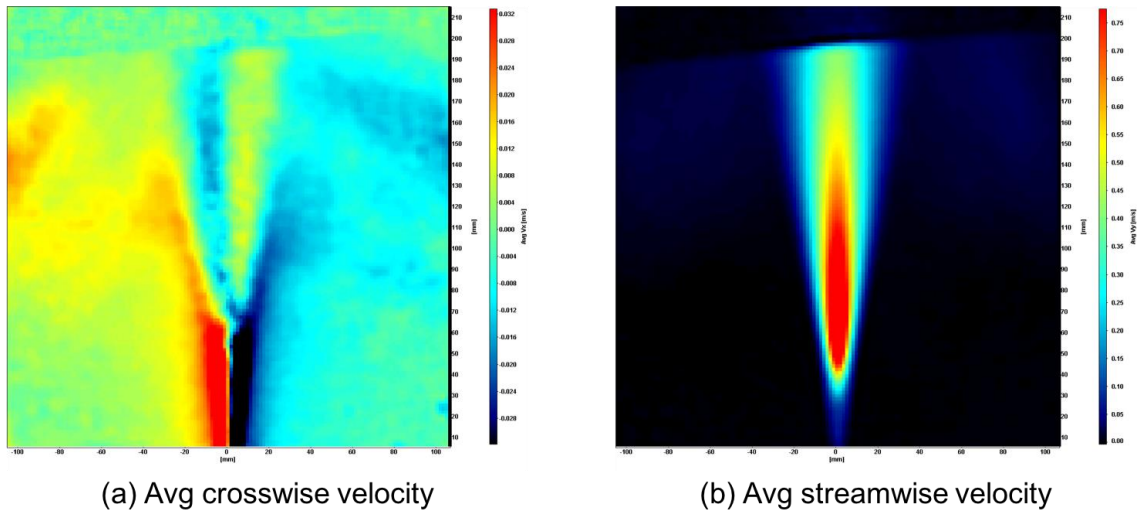


Figure 81. Average (a) crosswise and (b) streamwise jet velocity over time domain

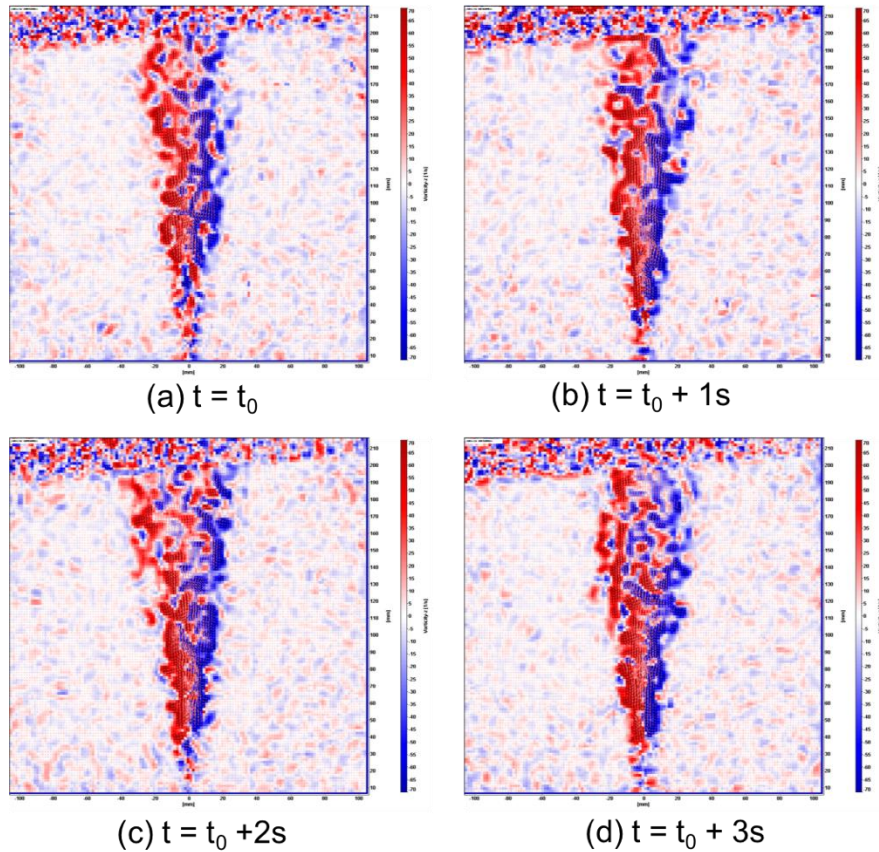


Figure 82. Define t_0 is an arbitrary time point during the linear stratification experiment, velocity vectors are plotted in superposition with vorticity fields at (a) $t = t_0$, (b) $t = t_0 + 1s$, (c) $t = t_0 + 2s$, and (d) $t = t_0 + 3s$.

Figure 81 shows the crosswise and streamwise jet velocity averaged over the measurement duration. From the profiles, it is obvious that the jet is quite symmetric of the jet centerline. Similar to **Figure 78**, we also see an inflection of the crosswise jet momentum after 35 jet diameters away from the jet inlet. As shown in **Figure 82**, the vorticity plots at different time stamps also show that there are some opposite vorticities formed on both sides and strong turbulences are presented after 35 jet diameters. This will be studied in detail in future work.

5 CFD SIMULATION FOR THE SCALED FACILITY

Complementary to the experiments of the scaled tank facility, several CFD simulations were executed using the commercial code STAR-CCM+ to validate RANS turbulence models against our experimental data. Large Eddy Simulations (LES) using NEK5000 were performed as well.

5.1 Geometry, Boundary Conditions, and Mesh

The scaled tank facility, with dimensions of 300mm x 300mm x 250mm was modeled. The inlet of 2 mm in radius was extruded by a total of 5mm. At the inlet, a fully developed flow boundary condition was imposed, the walls were set to no-slip boundary conditions, and the top of the tank was set as a pressure outlet. To determine the cell sizes needed for the LES simulations, several RANS simulations were executed to estimate the length and time scale ratios to ensure that the turbulence scales are captured in the simulations. In addition, the length scales obtained from the experiments were taken into account to ensure that the mesh was fine enough to capture the structures found in the PIV measurements. The mesh was generated using the commercial code ANSYS ICEM-CFD 18.1. The mesh is a conformal, structured hexahedral mesh, with 13.3 Million cells. Because of the nature of the experiment, the mesh was refined along the jet trajectory. Snapshots of the complete geometry, a mid-plane cross-section, top, and bottom views of the tank are presented in **Figure 83(a-d)**.

The length scales and the acquisition frequency from the experiments in the uniform environment are provided in **Table IX**. Taking into account the length scale ratio (from the RANS simulations), and Taylor length scale at 5D (148.3 μm), the smallest cell size along the potential core region at $y/D=0$ was set to 30 μm .

Table IX: Taylor Length Scales from the PIV measurements.

Location y:	5D (Light Fluid)	30D(Heavy Fluid)	60D(Heavy Fluid)	90D(Heavy Fluid)
Taylor Length Scale (μm)	148.3	375.22	404.93	561.84
Acquisition Frequency (Hz)	62500	2000	2000	2000

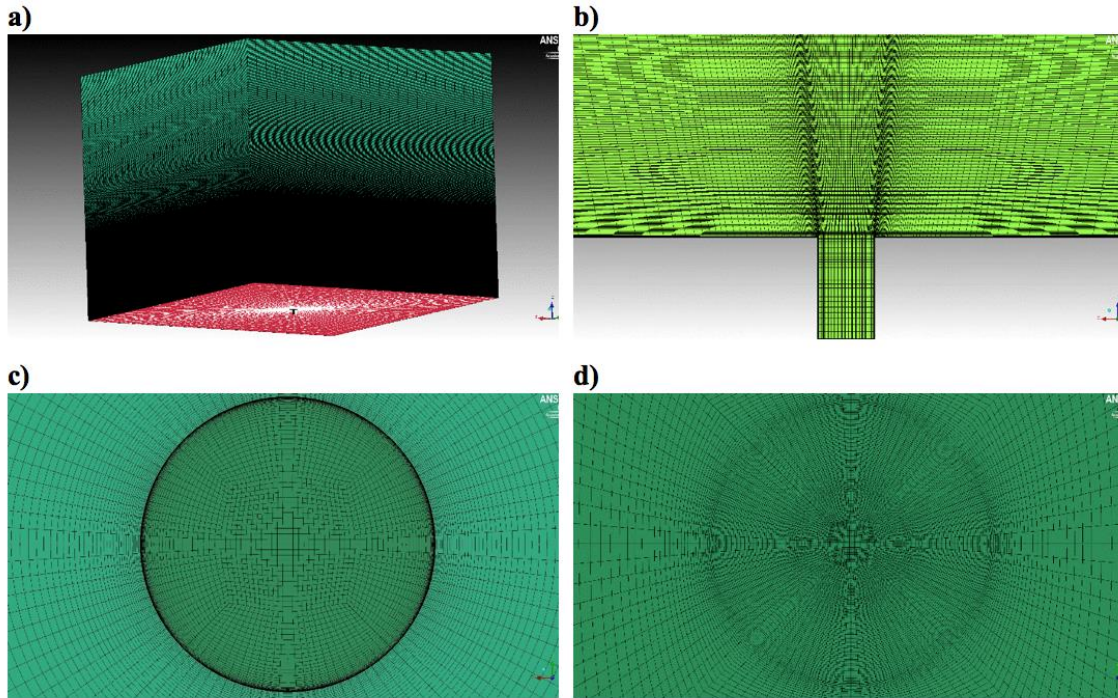


Figure 83: Mesh generated in ICEM-CFD: a) Complete domain, b) Cross-section at the center of the tank, c) View from the bottom of the tank, and d) view from the top of the tank.

5.2 Steady State Simulations

The first simulations that were executed used the Realizable $k\epsilon$ turbulence model for the uniform environment with the lighter fluid. The Realizable $k\epsilon$ model was used because of its ability to better predict the spreading rate for round jets. As previously stated, the nearfield region was investigated in the experiment with the lighter fluid. The comparison of the experimental and CFD results are shown in **Figure 84**. As shown in **Figure 84a**, the velocity profile of the CFD simulation at $y/D=5$, is larger; however, at higher y/D distances (**Figure 84b-d**), the profiles from the CFD simulations decay faster than that of the experiments. While the velocity is under and over predicted in the simulations, the general spread of the jet is well captured by the Realizable $k\epsilon$ model.

With a jet Reynolds number of 5300, as the jet travels away from the inlet, the jet is relaminarizing rather quickly, which could pose a challenge for the turbulence models.

Furthermore, by taking advantage of the symmetry of the experiment, several 2D-axisymmetric simulations were executed to avoid the long computation times from the 3D simulations. The mesh generated for the 2D-axisymmetric simulations was made by only keeping the cells at the mid-plane of the geometry. In this manner, the same cell distribution is maintained between the 3D and 2D simulations (at the mid-plane). The velocity profiles at several axial locations for the 2D-axisymmetric and 3D simulations are shown in **Figure 85(a-d)**. **Figure 85** shows that the 2D-axisymmetric simulation provides an almost identical profile to that of the 3D simulation. With this in mind, 2D-axisymmetric simulations were run to test different turbulence models to investigate if other models would better predict the centerline velocities.

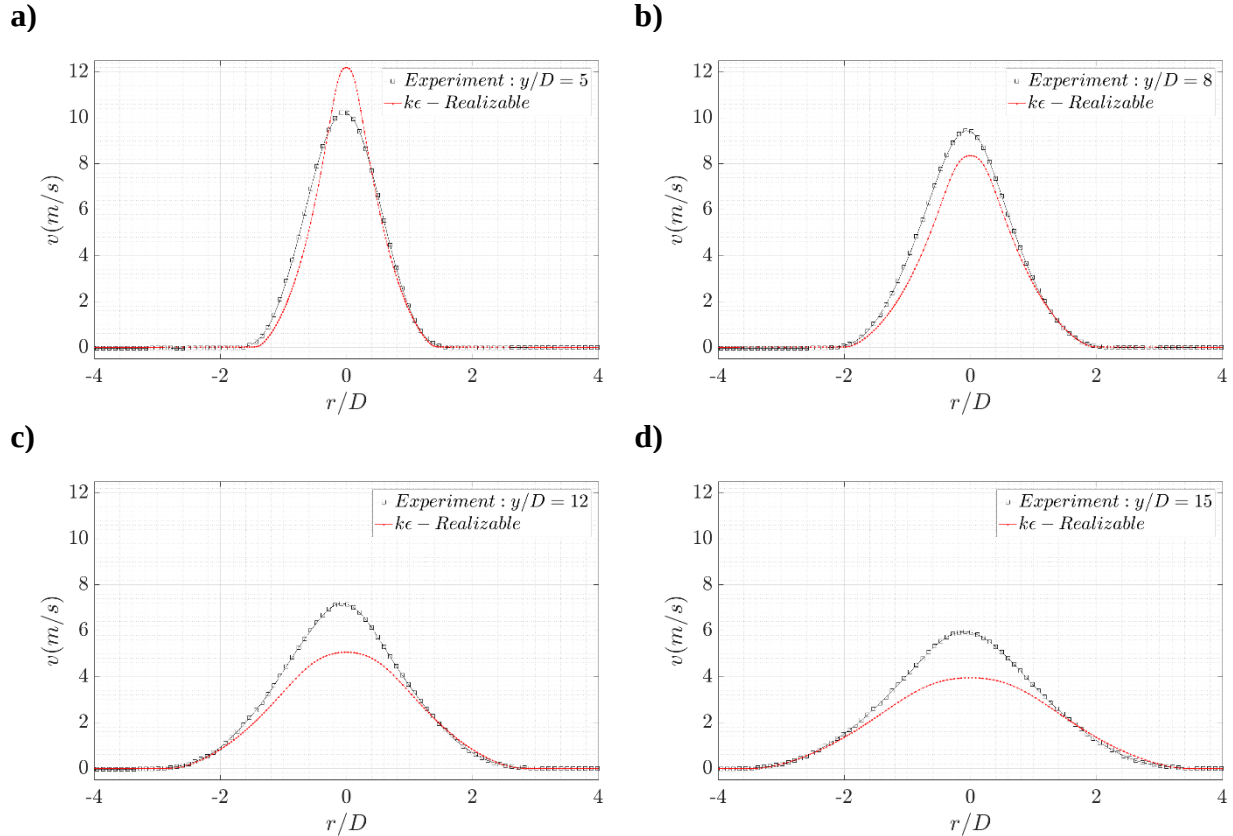


Figure 84. Profiles of the streamwise velocity component, v , at a) 5D, b) 8D, c) 12D, and d) 15D.

To investigate if the differences occur due to the turbulence model selection, the results from simulations that used the Realizable $k\epsilon$, Standard $k\epsilon$, $k\omega$ -SST, and the Reynolds Stress model were compared. As shown in **Figure 86(a-d)**, the velocity profiles for the 2D simulations with the Realizable $k\epsilon$, $k\omega$ -SST, and the Reynolds stress models produce nearly identical results. The only difference is that, compared to the other models, the $k\omega$ model predicts slightly lower velocities at the centerline at about $y/D=8$. The model that predicted different results was the Standard $k\epsilon$ model. This model under-predicted the velocity at the centerline (at $y/D=5$), did not capture the jet spread, and it tends to decay at a slower rate compared to the other models. With this being said, it was concluded that the Realizable $k\epsilon$ would be the adequate model to conduct further tests.

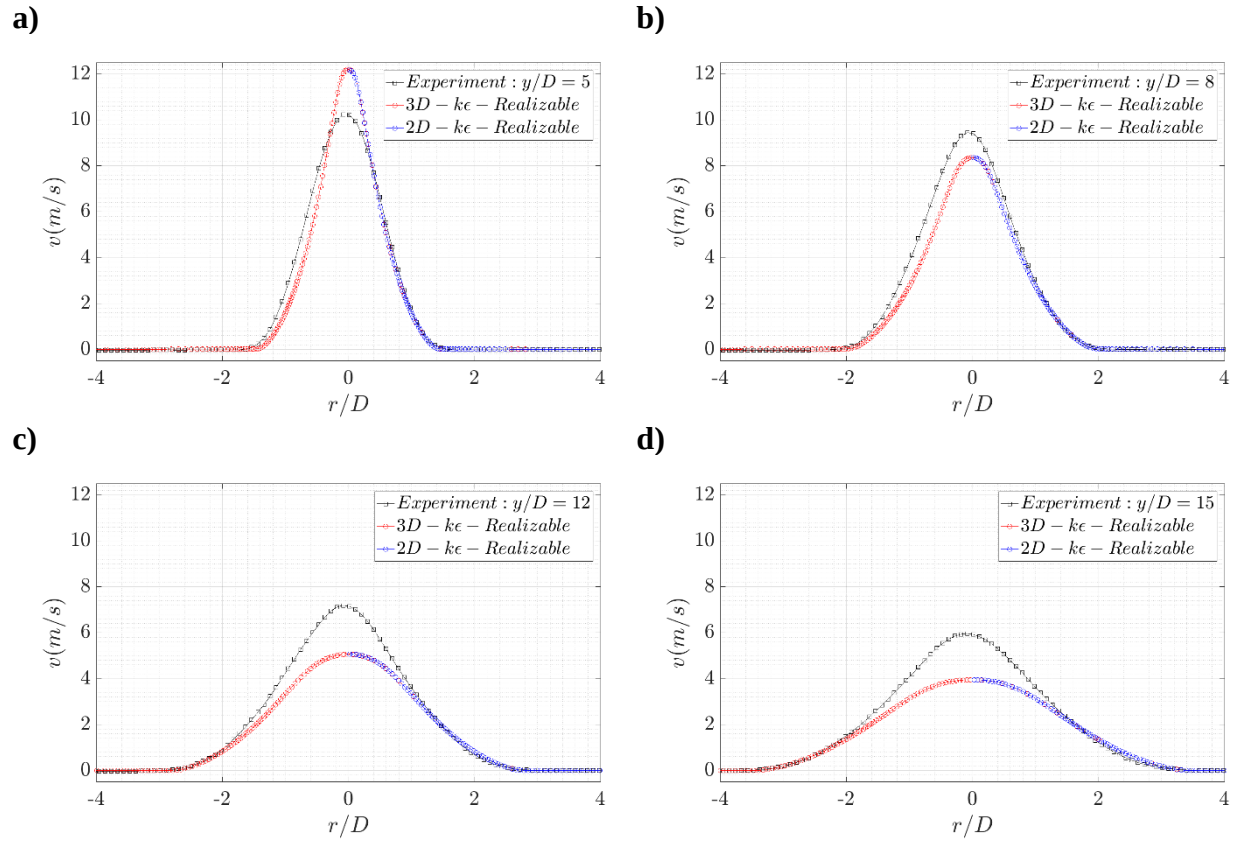


Figure 85. Experiments, 3D, and Axisymmetric simulations: Profiles of the streamwise velocity component, v , at a) 5D, b) 8D, c) 12D, and d) 15D.

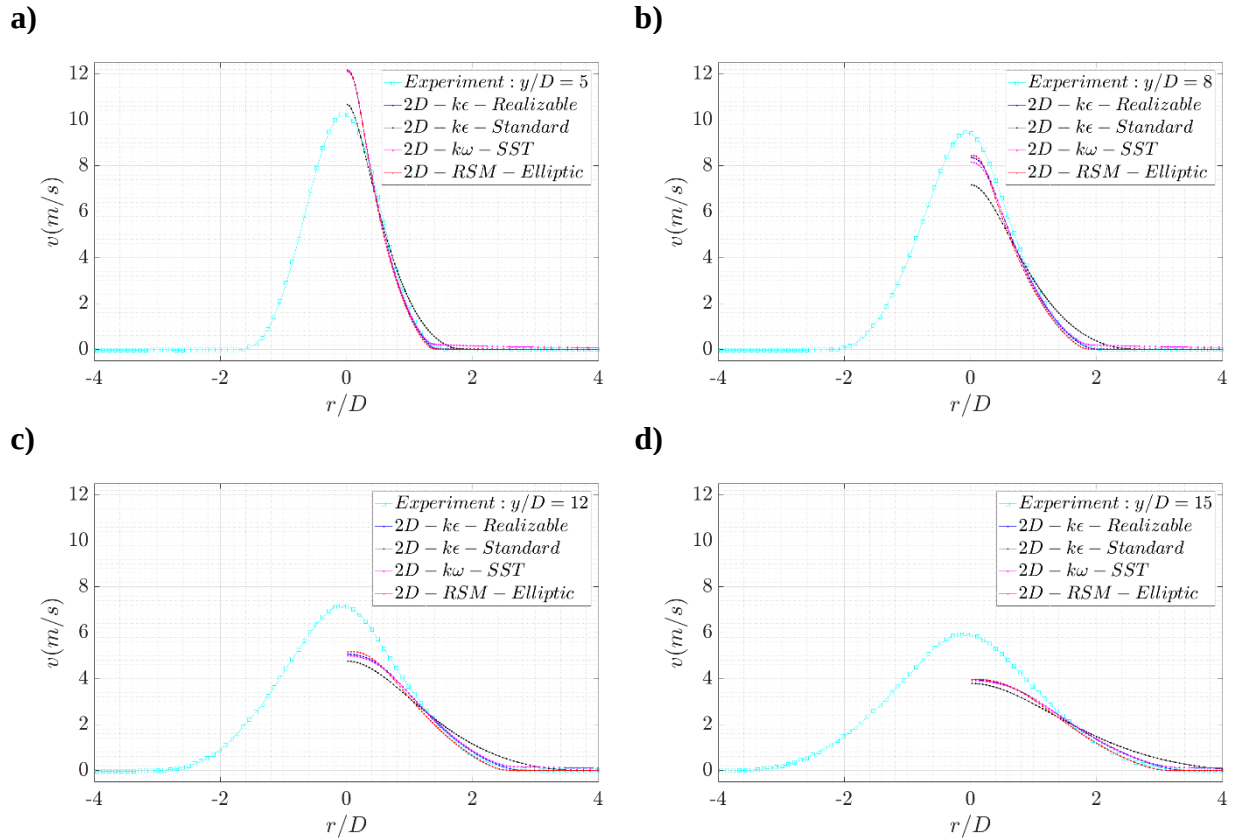


Figure 86. Profiles of the streamwise velocity component, v , at a) 5D, b) 8D, c) 12D, and d) 15D.

5.3 Transient Simulation – Simulation of the Sharp Interface Experiments

A transient 2D-axisymmetric RANS simulation of the experiment with the sharp density interface was set up to look for some similarities of the behavior of the jet as it reaches the interface. RANS simulations suppress fluctuations in the flow, and for this reason a 3D large eddy simulation will need to be executed to provide direct comparisons between the simulation and experiments. However, to get some insight of how the jet may behave near the interface, a RANS simulation was executed with the Realizable $k\epsilon$ turbulence model. The time step selected for this simulation was set to 10^{-5} seconds. The density fields at several time steps are shown in **Figure 87(a-f)**. Figure 87a is a snapshot of when the interaction at the interface starts taking place. As time passes, the jet starts merging with the interface, and eventually crosses the boundary (by **Figure 87c**), where the jet tends to expand in the cross-stream direction as shown in **Figure 87(d-f)**.

In **Figure 87**, the collapse of the jet observed in the experiments does not appear to be present. To ensure that this is the case, a time series of the density near the interface was recorded. The monitoring points and the time series of the density are shown in **Figure 88a** and **Figure 88b**, respectively. Surprisingly, a slight oscillation of the density is observed in the density time series for location $y = 0.119\text{m}$. Even though a small time step was selected, the oscillation is not as drastic as of that one seen in the experiments.

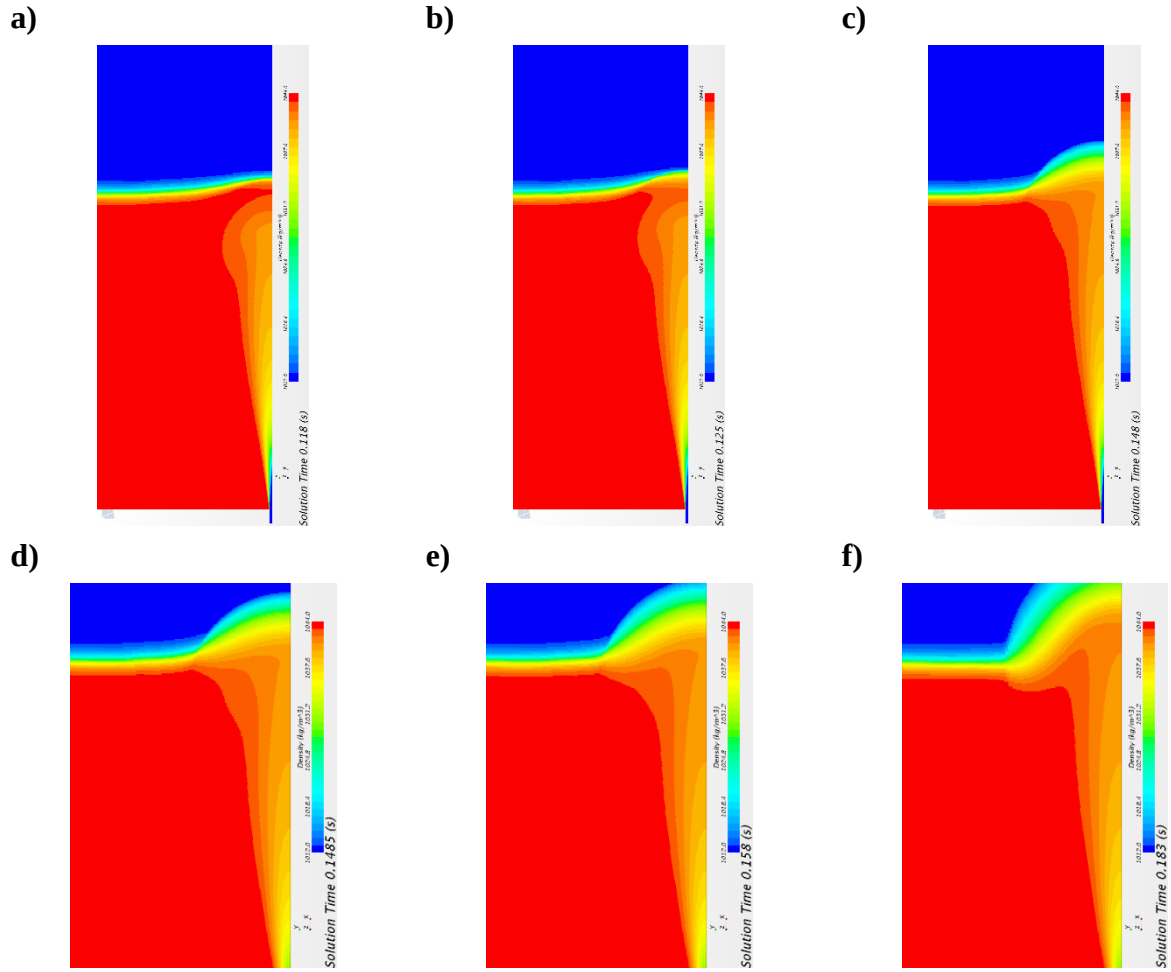


Figure 87. 2D-Axisymmetric RANS simulation of the sharp interface experiment at different time steps (a-f): (a-c) Zoomed out view and (d-f) zoomed in view.

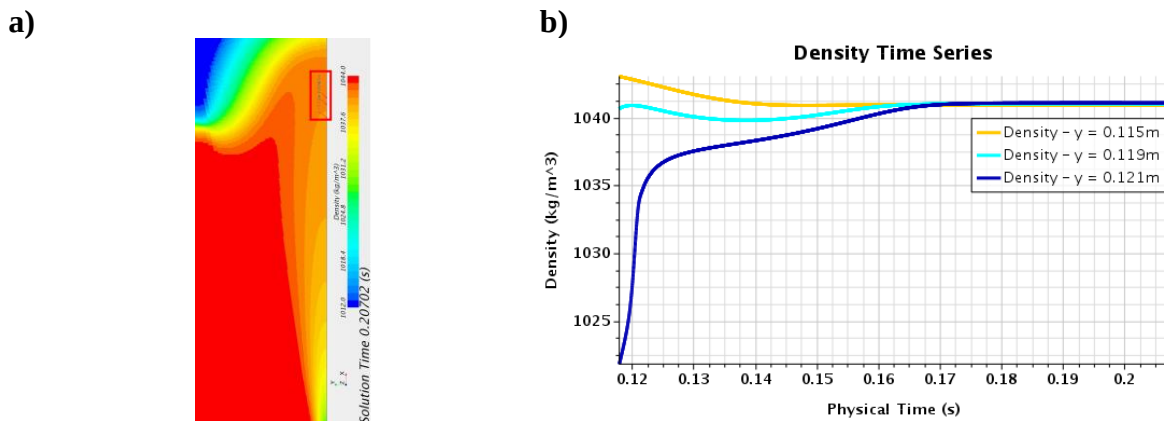


Figure 88. a) Location of the monitoring points along the centerline (red box) and b) time series of the density at the selected locations.

5.4 Large Eddy Simulations

Furthermore, as previously described, minor oscillations were observed in the RANS simulation of the experimental run with the sharp interface created by the Glycerol and Na_2SO_4 . A LES simulation is the perfect candidate to compare this type of transient simulation, since several more scale structures are resolved and not dampened. From the simulation and experimental results, a time step of $1\text{e-}6$ seconds was deemed appropriate to resolve the scales of interest for this setup. A LES simulation was set up; but unfortunately, not enough time steps elapsed to provide statistical quantities at the moment. A few images of the velocity magnitude fields from a large eddy simulation of a jet in a uniform environment are shown in **Figure 89**. Work on this topic is currently on-going. Results will be summarize in a follow-up publication.

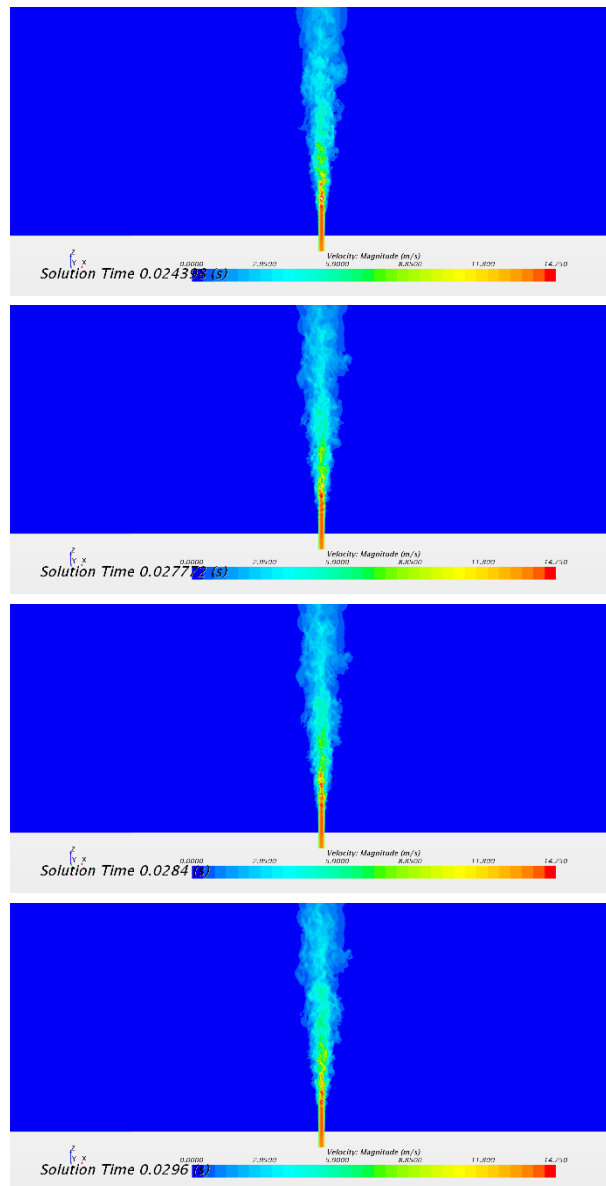


Figure 89. Velocity magnitude fields obtained from a Large Eddy Simulation of a jet in a uniform environment.

6 CONCLUSIONS - PART I

Using high-resolution, high-speed PIV and LIF techniques, we are able to perform high fidelity turbulent round free jet experiments in a uniform environment with DESTROJER facility. Benchmark database is available for the flow field for turbulent round free jets in uniform environments with nominal jet Reynold numbers range from 5'000 up to 22'500.

To make optical investigation possible for the stratified environment, our group at ECMFL proposed and proved a novel method to match refractive index for solutions with higher density differences using ternary plots. The methodology is successfully demonstrated using a ternary combination of water, isopropanol, and glycerol, for which RIM in the presence of a density ratio of 8.6% has been achieved. Also, utilizing the method, we proposed solution pairs which can potentially achieve a density difference of 7.62% using water, glycerol and sodium sulfate.

In the mini-DESTROJER (scaled) facility, using the study of the ternary plots, we create the uniform environment in the tank but shot the jet with another fluid with 8.6% density difference. Together with the wire-mesh sensors, we successfully build a stratified layer with a density difference of 3.16%. Qualitative analyses for LIF signals reveals the mixing mechanism when we have a jet impacting a sharp density interface and a linear stratification environment.

Work on validating CFD RANS models and LES is on-going.

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PART II – EXPERIMENTS AT GWU

GW's team has accomplished several significant development of diagnostic and data analysis for this validation effort. In short they are:

- The co-PI shared his design and expertise with UM.
- To establish a stratified that could be studied at high-Reynolds number, an index matching strategy was developed. It enable having fluids that are refractive index and dynamic viscosity matched at up to 7.5% density difference.
- The development of PIV was further advanced with the first time-resolved PIV measurements that are statistically resolved and covers a field of view of 0.5 m x 0.7 m.
- The first truly multi-spatio-temporal velocimetry measurement with PIV combined with long distance micro-PIV to resolve velocity field time history down to the Kolmogorov scale, representing an unprecedented coverage of 4 order of magnitude in space and 5 order of magnitude in time.
- GW has conducted extensive refinement to the experimental protocol to improve repeatability and reproducibility of the facility.
- GW developed extensive data analysis development (still ongoing), to characterize this non stationary and non ergodic flow. Such analysis will be the cornerstone of future CFD validation. Data and analysis tools will be shared with NE-KAMS in the near future.
- Two numerical teams are currently using the GW data to validate their unsteady CFD codes.
- One first publication in Experiments in Fluids (the premier journal for experimental methods developments) has been published, two more publications are under review for PLIF strategy and multi-spatio-temporal PIV. Once the data analysis is more complete, further publications will be submitted in the coming year.

7 Experimental facility

We shared our drawings of the facility with University of Michigan team. The Research Professor there came to GW's lab to discuss our design and make a series of measurements with us. We also shared insights on lesson learned from operating our facility to enable slightly improving the facility. We also shared the manufacturer of the acrylic components with our collaborator. For simplicity the facility is not reproduced from the section of UM.

The experimental facility consists of a round, axisymmetric, incompressible jet that discharges upward in a cubic tank with 914mm-side, Fig. 1. The jet nozzle is centered on the tank bottom face; a removable flat plate is set on the tank bottom to provide a flat surface at the same elevation than the nozzle exit. A linear motor drives a piston in a 203mm-diameter cylinder, which generates the jet. Since the fluid in the cylinder is initially at rest, the issuing flow has little to no initial disturbances. After the cylindrical chamber, the fluid goes through a first contraction section followed by a contoured nozzle with 32:1 contraction ratio and a $D = 6.35\text{mm}$ exit diameter. To minimize the interaction between the jet and the side walls, the tank has a width to nozzle diameter ratio of 144. It is made of clear acrylic to facilitate deployment of optical diagnostics.

The fluid in the cylindrical chamber has kinematic viscosity of $\nu = 1.162 \times 10^{-6} \text{m}^2 \cdot \text{s}^{-1}$, and the velocity at the exit of the nozzle is $U_o = 3.66 \text{m} \cdot \text{s}^{-1}$. The piston has a total travel of 140mm, which

results in a total run time of 42 s. The change in height in the tank from each run is 9.7mm or about 1.5D.

The stratified jet facility at GW can be operated over a range of Reynolds number (Re). To be over the mixing transition, we elected a nominal $Re = 20,000$. The jet is positively buoyant and discharges in a linearly stratified environment using the two tanks method.

7.1 Index matching

The details of the work are given a journal publication, Clement et al 2018, which is attached to this report.

To study the vertical discharge of a buoyant jet in a linearly stratified environment, two refractive index matched solutions of different densities are employed. The light one is a glycerol solution with a concentration of 6.31% weight (% wt.) and the heavy one is a sodium sulfate solution with a concentration of 5.00% wt. Their density difference is set at 3.00%, while having the refractive index matched within 1.4×10^{-4} and a dynamic viscosity difference of only 0.7% at 20°C. Subsequent numerical simulations of the flow are simplified by suppressing viscosity variations and leaving only buoyancy effects.

7.2 Stratification establishment

The stratification is created using the so-called “Two-Tank Method”. The light and dense solutions are initially stored in two large reservoirs, Tank A and B, respectively. To create a linear stratification, fluid is pumped from Tank A into Tank B at a flow rate Q , and from Tank B into the facility tank at a flow rate $2Q$, over a thin, perforated foam board that floats. After the tank is filled, the floating foam board is left on the top of the tank fluid and the hole filled with blanks. This provides a solid surface with an open gap around its circumference that lifts as the fluid rises during a run.

Prior to filling the experimental facility test section, the cylinder, which encases the piston, is filled with the light solution from a small dedicated reservoir. A horizontal plate with rubber backing seals the nozzle and isolates the cylinder from the test section. The plate is slid to the side of the test section before initiating the jet and provides minimal disturbance to the initially quiescent fluid in the test section. Multiple jet runs can be accomplished by placing the plug back on the nozzle and filling the cylinder from the small reservoir. Special attention is given to make sure there is no initial circulation in the large tank.

Before and after each run, a conductivity probe travels the tank elevation to measure the density profile. Only the salt solution has conductive ions and the relative concentration of glycerol and salt solutions, and therefore density, can be directly deduced from the conductivity measurements, Fig. 94.

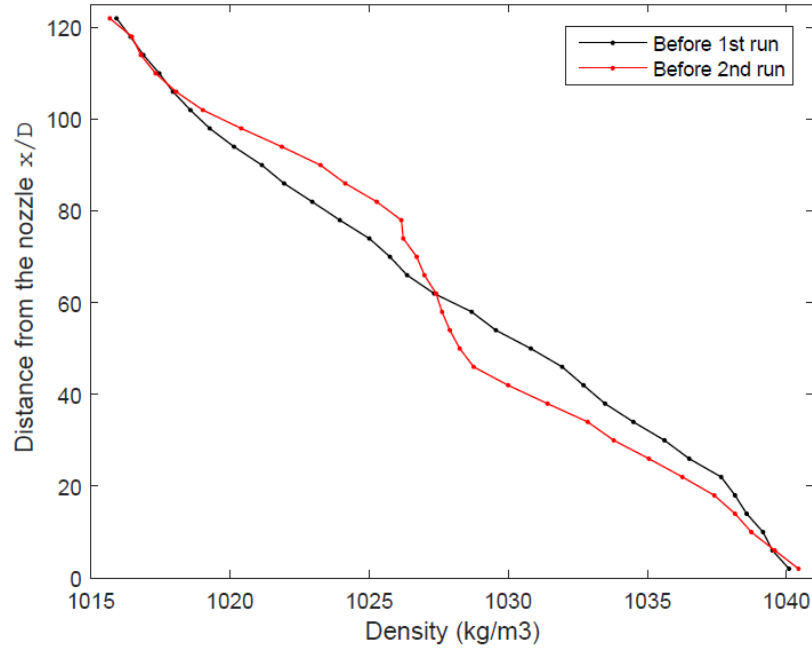


Figure 90. Density profile across the tank before each run.

8 Multi-spatio-temporal resolution PIV configuration

8.1 Camera selection

During the discharge of the buoyant jet, the surrounding stratified environment is continuously changing and the flow might not reach statistical stationarity. Therefore, it was elected to record the entire time history of the velocity fields in a time-resolved (time series) manner: initial conditions to verify that the fluid is quiescent, the entire run, and the settling down after the jet ends. As a result, data need to be acquired for more than one minute, which puts constraints on the camera selection. The 12 cameras are one single side of the tank. Details of the cameras configuration are given in Fig. 95.

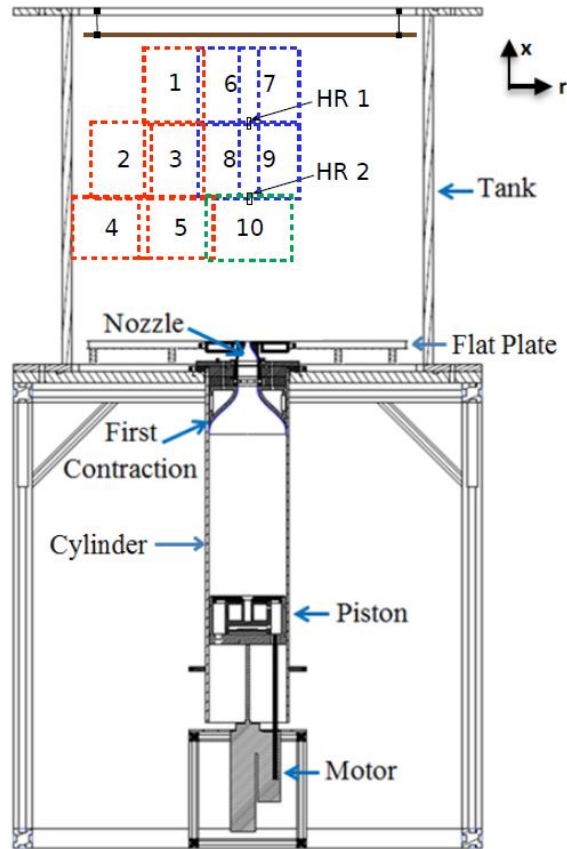


Figure 91. Camera positioning within the test section.

Cameras 1 to 9 are used to record the off-center and far field of the jet. They stream to hard drive at up to 150 fps and with a resolution of 1.3 Mpixels. The magnification of all these cameras is identical and data acquisition rate adapted with location to still have time-resolved measurements.

Camera 10-12 are identical, but configured differently. They have higher frame rates and resolution than the cameras 1-9. At the maximum resolution, (4 Mpixels, $2,336 \times 1728$ pixels), the cameras can stream to harddrive at 560 fps and 8 bit. At a frame rate of 2,304 fps, which is used for the high resolution measurements, a resolution of nearly 1 MPixel is achieved. The workstations associated with each camera have 2 TB of memory, compare too 10s of GB for most CMOS cameras. This enables nearly 15 mn of recording time!

Camera 10 records the flow around the centerline in the lower section of the jet. There the flow has higher velocity and smaller turbulent structure are expected, which motivated the use of this higher resolution camera.

To capture the turbulent kinetic energy spectra along the centerline, two cameras are used at a spatial resolution that is nearly one order of magnitude larger than for the large field of view measurements.

8.2 Laser planes configuration

The large dynamic range in camera spatial resolution forces special configuration of the laser illumination. In particular, it was preferable to control the laser sheet thickness locally as to prevent volumetric averaging in depth. The intensity is also controlled locally to accommodate the different sensitivity of the cameras. In total, three large laser sheets are used for large field of view

data (cameras 1-10) and two for the high-spatial resolution data (cameras 11 and 12). The optical setup is shown in Fig. 96.

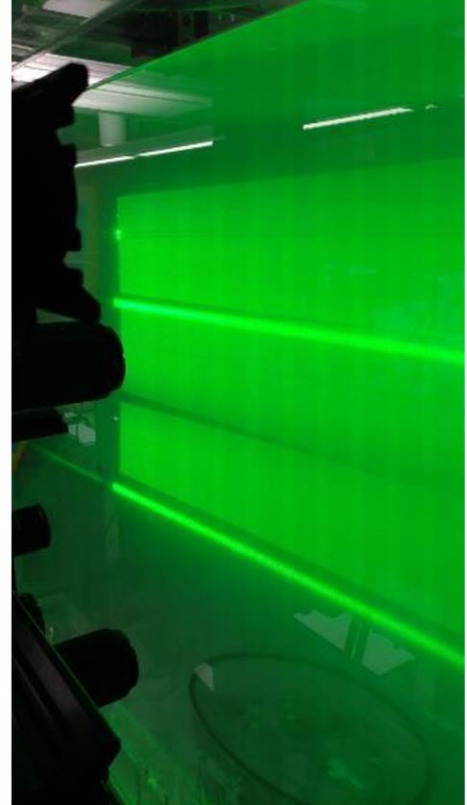
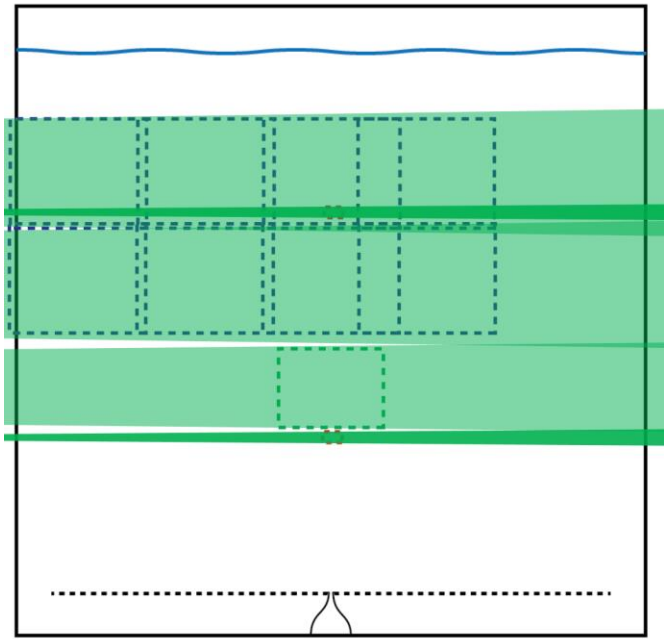


Figure 92. PIV planes.

To prevent cross-talk between the laser planes on the cameras, the timing of the lasers and cameras is carefully controlled with a series of 3 external pulse generators and monitored with a 500 MHz oscilloscope with 20 channels.

The PIV data are processed using Davis 8.3, with a 50% overlap, 2 passes with circular windows containing 96×96 pixels and 2 passes with circular windows containing 32×32 and 48×48 , for low and high resolution, respectively. A universal outlier detection is then performed based on the difference between neighboring vectors. No temporal smoothing is used to avoid altering the velocity spectra obtained from the time evolution of the velocity fluctuations.

For the large field of view images, calibration is performed with a large in-house calibration target that covers the entire tank. During calibration, the RMS of the fit is below 0.03 pixels for cameras 1 to 10, which is low and ensures distortions from calibration are negligible compared to the PIV

processing uncertainty. For the high resolution images, only scaling is performed using a ruler positioned in the calibration plate. A simple scaling is sufficient for the high resolution measurements, because optical aberrations are strongly limited by the small size of the field of view and high quality of the lens used.

9 Results

9.1 Mean large scale behavior of the jet

The global behavior of the jet is obtained by stitching the velocity fields obtained from cameras 1 to 10. The time averaged velocity field (averaged over the 39 s of the jet) is given in Fig. 97.

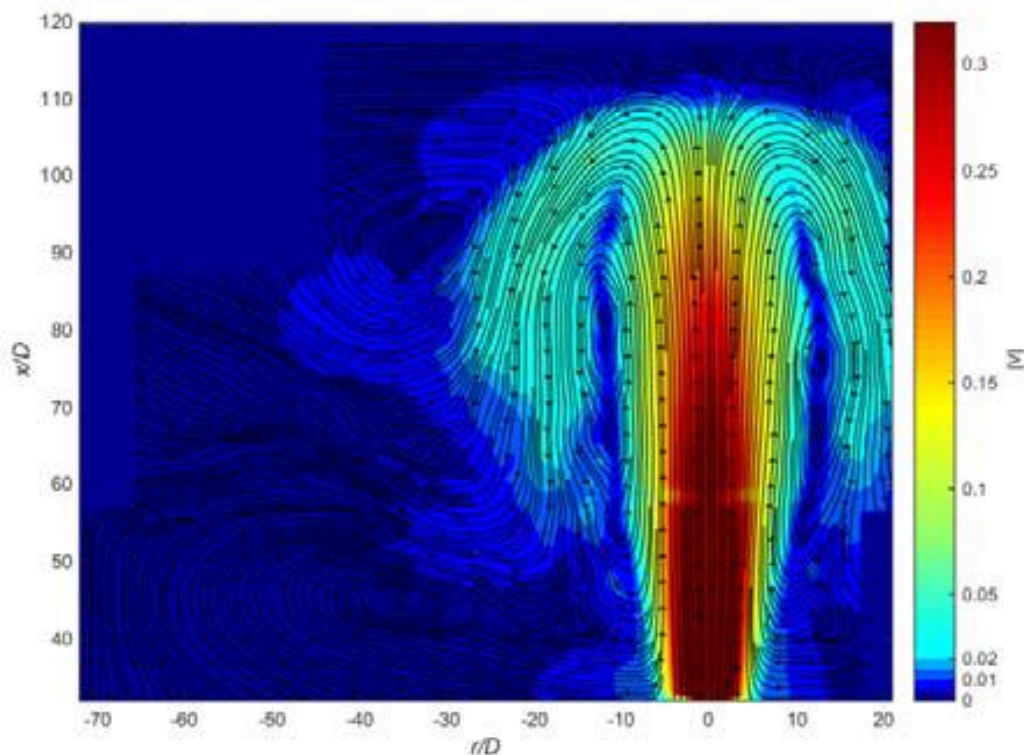


Figure 93. Mean flow as recorded by cameras 1-10.

Dense fluid is entrained at the bottom of the jet, increasing its density until the jet becomes heavier than the surrounding environment. The jet then reaches a maximum height (the dome) and falls back on the sides. A shear layer forms between the upward jet and the downward current on the sides, generating large scale vortices. On the sides, the fluid reaches the neutral buoyancy height and spreads horizontally, close to the center of the linear stratification. It can also be observed that the downward current on the sides of the jet entrains light fluid from the top of the tank, creating another set of large vortices. The only study that allows comparison is LES performed at lower Reynolds number for a bubble-driven buoyant plume in a stratified environment. Similar behavior is observed, with large scale vortices located in the same regions of the flow.

The centerline velocity decay follows similar trends than recorded in previous studies with the dome being marked by the zero velocity region, Fig. 98.

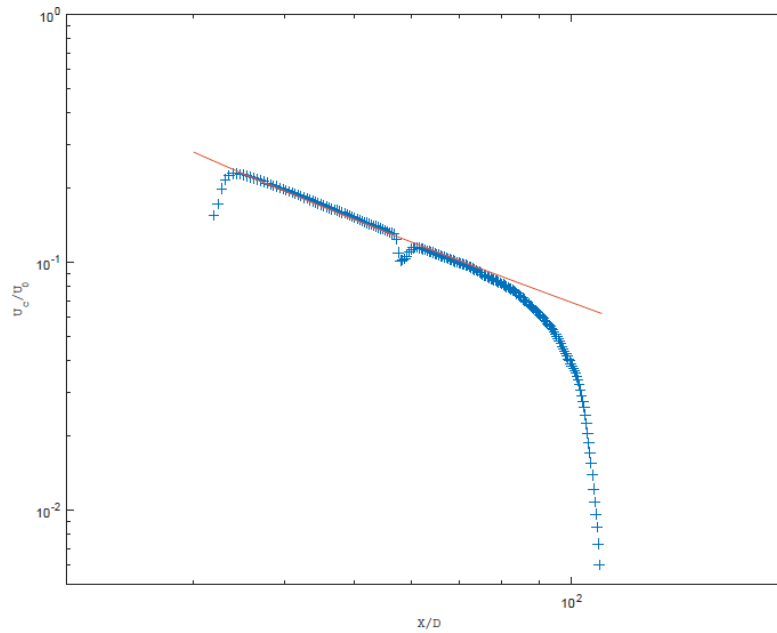


Figure 94. Mean centerline velocity decay.

9.2 Velocity Spectra from multi-spatio-temporal scale PIV

On top of measuring the general behavior of the jet, the smallest scales of turbulence can also be resolved with the proposed experimental setup. Because no data are available for a buoyant jet in a linearly stratified environment, the design of the instrumentation was made based on theoretical lengthscales for a non-buoyant jet.

The repartition of energy in a turbulent flow between its different length (or time) scales is best represented by the spectrum of the turbulent kinematic energy, which is given by the power spectral density of the velocity fluctuations. In Fig. 99, the power spectra of the axial velocity fluctuations are given for both fields of view, at 50 D and on the jet centerline. For the large field of view, the PSD is calculated with windows of 256 points in length and a stride of 64. For the reduced field of view, the PSD is calculated with windows of 2,048 points and a stride of 512.

Both spectra show the existence of the inertial subrange ($-5/3$ slope) over approximately one frequency decade, which is expected for a jet at $Re = 20,000$. The inertial sub-range has also been observed using PIV, using a FOV close to the large FOV of the present study. However, starting at about 40 Hz, the large FOV spectrum shows the appearance of aliasing, which is consistent with Nyquist frequency for PIV.

It can be noted that some discrepancies can be observed on the high spatial resolution spectrum at frequencies. The noise there is due to limitation in PIV processing in resolving low velocities. Nevertheless this could be improved by using a pyramidal processing scheme such as the one proposed by other groups.

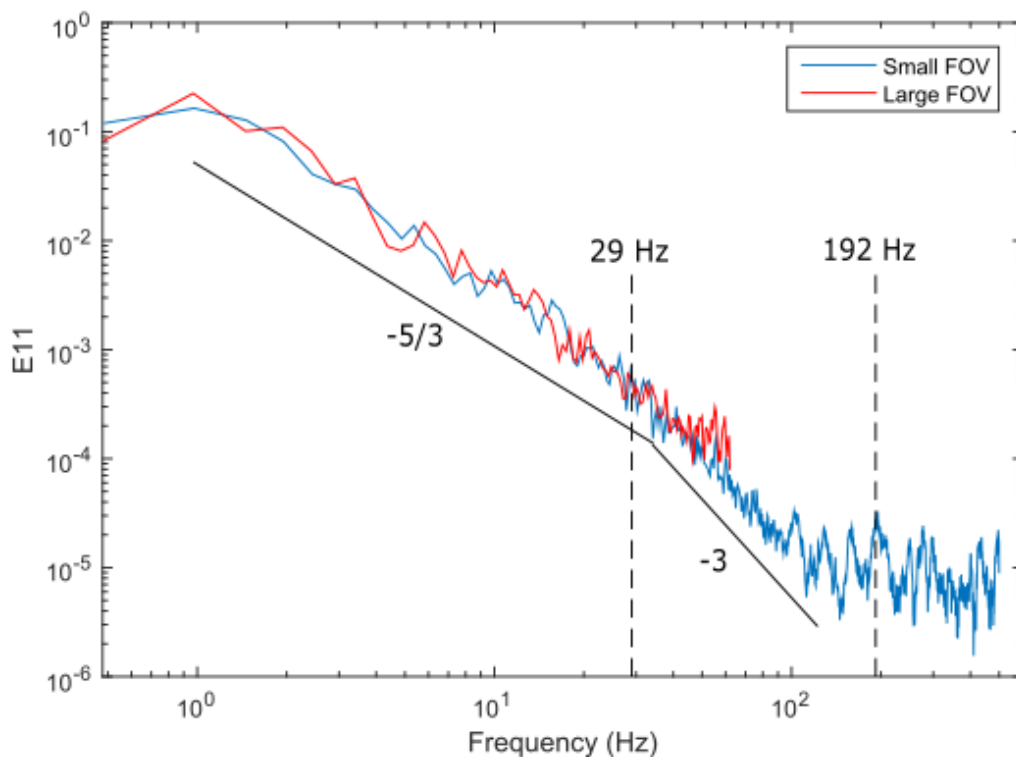


Figure 95. PSD of axial velocity fluctuations on centerline.

9.3 Dynamic evolution of the jet

Using nonlinear decomposition of the flow, we showed that the flow is not stationary and non-ergodic. This requires special consideration in treating data in particular to validate CFD code. An example of this can be seen by plotting the turbulent kinetic energy in a domain of the flow, Fig. 100. Large and low frequency oscillations are the indication of a slow process that could not have been captured with traditional velocimetry. This analysis is ongoing in collaboration with international teams with whom we are collaborating.

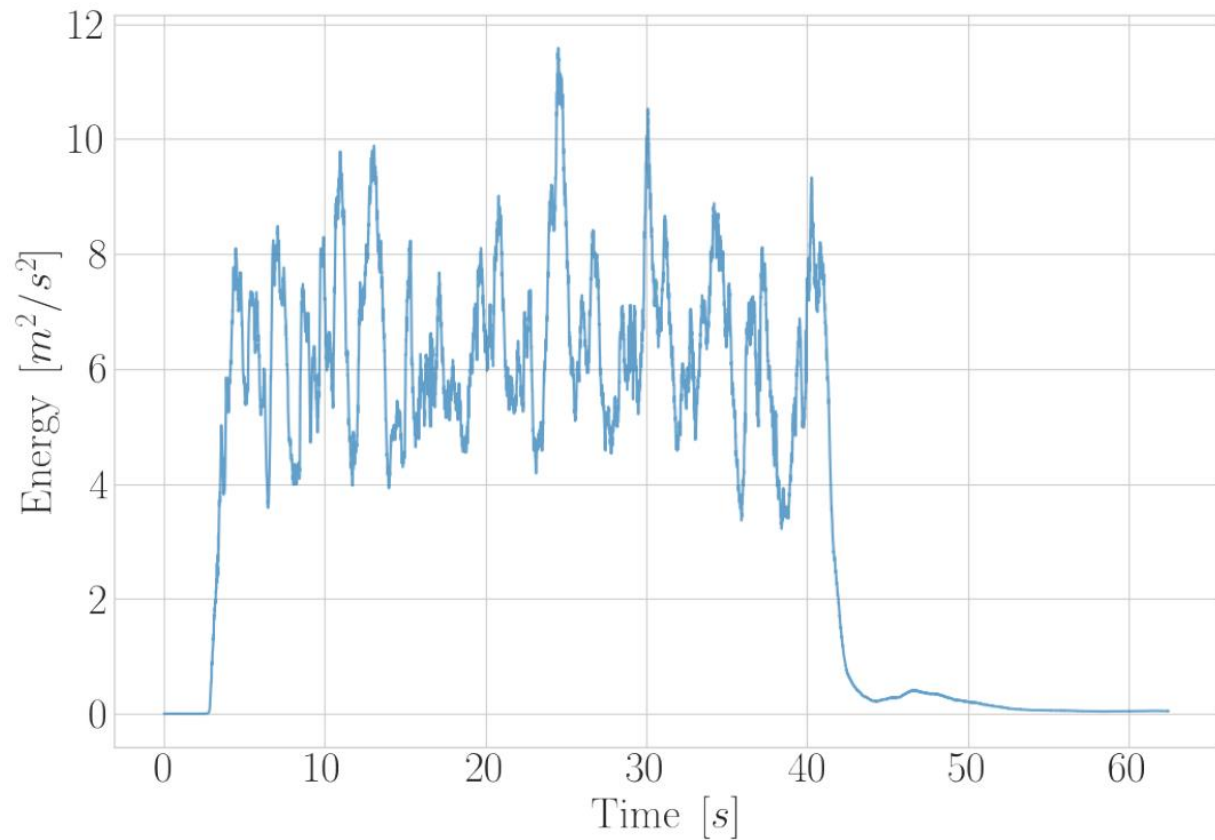


Figure 96. kinetic energy of the jet over a domain of the flow.

10 REFERENCES – PART II

Westerweel J., “Efficient detection of spurious vectors in particle image velocimetry data”, *Experiments in Fluids*, **16**(3), 1994.

11 PUBLICATIONS

11.1 Peer-Reviewed Journals

- B. Krohn, A. Manera and V. Petrov, “A novel method to create high density stratification with matching refractive index for optical flow investigations.” *Experiments in Fluids*, **59**(4), pp. 66 (2018).
- SA CLEMENT, A GUILLEMAIN, AB MCCLENEY, and PM BARDET. Options for matching refractive index and viscosity of aqueous solutions to study variable density flows, *Experiments in Fluids*. **59**(32), 2018.

11.2 Peer-Reviewed Journals – under review

- SA CLEMENT, AB MCCLENEY, and PM BARDET. Multi-spatio-temporal scales PIV applied to a buoyant jet in a linearly stratified jet. *Experiments in Fluids*.
- SA CLEMENT and PM BARDET. New data on fluorescence of Rhodamine 6G over a large range of concentration. *Journal of spectroscopy*.
- S. Qin, B. Krohn, J. Downing, V. Petrov, and A. Manera, “High Resolution Velocity Field Measurements of Turbulent Round Free Jets in Uniform Environments,” *invited for publication in Nuclear Technology*.
- B. Krohn, S. Qin, J. Downing, V. Petrov and A. Manera, “An Experimental Study of Local Self-Similarity in the Mixing Transition of a Turbulent Free Jet,” *invited for publication in Nuclear Science and Engineering*.

11.3 Peer-Reviewed Journals – in preparation

- SA CLEMENT and PM BARDET. Velocity fields history of a buoyant jet in a stratified environment with confinement. *Journal of Fluid Mechanics*. In Preparation.
- C FORT, SA CLEMENT, AB MCCLENEY, MA ANDRE, and PM BARDET. Super-sampling for high magnification PIV. *Experiments in Fluids*. In Preparation.
- SA CLEMENT, R FORCHA, and PM BARDET. PLIF in index matched experiments in stratified environments. *Experiments in Fluids*. In Preparation.

11.4 Conference Proceedings

- S. Qin, B. Krohn, J. Downing, V. Petrov, and A. Manera, “High Resolution Velocity Field Measurements of Turbulent Round Free Jets in Uniform Environments,” *Proceedings of 17th International Topical meeting on Nuclear Reactor Thermal hydraulics*, September 3-8, 2017.
- B. Krohn, S. Qin, J. Downing, V. Petrov and A. Manera, “An Experimental Study of Local Self-Similarity in the Mixing Transition of a Turbulent Free Jet,” *Proceedings of 17th International Topical meeting on Nuclear Reactor Thermal hydraulics*, September 3-8, 2017.
- B. Krohn, S. Qin, V. Petrov and A. Manera, “Refractive Index Matching for Optical Flow Investigation with High Density Stratification,” *Proceedings of the ASME 2018 5th Joint US-European Fluids Engineering Summer Conference (FEDSM2018)*, July 15-20, 2018

- B. Krohn, S. Qin, V. Petrov and A. Manera, “Coherent Structures and Correlations Fields in the Mixing Transition of a Turbulent Round Free Jet,” *Proceedings of the ASME 2018 5th Joint US-European Fluids Engineering Summer Conference (FEDSM2018)*, July 15-20, 2018.
- SA CLEMENT, R FORCHA, and PM BARDET. Spatial and temporal evolution of a buoyant jet in a linearly stratified environment, *ANS National Meeting*, Washington, DC, Oct. 30-Nov. 3 2017.
- AB MCCLENEY, SA CLEMENT, and PM BARDET. Multi-scale, long recording, time-resolved PIV for turbulence statistics and uncertainty reduction in a turbulent jet. *18th International Symposium on Applications of Laser Techniques to Fluid Mechanics*, Lisbon, Portugal, 04-07 July 2016
- AB MCCLENEY, and PM BARDET. Multiscale measurements on a turbulent jet and refractive index matching for a buoyant jet in a stratified environment. *Proceedings of ANS Annual Conference*, Washington, DC, November 2015
- AB MCCLENEY, and PM BARDET. Initial condition effects on Kelvin-Helmoltz instabilities and development of a round jet. *NURETH 16*, August 2015.

11.5 Awards

2017 Best paper award, NURETH-17 conference (selected within over 700 manuscripts): S. Qin, B. Krohn, J. Downing, V. Petrov, and A. Manera, “High Resolution Velocity Field Measurements of Turbulent Round Free Jets in Uniform Environments”.

APPENDIX I –UM ARTICLE #1

Proceedings of the ASME 2018 5th Joint US-European Fluids Engineering Summer Conference
FEDSM2018
 July 15-20, 2018, Montreal, Quebec, Canada

FEDSM2018-83245

REFRACTIVE INDEX MATCHING FOR OPTICAL FLOW INVESTIGATION WITH HIGH DENSITY STRATIFICATION

Benedikt Krohn, Sunming Qin, Annalisa Manera and Victor Petrov
 University of Michigan
 Ann Arbor, Michigan, USA

ABSTRACT

Turbulent mixing in density stratified environments represents a challenging task in experimental turbulence research. When optical measurement techniques like Particle Image Velocimetry (PIV) are applied to stratified liquids, it is common practice to combine two aqueous solutions with different densities but equal refractive indices. As a result, light deflections/distortions due to the mixing of the fluids can be suppressed. While refractive image matching (RIM) was developed in the late '70s, the limit of a 4% density ratio had yet to be reported before this work. In the present work, a methodology based on the behavior of changes in a multi component system while mixing is presented. This methodology allows RIM for solutions with higher density differences. The applicability of this methodology is experimentally demonstrated with a turbulent buoyant jet using a ternary combination of water, isopropanol and glycerol, for which an index matched density ratio of 8.6% has been achieved. Measurements were conducted with a high fidelity synchronized PIV/PLIF system and the results are qualitatively compared in terms of turbulent statistics.

INTRODUCTION

The influence of density gradients on the dynamics of mixing fluids presents many challenges in turbulence research. Such flows can be of large scale likethose present in the atmosphere and ocean currents. Small scale cases can even be on the microscale like the turbulence of computer chip cooling systems.. Of particular interest, density effects play a major role in nuclear power plants (Paladino et al. 2012), ranging from design and operation of safety systems to plant component behaviors in accident and operational conditions. Here, the interaction of two miscible fluids with different densities occurs due to high temperature gradients, chemical reactions of different agents or by the mixing of two different fluids. The dynamics of fluid motion can generally be described by the Navier-Stokes (NS) equations, which identify the momentum balance, the mass conservation, and the energy balance of the

flow. However, there is no analytical solution yet so it is common practice to solve the NS equations numerically by making use of computational fluid dynamics (CFD) simulations. These computations usually employ correlations and models at various scales. Due to unaffordable computational efforts, modelling is crucial since scales at which turbulence occurs in practical applications renders a direct numerical solution of the NS equations impossible.

The most prominent CFD models are based on space filtering within the use of large eddy simulations (LES) and time filtering when Reynolds Averaged Navier Stokes (RANS) equations are used. RANS equations employ the statistical approach to decompose the time dependent variables of the NS equations into a time averaged and a fluctuating quantity; i.e. the velocity is decomposed into $\mathbf{u} = \bar{\mathbf{u}} + \mathbf{u}'$. The filtered equations to describe fluid motion take the following form, with ρ being the density field, Φ being the scalar field (e.g. temperature), Γ the diffusivity, and η the dynamic viscosity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial(\rho \bar{u}_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j) \\ = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\eta \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right] \\ + g_j(\rho - \rho_0) \end{aligned} \quad (2)$$

$$\frac{\partial(\rho \bar{c})}{\partial t} + \frac{\partial}{\partial x_j}(\rho \bar{c} \bar{u}_j) = \frac{\partial}{\partial x_j} \left(\Gamma \frac{\partial \bar{c}}{\partial x_j} \right) - \frac{\partial}{\partial x_j}(\rho \overline{u'_j c'}) \quad (3)$$

Reynolds decomposition leads to the covariance of velocity components $\overline{u'_i u'_j}$ and turbulent fluxes $\overline{u'_i c'}$ which need to be modeled. A wide range of models exist for the velocity covariance, with each being tailored to a specific flow situation; however, the modelling of turbulent fluxes is mainly based on the standard gradient diffusion hypothesis

(SGDH). Here, the flux is linearly related to its mean gradient under the assumption of local thermodynamic equilibrium:

$$-\overline{\rho u'_j c'} = \Gamma_t \frac{\partial \varepsilon}{\partial x_j} \quad (4)$$

with Γ_t being the turbulent diffusivity. Buoyant flows can be generally characterized in terms of the Reynolds and densimetric Froude numbers,

$$Re = \frac{\bar{u}L}{\nu}, \quad Fr = \frac{\bar{u}}{\sqrt{gL}} \quad (5)$$

with the kinematic viscosity ν and the acceleration due to gravity g . When considering geophysical or engineering applications, Xiang et al. (2015) pointed out that Reynolds numbers are usually large (of the order 10^6 or higher) while the Froude number, even for a strong stratified atmosphere would be of the order 10^{-1} . Turbulent time scales associated with such flows are typically three orders of magnitude shorter than those associated with buoyancy frequencies, thus they could be considered negligible. However, without adding further energy into the fluid, the velocity decreases with increasing turbulent length scales and eventually buoyancy forces take over. Once buoyancy effects dominate the inertia of the flow, it has been noticed that currently available models for turbulent momentum fluxes tend to overestimate thermal stratification while underestimating turbulent mixing (Petrov and Manera 2011). Even LES approaches fail to correctly reproduce thermal stratification. This is due to the local isotropy assumptions currently at the basis of most LES subgrid scale (SGS) models, which break down in cases where flow interacts with stratified layers. The breakdown is the result of baroclinic forces creating a significant redistribution of turbulent kinetic energy and scales, leading to anisotropic turbulence. Also, the small scales of the passive scalar advected by a turbulent velocity field display a persisting anisotropy (Bos 2014).

The understanding of the underlying physical principles of these flows is not trivial and there is an emerging need for experimental investigations to improve the existing models. A promising possibility to answer this question is to apply optical measurement techniques like Particle Image Velocimetry (PIV) and Laser Induced Fluorescence (LIF) to actual flows. These methods allow for the acquisition of the temporal evolution of velocity and temperature (or concentration) fields (Adrian and Westerweel 2011). Unfortunately, a variable density or temperature field is usually connected to a variable refractive index (RI). Therefore the applicability of an optical measurement technique like PIV or LIF is limited to very small density differences to avoid blurred images. In order to overcome these limitations, most of the available experiments have focused on low-Re cases, where the Froude number is of the order of 1 and the flow is strongly affected by density stratification. This is still the case even though Riley and De Bruyn Kops (2003) pointed out the significant difference in the dynamics of such stratified flows compared to high-Re

conditions. A few experiments with strong density stratification have been reported. E.g. Augier et al. (2014) generated a density gradient of 20% using water – salt (NaCl) solutions, but the authors did not match the RI and argued that possible effects of RI variation are sufficiently small due to weak small scale mixing. Daviero et al. (2001) pointed out that refractive index matching (RIM) can address the limitation of optical techniques by making use of liquids with different density but equal RI. The method was first introduced to the experimental society by McDougall (1979) who applied laser Doppler velocimetry (LDV) to an aqueous combination of Epsom salt and sugar to reach a density difference of 0.015 g/cm³ (~1.5%). Other solutions were published by Hannoun (1985), who used an aqueous combination of ethanol and salt (NaCl) to reach a density difference of 0.03 g/cm³ (~3%).

Focusing on variable densities and equal refractive indices in fluid mixing, all methods reported in scientific literature use two aqueous solutions. Although this is a start, in cases with larger density differences it is of paramount importance to keep the RI constant with changing mixing scalar. Using two binary aqueous solutions, it is therefore necessary to investigate the RI across the whole composition diagram (for two binary solutions a ternary diagram is needed), in order to identify the regions where the RI remains constant along the connecting line of two chosen solutions.

METHOD

In the present study we demonstrate a method that allows for index matched density differences up to 8.6%. The methodology is applied to PIV measurements of the velocity field of a buoyant turbulent jet. As pointed out previously, the density difference can be achieved by either varying temperatures of both liquids, or by using two miscible liquids of different densities. If optical measurement techniques are used in an environment with temperature gradient, the resulting variable RI as function of the temperature field makes it impossible to collect unbiased results. Therefore the focus of this work is to achieve high density ratios of two miscible agents without temperature variation.

In previous studies, attempts were undertaken to model the excess RI based on the nonlinear rate of change in density (Augier et al. 2014; Daviero et al. 2001). The basic principle was to relate optical distortion to the specific excess volume within a mixture. This assumption may hold for weak polar molecules, as they are of interest in petro-chemistry, but this relation is no longer applicable for molecules with high polarity – especially water.

Motivated by the field of petro-chemistry, Touriño et al. (2004) reported empirical correlations in order to predict the RI in ternary mixtures, specifically with chlorobenzene + n-hexane + (n-heptane or n-octane). This approach has then been refined by Yahya and Saghir (2015) who applied it to a variety of ternary hydrocarbon mixtures. Both found their predictions in substantial agreement for experimental results. The method is based on the concept of thermodynamic excess properties that are present when mixing two or more differing liquids.

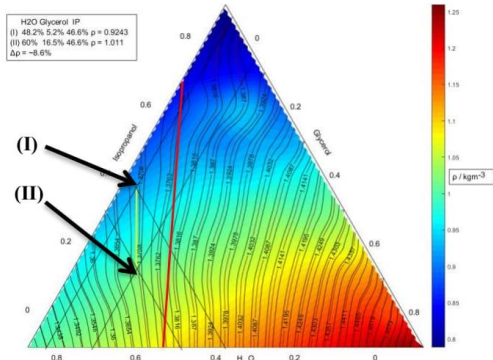


Fig. 1 Contours of constant refractive index in superposition of the density (colormap) for the ternary system H₂O - Glycerol - Isopropanol

There was no data reported in scientific literature for suitable aqueous solutions with information of both the RI and the density that would exhibit large density ratios. Therefore, a combination of two aqueous solutions was chosen in the present work, in particular a mixture of H₂O, Isopropanol (CH₃CHOHCH₃) and Glycerol (H₂O-CH₂OHCHOHCH₂OH). All three liquids are fully miscible among each other, and the two solutions exhibit a large density difference. Measurements of the refractive index and the density at a temperature of 298.15 K and atmospheric pressure over the whole composition diagram of the H₂O - Isopropanol - Glycerol system were performed. A Sper Scientific 300037 Digital Refractometer with a range of $1.3330 < n_D < 1.5318$ and an accuracy of 0.1% at a resolution of 0.0001 was used to measure the RI. The density was measured using a 50 ml volumetric flask, class A in combination with a Zeiss Z136EZ Precision digital scale, with an accuracy of 0.5g, which translates to an uncertainty of ~1%.

Contours of constant RI in superposition to the density of the ternary system are shown in figure 1. Mixtures of any two compositions, such as (I) and (II) in figure 1, then consequently lie on a straight line connecting the two points on the ternary diagram. It is therefore crucial to detect a region in which the RI is not changing along the connecting line when measurements of flow velocities in the mixing layer of both fluids are desired. The red line in figure 1 represents a combination of two aqueous solutions with identical refractive indices (here $n_D = 1.3762$) and a density difference of about 22.6%. They are not suitable for optical measurements due to the index variation along the mixing line. This case would lead to light scattered by seeding particles to be deflected while traveling towards the camera, consequently biasing the measurements. Alahyari and Longmire (1994) mentioned, that a variation in the index as small as $2 \cdot 10^{-4}$ is sufficient to render PIV images unusable. In turn, a constant RI with a changing mixing scalar can be achieved along the yellow line in figure 1, where the refractive index remains at $n_D = 1.3708$ (within a

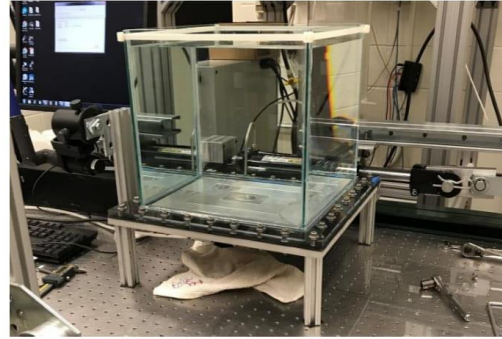


Fig. 2 Photograph of the miniDESTROYER facility

variation less than $1 \cdot 10^{-4}$). A density difference of 8.6 % can be realized along this line, and is therefore selected for the demonstration of this method. The corresponding mass fractions and their densities at a RI of $n_D = 1.3708$ are given in table 1. The kinematic viscosity of both ternary solutions was measured by a Cannon-Fenske Routine Viscometer and found to be 4.187cP for solution (I) and 4.464cP for solution (II).

Table 1 Nominal mass fractions and density of the two liquids with 8.6% density difference

Mixture	H ₂ O	Glycerol	Isopropanol	ρ
(I)	0.482	0.052	0.466	0.9243
(II)	0.600	0.165	0.235	1.011

EXPERIMENTAL SETUP

Experiments have been performed in the miniDESTROYER facility (mini density stratified turbulent round free jet experiment). A photograph of the facility is shown in figure 2. It is composed of a $30 \times 30 \times 30$ cm³ tank, equipped with a stainless steel nozzle that exits flush with the bottom plate that is used to form the incoming vertical jet. The nozzle has a diameter of $d_n = 2$ mm and a length of 25 hydraulic diameters. A linear actuator attached to a servo motor drives a piston that injects the liquid vertically through the nozzle at a constant nominal inlet velocity of 10.58 m/s into the tank. The corresponding outer scale Reynolds number is $Re = 5300$. To measure the flow field in the vertical mid-plane of the jet, a synchronized high speed PIV/PLIF system is used. It is comprised of a high speed double pulsed Nd:YLF Laser with a maximum pulse frequency of 10 kHz at a wavelength of 527 nm and 70 mJ energy/pulse, as well as two Phantom Miro LAB 340 cameras with a spatial resolution of 2560×1600 pixels (pixel size of $10 \times 10 \mu\text{m}^2$). The cameras have a 12 bit digital output and a maximum recording frequency of 800 Hz at full scale. To gain optical access in the entire jet domain, the walls of the tank are made of glass. A combination of two spherical lenses, to focus the laser beam, and a third planar concave lens are used to create a light sheet. For each camera a Kenko Tokina AT-X M100 PRO D macro lens in combination with a Nikon TC-201

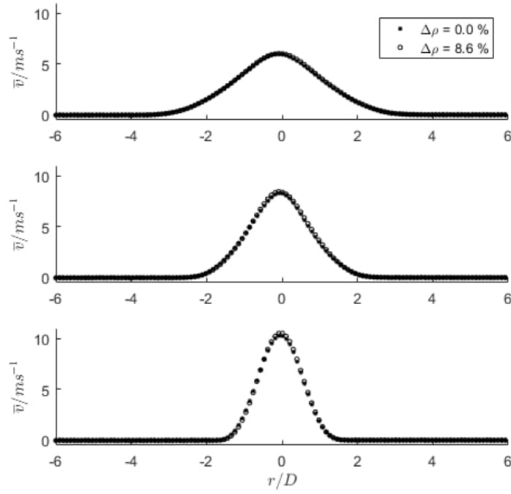


Fig. 3 Horizontal profiles of stream wise mean velocity extracted at $L/D=5,10\&15$.

A Teleconverter is used to magnify the recorded images. Two experiments have been conducted:

- A reference case with solution I being injected to solution I (no differences in density or RI)
- A stratified case with the lighter liquid (solution I) being injected into the heavier liquid (solution II) at 8.6% density difference with RIM

For a qualitative comparison, a total of 3226 Image sets were recorded. Turbulent statistics were obtained the following way. The ensemble averaged quantities were calculated according to:

$$\bar{u} = \frac{1}{N} \sum_{i=1}^N u_i \quad (8)$$

where N is the overall number of the recorded instantaneous fields and u_i is the instantaneous stream wise component of the velocity vector. Corresponding formulas apply for the cross wise velocity component and the transport scalar. Fluctuations were calculated according to the unbiased standard deviation of each quantity:

$$u' = \left[\frac{1}{N-1} \sum_{i=1}^N (u_i - \bar{u})^2 \right]^{1/2} \quad (9)$$

The shear stress component and turbulent fluxes were computed within the concept of covariance in two quantities:

$$\overline{u'c'} = \frac{1}{N-1} \sum_{i=1}^N (u_i - \bar{u})(c_i - \bar{c}) \quad (10)$$

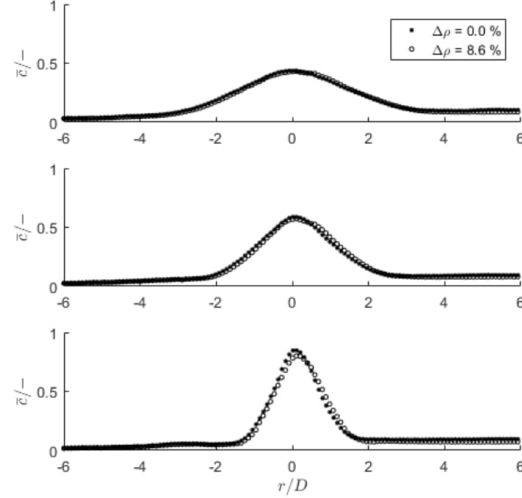


Fig. 4 Horizontal profiles of mean transport scalar extracted at $L/D=5,10\&15$.

RESULTS AND DISCUSSION

Figure 3 shows horizontal profiles of the stream wise mean velocity for three distances downstream of the nozzle exit. Both experiments are shown in superposition¹. The centerline velocity decreases and the profile spread increases as the jet progresses. A similar shape is found in the evolution of the transport scalar, shown in fig. 4. While an average concentration of almost one is found in the core of the jet at $L/D=5$, the Gaussian shaped profile spreads as the jet develops and entrainment of the jet environment contributes to a decreased core concentration. It is interesting to observe that both jets, with or without density difference, exhibit almost identical underlying mean fields. Only a slight difference in the profiles of mean transport scalar is present, which very likely originates from measurement uncertainties.

A similar behavior is observed in the turbulence dynamics, shown in fig. 5 & 6, where fluctuations in cross wise velocity component and the shear stress are plotted respectively. Apparently the density difference between the jet and its environment has no influence on cross wise velocity fluctuations. In both cases, largest amplitudes are found in the core of the jet which decrease further downstream, while the spatial extend increases. This is in conjunction with the evolution of shear at the boundaries of the jet (shown in fig. 6).

Up to this point in the analysis, buoyant forces seem to have no influence on the dynamics the jet. The situation changes dramatically in the dynamic of stream wise turbulence.

¹ In the following section all figures show horizontal profiles at the three distances $L/D=5, 10$ & 15 , downstream of the jet nozzle. Both experiments, with and without density difference, are shown in superposition.

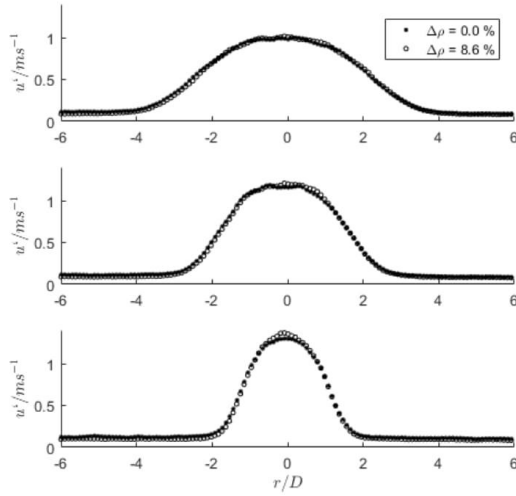


Fig. 5 Horizontal profiles of cross wise velocity fluctuations extracted at $L/D=5,10\&15$.

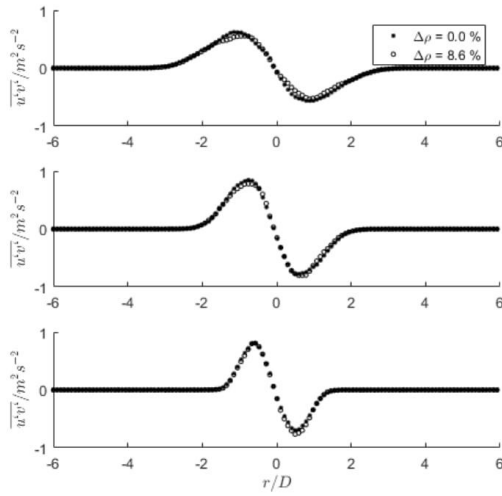


Fig. 6 Horizontal profiles of shear stress, extracted at $L/D=5,10\&15$.

Reduced stream wise velocity fluctuations are observed in the buoyant jet (seen in fig. 7, where profiles of stream wise velocity fluctuations are shown for both experiments). The difference is most pronounced at the beginning of the jet, where the jet is mostly composed of light liquid. A significant amount of turbulence is compensated by buoyant forces that slightly accelerate the jet stream wise.

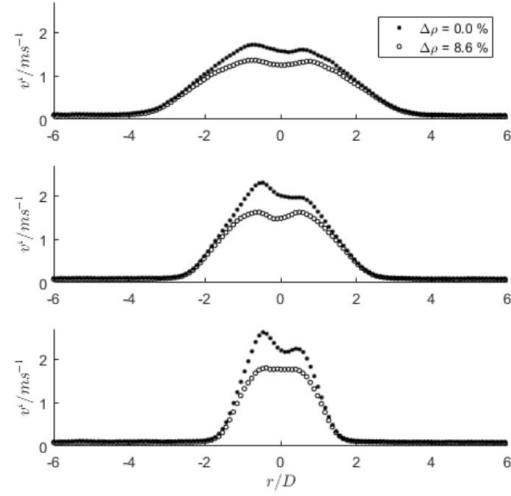


Fig. 7 Horizontal profiles of stream wise velocity fluctuations extracted at $L/D=5,10\&15$.

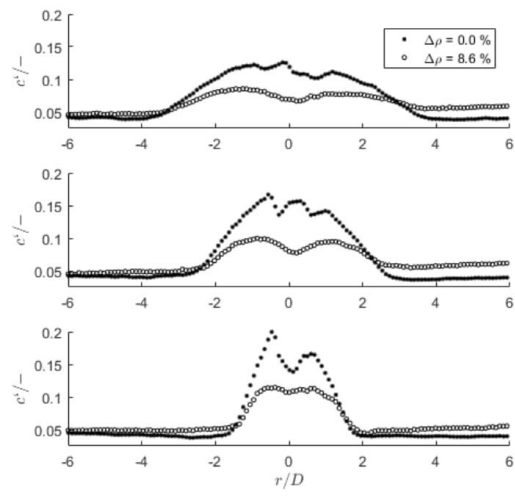


Fig. 8 Horizontal profiles of transport scalar fluctuations, extracted at $L/D=5,10\&15$.

This damping effect reduces further downstream as the density of the jet, relative to its environment, equilibrates with increasing entrainment and results in reduced turbulence damping. The same effect is visible in fluctuations of the transport scalar. It is shown in fig. 8 where buoyancy forces dampen the amplitude of scalar fluctuations by almost 50%. In fact, buoyancy forces within the jet cause in a magnification of asymmetry within the turbulence dynamic.

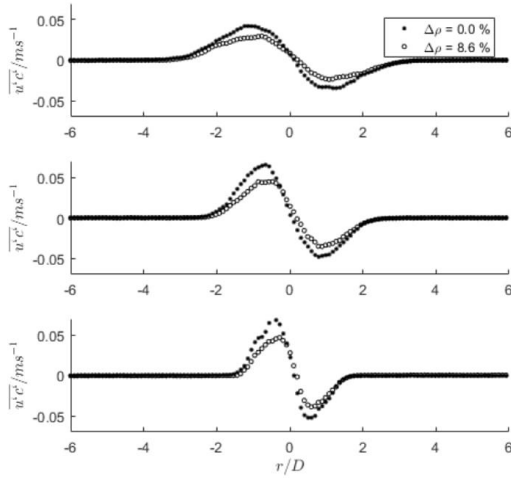


Fig. 9 Horizontal profiles of span wise turbulent flux, extracted at $L/D=5,10\&15$.

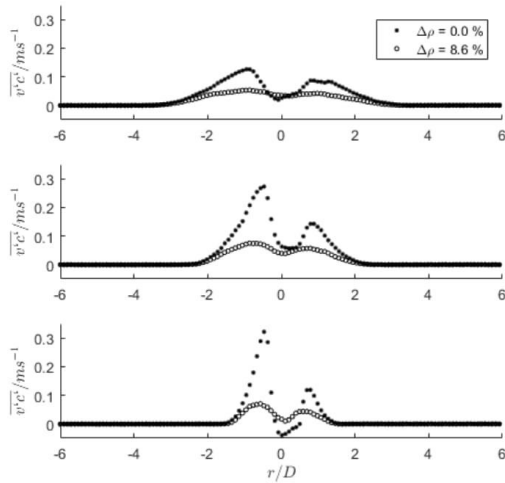


Fig. 10 Horizontal profiles of stream wise turbulent flux, extracted at $L/D=5,10\&15$.

As a result, this increased asymmetry is present within the amplitudes of turbulent fluxes. Both measured components, the cross wise- and the stream wise turbulent flux are shown in figs. 9 & 10, respectively. The cross wise flux follows the gradient of the mean transport scalar. Since the jet was marked, positive flux amplitude left of the core, and negative flux amplitude right of the core, indicate influx or engulfment of surrounding liquid into the jet. Due to the reduced stream wise

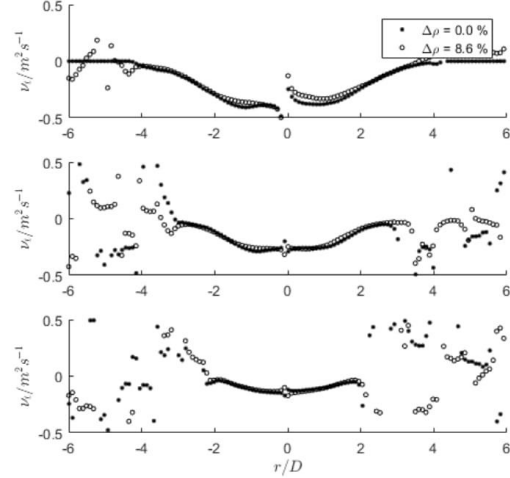


Fig. 11 Horizontal profiles of eddy viscosity, extracted at $L/D=5,10\&15$.

velocity fluctuations, and with it reduced scalar fluctuations, the amplitude of the stream wise turbulent flux is dramatically lower in the buoyant case (see fig. 10). Following the standard gradient diffusion hypothesis, the eddy viscosity can be obtained from those experimental results. The definition is as follows:

$$\overline{u'v'} \equiv -\nu_t \frac{\partial \bar{v}}{\partial x} \quad (11)$$

This linear relation of shear stress component to the mean velocity gradient is commonly applied to simple turbulence models. Figure 11 shows profiles of the eddy viscosity for both experiments. Despite the fact that for both cases the eddy viscosity is not constant across the jet, density differences don't affect this closure. This comes as no surprise since the shear field as well as the mean velocity field is almost identical for both cases.

The situation changes dramatically when it comes to the modelling of turbulent fluxes. Several turbulence models have been developed to address an improved prediction of the shear stress, but up to date only one approach to improve the prediction of turbulent fluxes is present (Manera, 2009). The relation is described in equation (4) and is also referred to as the Boussinesq assumption (Boussinesq, 1987). Figure 12 shows profiles of the eddy diffusivity for both experiments. We observe that the eddy diffusivity is not constant across the jet. Focusing on the left half of the jet, the eddy diffusivity for the buoyant jet follows the same dynamic compared to the uniform jet. But at approximately half of the jet radius away from the core, the amplitude departs towards lower values and buoyancy forces significantly suppress the eddy diffusivity.

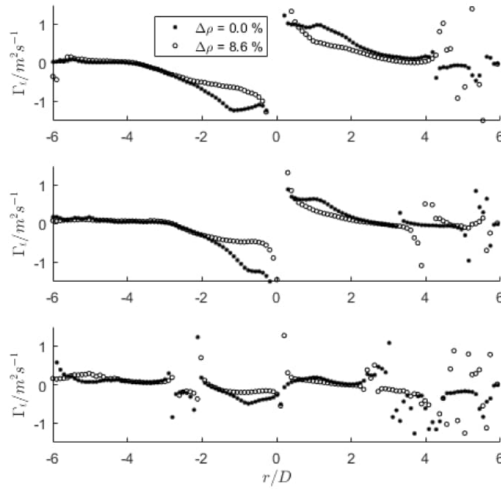


Fig. 12 Horizontal profiles of eddy diffusivity, extracted at $L/D=5,10\&15$.

CONCLUSIONS

In the present work we outlined a methodology to systematically identify combinations of two aqueous solutions characterized by constant refractive indices over large density changes, suitable to be used in turbulence research in which optical measurement techniques are employed. The method is based on the prediction of excess properties when three components are intermixing. We successfully achieved RIM with a density difference of 8.6% by using the ternary system H_2O – Isopropanol – Glycerol. To the author's best knowledge this is the highest density difference with RIM reported in available scientific literature. The identified solutions were used to study a turbulent buoyant jet, where the less dense liquid was injected into a reservoir of high dense liquid through a round nozzle. Measurements have been performed with a high fidelity synchronized PIV/PLIF system. In terms of turbulent statistics, we showed preliminary results of the buoyant jet with respect to a uniform jet and discussed the observations qualitatively.

While the mean velocity, the mean transport scalar and the shear field are found to be unaffected by buoyant forces, significant deviations in turbulent dynamics of the two jets are observed. It appears that buoyancy significantly suppresses the amplitude of vertical velocity fluctuations as well as fluctuations of the transport scalar. The same effect is reflected by an investigation of turbulent fluxes. It is interesting to observe that the evolution of the spatial extend of the jet remains unaffected by the density gradient. An investigation of a linear eddy viscosity showed almost no difference between both jets, since neither the mean field nor the shear field is

influenced. But the suppressed amplitudes of transport scalar and turbulent fluxes exert considerable influence on the eddy diffusivity. The result is of most importance, since it renders the Boussinesq assumption unpractical for such flows.

NOMENCLATURE

Symbol	Unit	Description
ρ	kg/m^3	Density
t	s	Time
u_i	m/s	Velocity component i
x_j	m	Coordinate j
p	Pa	Pressure
η	$Pa \cdot s$	Dynamic viscosity
g	m/s^2	Acceleration of gravity
c	-	Transport scalar
$\bar{u}$	m/s	Mean velocity
u'	m/s	Velocity fluctuation
$\overline{u'_i u'_j}$	m^2/s^2	Reynolds stress
$\overline{u'_i c'}$	m/s	Turbulent flux
ν_t	m^2/s	Turbulent viscosity
Γ_t	m^2/s	Turbulent diffusivity
Re	-	Reynolds number
Fr	-	Froude number
n_D	-	Refractive index
d	m	diameter

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APPENDIX II –UM ARTICLE #2

Proceedings of the ASME 2018 5th Joint US-European Fluids Engineering Summer Conference
FEDSM2018
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FEDSM2018-83280

COHERENT STRUCTURES AND CORRELATION FIELDS IN THE MIXING TRANSITION OF A TURBULENT ROUND FREE JET

Benedikt Krohn, Sunming Qin, Victor Petrov, Annalisa Manera
 University of Michigan
 Ann Arbor, Michigan, USA

ABSTRACT

Turbulent free jets attracted the focus of many scientists within the past century regarding the understanding of mass- and momentum transport in the turbulent shear field, especially in the near-field and the self-similar region. Recent investigations attempt to understand the intermediate fields, called the mixing transition or ‘the route to self-similarity’. An apparent gap is recognized in light of this mixing transition, with two main conjectures being put forth. Firstly the flow will always asymptotically reach a fully self-similar state if boundary conditions permit. The second proposes partial and local self-similarity within the mixing transition. We address the later with an experimental investigation of the intermediate field turbulence dynamics in a non-confined free jet with a nozzle diameter of 12.7 mm and an outer scale Reynolds number of 15,000. High speed Particle Image Velocimetry (PIV) is used to record the velocity fields with a final spatial resolution of $194 \times 194 \mu\text{m}^2$. The analysis focuses on higher order moments and two-point correlations of velocity variances in space and time. We observed local self-similarity in the measured correlation fields. Coherent structures are present within the near-field where the turbulent energy spectrum cascades along a dissipative slope. Towards the transition region, the spectrum smoothly transforms to a viscous cascade, as it is commonly observed in the self-similar region.

INTRODUCTION

The dynamics of turbulent jets have been intensively studied during the past century. Theoretical descriptions of the observed dynamics have first been addressed by Tollmien [1], based on Prandtl’s mixing-length theory. Later on numerous authors devoted theoretical works in order to describe the dynamics, and the vast majority made use of a statistical approach, which remains up to today the most promising method. During the course of these studies, authors outlined three distinguished stages, namely the near-field where jet dynamics begin to form, the far field, where a self-similar

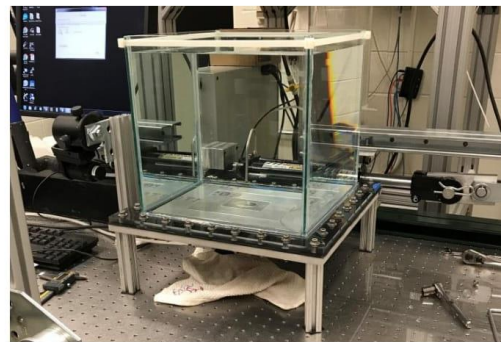


Fig. 1 Photograph of the miniDESTROYER facility

behavior was observed and the intermediate field, also referred to as the transition region, where initial effects and boundary conditions of the jet evolve and eventually reach a self-similar state [2,3]. This transition towards a well-mixed state in turbulent jets is less conspicuous than in shear layers. With turbulent jets behaving three-dimensionally, such a transition is not correlated with a transition to three-dimensionality, as it can be in shear layers, for example. A significant Reynolds number dependence on the behavior of the momentum field was observed, which can be gleaned from both uniform and buoyant jets [4]. While most of the turbulent dynamics have been focused on describing the near field and the far field, only a few published studies attempt to address the transition region. In the present paper we address this transition region under the influence of buoyant forces by making use of high fidelity synchronized velocity and scalar field measurements.

EXPERIMENTAL SETUP

An experimental water jet facility was built, designed to study the influence of density variations within an unconfined turbulent free jet. Figure 1 shows a photograph of the

miniDESTROJER (mini Density Stratified Turbulent Round free Jet Experiment). It is composed of a $30 \times 30 \times 30 \text{ cm}^3$ tank, equipped with a stainless steel nozzle that exits flush with the bottom plate that is used to form the incoming vertical jet. The nozzle has a diameter of $d_n = 2 \text{ mm}$ and a length of 25 hydraulic diameters. A linear actuator attached to a servo motor drives a piston that injects the liquid vertically through the nozzle at a constant nominal inlet velocity of 10.58 m/s into the tank. The corresponding outer scale Reynolds number is $Re = 5300$. To measure the flow field in the vertical mid-plane of the jet, a synchronized high speed PIV/PLIF system (Particle Image Velocimetry and Planar Laser Induced Fluorescence) was used. It is comprised of a high speed double pulsed Nd:YLF Laser with a maximum pulse frequency of 10 kHz at a wavelength of 527 nm and 70 mJ/pulse, as well as two Phantom Miro LAB 340 cameras with a spatial resolution of 2560×1600 pixels (pixel size of $10 \times 10 \mu\text{m}^2$). The cameras have a 12 bit digital output and a maximum recording frequency of 800 Hz at full scale. To gain optical access in the entire jet domain, the walls of the tank are made of glass. A combination of two spherical lenses, to focus the laser beam, and a third planar concave lens are used to create a light sheet. For each camera a Kenko Tokina AT-X M100 PRO D macro lens in combination with a Nikon TC-201 Teleconverter is used to magnify the recorded images. Two experiments have been conducted:

- A reference case with solution I being injected into solution I with no differences in density or refractive index (RI)
- A stratified case with the lighter liquid (solution I) being injected into the heavier liquid (solution II) at 8.6% density difference with refractive index matching (RIM)

In order to create a large density difference without variation of the RI, two liquids were used that are composed of a mixture of Water, Isopropanol and Glycerol. Krohn et al. described in detail the procedure to find index matched solutions that allow for large density differences [5]. A total of 3226 frames were recorded for each experiment. Vector computation was performed with DaVis 8.4 [6] by making use of the Whittaker Shannon interpolation scheme [7].

Turbulent statistics were obtained the following way. The time averaged velocity components $\bar{u}$ and $\bar{v}$ were calculated according to:

$$\bar{u} = \frac{1}{N} \sum_{i=1}^N u_i \quad (1)$$

Here N is the overall number of the recorded instantaneous fields and u_i is the instantaneous streamwise component of the velocity vector. Corresponding formulas were applied for the crosswise velocity component and the transport scalar. Fluctuations were calculated according to the unbiased standard deviation of each quantity:

$$u' = \left[\frac{1}{N-1} \sum_{i=1}^N (u_i - \bar{u})^2 \right]^{1/2} \quad (2)$$

The shear stress component and turbulent fluxes were computed within the concept of covariance in two quantities:

$$\overline{u'c'} = \frac{1}{N-1} \sum_{i=1}^N (u_i - \bar{u})(c_i - \bar{c}) \quad (3)$$

Turbulence kinetic energy was computed within the assumption that the spanwise and the crosswise velocity component are comparable:

$$TKE = \frac{1}{2} (\overline{u'u'} + 2 \cdot \overline{v'v'}) \quad (4)$$

A detailed description of the turbulent dynamics is addressed in an accompanying paper by Krohn et al. [8]. Here we focus on spatial two point correlations of transport scalar and velocity components. Those provide insight on coherence of turbulent scales. The understanding of coherent motion defined by Robinson [9] is adapted: "a coherent motion is defined as a three-dimensional region of the flow over which at least one fundamental flow variable (velocity components, density, temperature, etc.) exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest local scales of the flow." Here the focus lies on two-point correlations of second and third order moments. Generally, the correlation is defined by:

$$R_{f',g'} = \frac{\overline{f'_0 g'_x}}{(\overline{f'_0 f'_0} \overline{g'_x g'_x})^{1/2}} \quad (5)$$

Subscripts in equation (5) indicate the variance of the reference point (denoted "0") and in the whole flow field (denoted "x"). Second order moments are defined as the fluctuations of a quantity, e.g. the spatial influence of scalar fluctuations in a single point of the flow field to the streamwise velocity fluctuations is a second moment correlation with:

$$f' \equiv c_i - \bar{c} \quad (6)$$

$$g' \equiv u_i - \bar{u} \quad (7)$$

Third orders are defined as:

$$f' \equiv c'c' - \overline{c'c'} \quad (8)$$

Similar equations apply for velocity components, and for the case of third order autocorrelations, the shear stress, as well as turbulent fluxes. Qin et al. showed that this definition allows for detection of energy containing scales [10], and gives insight to the structure of isotropy in turbulence [11].

RESULTS AND DISCUSSION

Turbulence dynamics

Figure 2 shows mean streamwise velocity field for the two experiments. It appears that the large density difference (here 8.6%) has no effect on the underlying mean velocity field. However, turbulence levels are strongly influenced; fig.3 shows fields of turbulent kinetic energy (TKE) for both experiments.

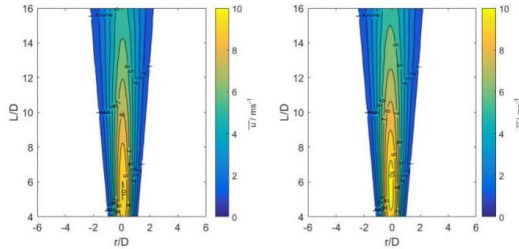


Fig. 2 Fields of streamwise mean velocity for the two experiments (left: uniform density, right: with 8.6% density difference)

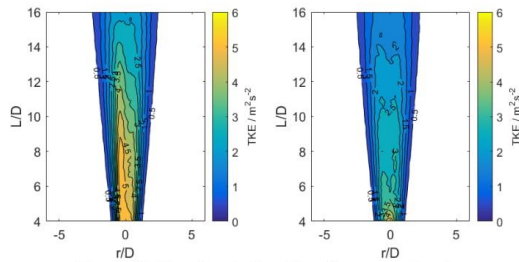


Fig. 3 Fields of turbulent kinetic energy for the two experiments (left: uniform density, right: with 8.6% density difference)

For the buoyant jet, significantly lower levels of turbulence are observed when compared to the jet with uniform density. This effect likely originates from gravitational effects that dampen turbulence. The more detailed analysis of turbulence dynamics is discussed in [8]. The authors observe that in fact the streamwise velocity fluctuations are responsible for the difference in turbulence, while crosswise fluctuations appear unaffected.

Coherent structures

The collection of instantaneous field measurements, like velocity and transport scalar, offers the possibility to analyze structural dynamics of fluid motion. When the fluctuation of a property in time is correlated with the fluctuation of a property in space, the spatial extent of its influence on the flow can be visualized. This allows conclusions to be drawn about how the variance of density affects the dynamics of the jet.

Figure 4 shows spatial two point correlation fields of scalar fluctuations ($f' = g' \equiv c'$). For the reference case without a density difference, scalar fluctuations are coherent within the core of the jet throughout the field of view. Across the developing shear field on each side of the core, the transport scalar is anti-correlated (negative values) and shows how structures within the core influence the entrainment of surrounding fluid into the jet.

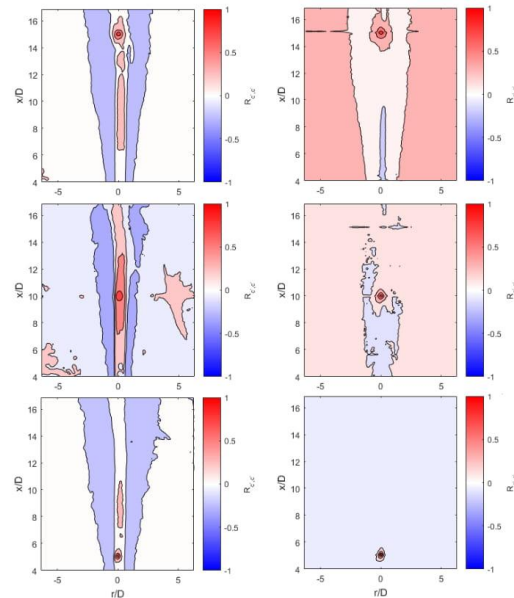


Fig. 4 Spatial two point autocorrelation of scalar fluctuations for the two experiments (left: uniform density, right: with 8.6% density difference). Reference points from top to bottom: $r/D=0$, $L/D=15, 10, 5$.

This is not observed for the buoyant jet. Here the penetration depth of scalar fluctuations are confined within the core and do not correlate with the shear region. This suggests that buoyancy decouples the partial coherence across the jet, and with it the jet progresses towards a more isotropic state when compared to the reference case. However, while the jet evolves, an anti-correlated region within the core upstream of the coherence field begins to develop.

The influence of velocity fluctuations on the dynamics of the transport scalar is shown in figs.5&6. Beginning with the dynamic of crosswise transport $R_{u',c'}$, two distinct islands of correlation and anti-correlation are observed. It appears that the spatial influence of crosswise velocity fluctuations affects scalar fluctuations towards the whole radial span of the jet. Within the left shear layer of the jet, the positively correlated island, together with the negative correlated island within the right shear layer, indicates influx of surrounding liquid towards the core of the jet. The observed structure maintains its shape but increases in size with progressing jet evolution, and density differences do not exhibit distinct changes on this coherence.

Significant influence is present for the streamwise coherence, which can be seen in fig. 6. Here the correlated velocity component is aligned with the gravitational field.

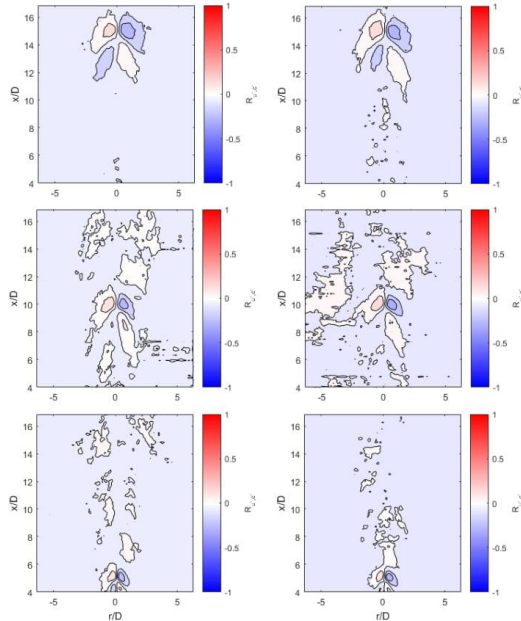


Fig. 5 Spatial influence of crosswise velocity fluctuations on scalar fluctuations $R_{w,c}$ for the two experiments (left: uniform density, right: with 8.6% density difference). Reference points from top to bottom: $r/D=0$, $L/D=15, 10, 5$.

Towards the whole transition region of the jet, the streamwise centerline velocity fluctuations correlate heavily with scalar variance in both shear layers of the jet. The inertia of the jet is in coherence with scalar fluctuations for a large spatial extent along the shear layers. This indicates how inertia causes the formation of shear layers, which are then responsible for engulfing and entraining surrounding liquid, and the structure of the jet is then dictated by its initial boundary condition.

In turn this coherence is completely broken within the buoyant jet. Here velocity fluctuations have only a limited spatial influence on the variation of the transport scalar. Density differences have a strong local effect on the structural dynamics and act as an instability that brings the jet to a more isotropic state compared to the reference case. Consequently, the observed coherence with initial conditions vanishes and a new dynamic structure is formed, which is phase correlated to a much smaller spatial extent. The effect is in agreement with the structure of turbulent isotropy along the center line of both jets. This isotropy can be visualized by analyzing the turbulent stress tensor and plotting the first- against its second invariant. The result is shown in fig. 7 by the so called “Lumley triangle” [12]. Each corner of the triangle describes a certain turbulent symmetry:

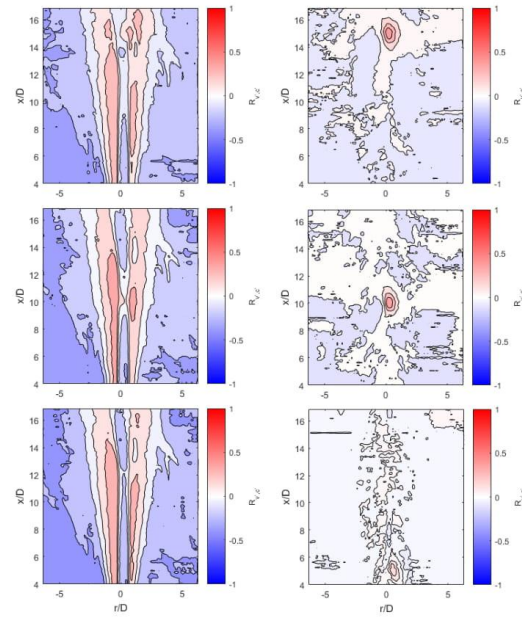


Fig. 6 Spatial influence of streamwise velocity fluctuations on scalar fluctuations $R_{v,c}$ for the two experiments (left: uniform density, right: with 8.6% density difference). Reference points from top to bottom: $r/D=0$, $L/D=15, 10, 5$.

- Upper left corner is 2-component axisymmetric,
- Upper right corner is single component turbulence
- Origin describes 3D isotropy.

Along the connecting line between single component and full isotropy, turbulence exhibits an axisymmetric prolate structure that is present for both experiments. Most importantly, the buoyant jet reaches a more isotropic state compared to the free jet at the same downstream distance from the nozzle.

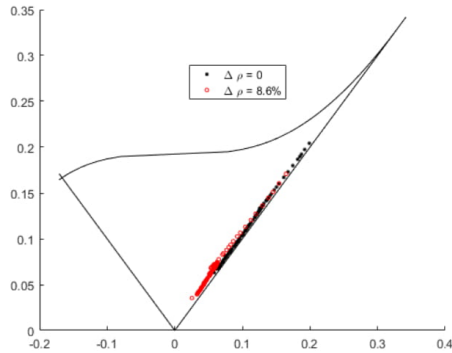


Fig. 7 Lumley triangle: The state of isotropy along the centerline for both experiments. Black line shows uniform jet, red line shows the buoyant jet with 8.6% density difference.

Correlation fields

The structure of turbulence can be also visualized by analyzing the two point autocorrelation of the third moment in velocity components (described with eq. 5 & 8). Figures 8 & 9 show the correlation fields $R_{u'u'u'u'u'u'}$ and $R_{v'v'v'v'v'v'}$, respectively. The plots confirm the initially observed phase correlation. In particular, the crosswise autocorrelation in fig. 8 exhibits a circularly shaped penetration depth in both experiments that extends only within the range of the core. However, the streamwise correlation (shown in fig. 9) shows a significant difference in phase coherence between the two experiments. For the reference jet, the shape of streamwise correlation is in phase along the longitudinal axis of the jet, and is limited by the center of both shear layers. This is not observed in the buoyant jet. Here the shape is almost circular and only weak correlation is present in the longitudinal jet direction and this weak correlation is only within its core. This confirms the suggested prolate shape of turbulence from fig. 7 and the evolution into a higher state of isotropy for the buoyant jet.

CONCLUSIONS

In the present work we studied the mixing transition of a non-confined, turbulent buoyant jet qualitatively. First results of a buoyant jet with 8.6% density difference are presented in which both liquids have identical refractive index. Velocity- and scalar fields were measured simultaneously with a synchronized high speed PIV/PLIF system.

Dynamic structures and higher order phase correlations were obtained by making use of spatial two point correlations. Strong coherence was found in the free jet scenario, which spans the whole field of view.

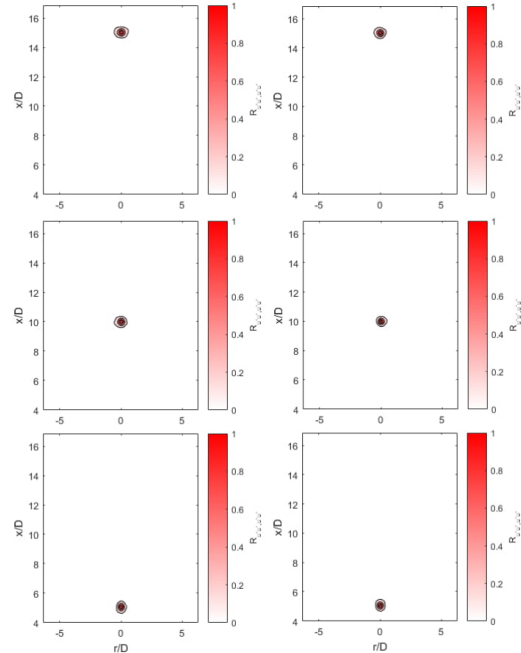


Fig. 8 Third moment spatial autocorrelation of crosswise velocity variance for the two experiments (left: uniform density, right: with 8.6% density difference). Reference points from top to bottom: $r/D=0, L/D=15, 10, 5$.

The spatial influence of vertical velocity variance on the scalar fluctuations was found to dominate the structure of the flow, and initial conditions remain phase correlated. In turn, the buoyant jet exhibits a different turbulent structure. Density effects appear to dominate the structural dynamics of the jet and lead to a break in turbulence symmetry. Consequently, the buoyant jet is found to reach a much higher state of isotropy compared to the uniform jet. The observation is present in the analysis of third order spatial autocorrelations and the invariant analysis of the turbulent stress tensor along the centerline of both jets.

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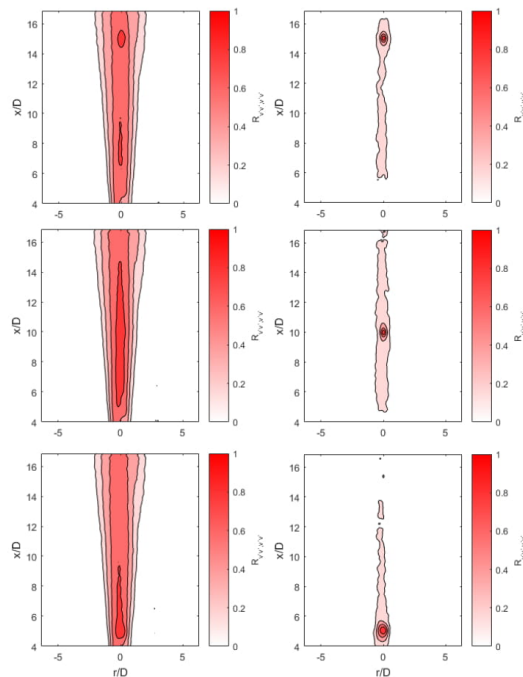


Fig. 9 Third moment spatial autocorrelation of streamwise velocity variance for the two experiments (left: uniform density, right: with 8.6% density difference). Reference points from top to bottom: $r/D=0$, $L/D=15, 10, 5$.

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APPENDIX III –UM ARTICLE #3

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RESEARCH ARTICLE



A novel method to create high density stratification with matching refractive index for optical flow investigations

Benedikt Krohn¹ · Annalisa Manera¹ · Victor Petrov¹

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Abstract

Turbulent mixing in stratified environments represents a challenging task in experimental turbulence research, especially when large density gradients are desired. When optical measurement techniques like particle image velocimetry (PIV) are applied to stratified liquids, it is common practice to combine two aqueous solutions with different density but equal refractive index, to suppress particle image deflections. While refractive image matching (RIM) has been developed in the late 1970s, the achieved limit of 4% density ratio was not rivalled up to day. In the present work, we report a methodology, based on the behavior of excess properties and their change in a multicomponent system while mixing, that allows RIM for solutions with higher density differences. The methodology is then successfully demonstrated using a ternary combination of water, isopropanol and glycerol, for which RIM in presence of a density ratio of 8.6% has been achieved. Qualitative PIV results of a turbulent buoyant jet with 8.6% density ratio are shown.

1 Introduction

Mixing of fluids with variable density poses an important challenge in turbulence research. The influence of density gradients on turbulence dynamics ranges from atmospheric flows and ocean dynamics, down to microscale turbulence in cooling systems of computer chips. Density effects play a major role also in nuclear power plants (Paladino et al. 2012), ranging from design and operation of safety systems to plant components behavior in accident and operational conditions. Typical situations involve the interaction and mixing of two miscible fluids with different densities. This difference can have its origin in temperature gradients, by chemical reactions of different agents in, e.g., flames or more general by two different fluids. The governing equations to describe fluid motion are the Navier–Stokes (NS) equations, which describe the momentum balance, the mass conservation and the energy

balance. However, there is no analytical solution found yet and it is common practice to solve the equations numerically by making use of computational fluid dynamics (CFD) simulations, which usually employ correlations and models at various scales. Those models are crucial since the scales at which turbulence occurs in practical applications renders a direct numerical solution of the NS equations impossible, due to unaffordable computational efforts. The most prominent models are based on space filtering within the use of large eddy simulations (LES) and time filtering when Reynolds averaged Navier–Stokes (RANS) equations are used. RANS equations employ the statistical approach to decompose the time dependent variables of the NS equations into a time averaged and a fluctuating quantity; e.g., the velocity u is decomposed into $u = \bar{u} + u'$. Using Einstein notation, the governing equations to describe fluid motion take the following form with ρ being the density field, Φ being the scalar field (e.g., temperature) with Γ the diffusivity and η the dynamic viscosity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \bar{u}_j)}{\partial x_j} = 0, \quad (1)$$

$$\frac{\partial (\rho \bar{u}_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\eta \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right] + g_j (\rho - \rho_0), \quad (2)$$

✉ Benedikt Krohn
 bkrohn@umich.edu
 Annalisa Manera
 manera@umich.edu
 Victor Petrov
 petrov@umich.edu

¹ Department of Nuclear Engineering and Radiological Sciences, University of Michigan–Ann Arbor, 2355 Bonisteel Blvd, Ann Arbor, MI 48109, USA

$$\frac{\partial(\rho\bar{\Phi})}{\partial t} + \frac{\partial}{\partial x_j}(\rho\bar{\Phi}u_{ij}) = \frac{\partial}{\partial x_j}\left(\Gamma\frac{\partial\bar{\Phi}}{\partial x_j}\right) - \frac{\partial}{\partial x_j}(\rho u'_j\bar{\Phi}'). \quad (3)$$

Apparently the cross correlation of velocity fluctuations $u'_i u'_j$ (also referred to as the Reynolds stresses) and the turbulent flux $u'_j \bar{\Phi}'$ need to be modeled. For Reynolds stresses a wide range of models exists, with each being tailored to specific flow situations, while the modelling of turbulent fluxes is mainly based on the standard gradient diffusion hypothesis (SGDH), which makes use of the Erdogan theorem by relating a flux to its mean gradient under the assumption of local thermodynamic equilibrium:

$$-\overline{\rho u'_j \bar{\Phi}'} = \frac{\mu_t}{\sigma_t} \frac{\partial \bar{\Phi}}{\partial x_j} \quad (4)$$

with μ_t being the turbulent viscosity and σ_t the turbulent Prandtl number. Buoyant flows can be generally characterized in terms of the Reynolds and densimetric Froude numbers,

$$Re = \frac{\bar{u}L}{\nu}, \quad Fr = \frac{\bar{u}}{\sqrt{gL}} \quad (5)$$

with the kinematic viscosity ν and the acceleration due to gravity g . Xiang et al. (2015) pointed out, when considering geophysical or engineering applications, the Reynolds number is usually large and of the order 10^6 or higher, while the Froude number, even for a strong stratified atmosphere would be of the order 10^{-1} . The associated turbulent time scales of such flows are typically three orders of magnitude shorter than those associated with buoyancy frequencies, and we could consider the effects to be of minor influence. However, without further energy input to the fluid, the velocity decreases with increasing turbulent length scales and eventually buoyancy forces take over. When buoyancy effects become dominant with respect to inertia of the flow, it has been noticed that currently available models for turbulent momentum fluxes tend to overestimate thermal stratification while underestimating turbulent mixing (Petrov and Manera 2011). Even LES approaches fail to correctly reproduce thermal stratification because the assumption of local isotropy, currently at the basis of most LES subgrid scale (SGS) models, break down in case of flow interactions with stratified layers. This because, in the presence of stratified layers baroclinic forces create significant redistribution of turbulent kinetic energy and scales, which leads to turbulence anisotropy, and the small scales of the passive scalar advected by a turbulent velocity field displays a persisting anisotropy (Bos 2014).

Understanding the underlying physical principles of these flows is not trivial and there is an emerging need to experimentally investigate stratified flows characterized by large density gradients. A promising possibility to answer this question is to apply optical measurement techniques

like particle image velocimetry (PIV) and laser induced fluorescence (LIF), to acquire the temporal evolution of velocity and temperature (or concentration) fields without being intrusive to the flow (Adrian and Westerweel 2011). However, a variable density or temperature field is usually connected with variable refractive index (RI), which limits the applicability of optical measurement techniques like PIV or LIF to very weakly stratified conditions. This is because a variable RI will result in blurred PIV images. In view of these limitations, most of the available experiments have focused on low- Re cases, where the Froude is of the order of 1 and the flow is strongly affected by density stratification, although a significant difference in the dynamics of stratified flows for high- Re conditions has been noticed (Riley and De Bruyn Kops 2003). A few experiments are reported that deal with strong stratified turbulence. Augier et al. (2014) generated a density gradient of 20% using water-salt (NaCl) solution, but the authors ignored the change in RI and argued that possible effects of RI variation are generally sufficiently small due to weak small scale mixing. Daviero et al. (2001) pointed out that refractive index matching (RIM) can overcome the limits of optical techniques by making use of liquids with different density but equal RI. The method has first been introduced to the experimental society by McDougall (1979) who applied laser Doppler velocimetry (LDV) to an aqueous combination of Epsom salt and sugar and reached a density difference of 0.015 g/cm^3 ($\sim 1.5\%$). Other solutions were published by Hannoun (1985), who used an aqueous combination of ethanol and salt (NaCl) and reached density differences of 0.03 g/cm^3 (corresponding to $\sim 3\%$).

When it comes to generating a system with variable density and equal refractive index in turbulence research, all methods reported in the scientific literature focus on a combination of two aqueous solutions. However, when larger density differences in a turbulent flow configuration are desired, it is of paramount importance to keep the RI constant along the gradient of one liquid within the other, i.e., the RI has to remain constant with the changing mixing scalar. Using two binary aqueous solutions, it is, therefore, necessary to investigate the RI across the whole composition diagram (for two binary solutions a ternary diagram is needed), to identify the regions where the RI remains constant along the connecting line of two chosen solutions.

2 Establishing refractive index matching for PIV measurements of flows with high density ratios

In the present study, we aim at demonstrating a methodology that allows achieving refractive-index matching (RIM) for solutions up to 8.6% density differences. The methodology

is successfully validated by performing PIV measurements of the velocity field of a liquid turbulent jet under the influence of high density gradients. As pointed out previously, the density difference can be achieved by either varying temperatures of both liquids, or using two miscible liquids. When using a temperature gradient, the resulting variable RI as function of the temperature field makes it impossible to collect unbiased results, if optical measurement techniques are used. In case of a two-liquid solution, RIM offers the possibility to overcome this restraint, but reported experiments have been limited by density ratios of up to 3% (Daviero et al. 2001; McDougall 1979; Hannoun 1985). In this work, we present a simpler approach to achieve much higher density ratios, which is defined as $\rho_{\text{rel}} = (\rho_{\text{high}}/\rho_{\text{low}})$.

Motivated by the field of petro-chemistry, Touriño et al. (2004) reported empirical correlations to predict the RI in ternary mixtures, applied to the systems chlorobenzene + *n*-hexane + (*n*-heptane or *n*-octane). This approach has then been refined by Yahya and Saghir (2015) who applied it to a variety of ternary hydrocarbon mixtures. Both found their predictions in substantial agreement to experimental results. The method is based on the concept of thermodynamic excess properties that occur when mixing of two or more differing liquids is involved. Generally, the partial molar property of a component in a real mixture differs from that of an ideal mixture, due to molecular interactions between the component molecules and the resulting mean free path (or average molecular radii) of the mixtures (Anwar and Tariq 2007). This deviation is called excess property and is defined in relation to those of pure substances (Garcia et al. 2002; Brocos et al. 2003). As we deal with a system of three components, the excess RI is defined as:

$$n^E = n_D - \sum_{i=1}^3 x_i \cdot n_{D,i} \quad \rho^E = \rho - \sum_{i=1}^3 x_i \cdot \rho_i. \quad (6)$$

Here n_D is the refractive index of the real mixture, x_i and $n_{D,i}$ are the mass fraction and the refractive index of the pure component i , respectively. A similar definition applies to the excess density ρ^E (or excess specific volume).

However, there was no data reported in the scientific literature for suitable aqueous solutions with information of both the RI and the density that would exhibit large density ratios. With the aim to create an index matched environment with large density gradient, a combination of two aqueous solutions was chosen in the present work, in particular, a mixture of H₂O, isopropanol (CH₃CHOHCH₃) and glycerol (H₂O-CH₂OHCHOHCH₂OH). All three liquids are fully miscible among each other, and the two solutions exhibit a large density difference. We have performed measurements of the refractive index and the density at a temperature of 298.15 K and atmospheric pressure over the whole composition diagram

of the H₂O-isopropanol-glycerol system. To measure the RI, a Sper Scientific 300037 Digital Refractometer with a range of $1.3330 < n_D < 1.5318$ and an accuracy of 0.1% at a resolution of 0.0001 was used. The density was measured using a 50-ml volumetric flask, class A in combination with a Zieis Z136EZ Precision digital scale, with an accuracy of 0.5 g, which translates to an uncertainty of ~1% in density measurements.

3 Results and discussion

The results of the measured RI field, the density, the excess RI and the excess density, for the whole composition diagram of the system H₂O-isopropanol-glycerol, are given in Table 2 in the Appendix. Figure 1 shows the resulting excess properties relative to their ideal behavior (left: relative excess density, right: relative excess refractive index).

In previous studies, attempts were undertaken to model the excess RI based on the nonlinear rate of change in density (Augier et al. 2014; Daviero et al. 2001). The basic principle was to relate optical distortion to the specific excess volume within a mixture. This assumption may hold for weak polar molecules, as they are of interest in the petro chemistry, but this relation is no longer applicable for molecules with high polarity index—especially water. Considering light to be of electro-magnetic nature, the interaction of molecules with strong differing dipole moment, like water and Isopropanol, leads to more complex structural properties when mixed. The effect is seen in Fig. 1. Here we observe regions of positive- and negative excess density, while the excess refractive index is of positive nature over the whole composition diagram. Most importantly, both plots show a different pattern and exhibit regions in which the RI remains constant while the density changes and vice versa.

Figure 2 shows contours of constant RI in superposition to the density of the ternary system. The color code for the density is chosen to be white at the density corresponding to pure water, with blue representing lower density and red representing higher density. Such diagrams are based on the property of equilateral triangles that the sum of the perpendicular distances L_1 , L_2 and L_3 from any point to each side of the diagram is a constant equal to the length of any of the sides L_T , and the composition of a mixture within the diagram can be calculated by:

$$x_1 = \frac{L_1}{L_T}, \quad x_2 = \frac{L_2}{L_T}, \quad x_3 = \frac{L_3}{L_T}. \quad (7)$$

Mixtures of any two compositions, such as (I) and (II) in Fig. 2 then consequently lie on a straight line connecting the two points on the ternary diagram. For the purpose of measuring flow velocities in mixing fluids it is, therefore, crucial to detect a region in which the RI is not changing

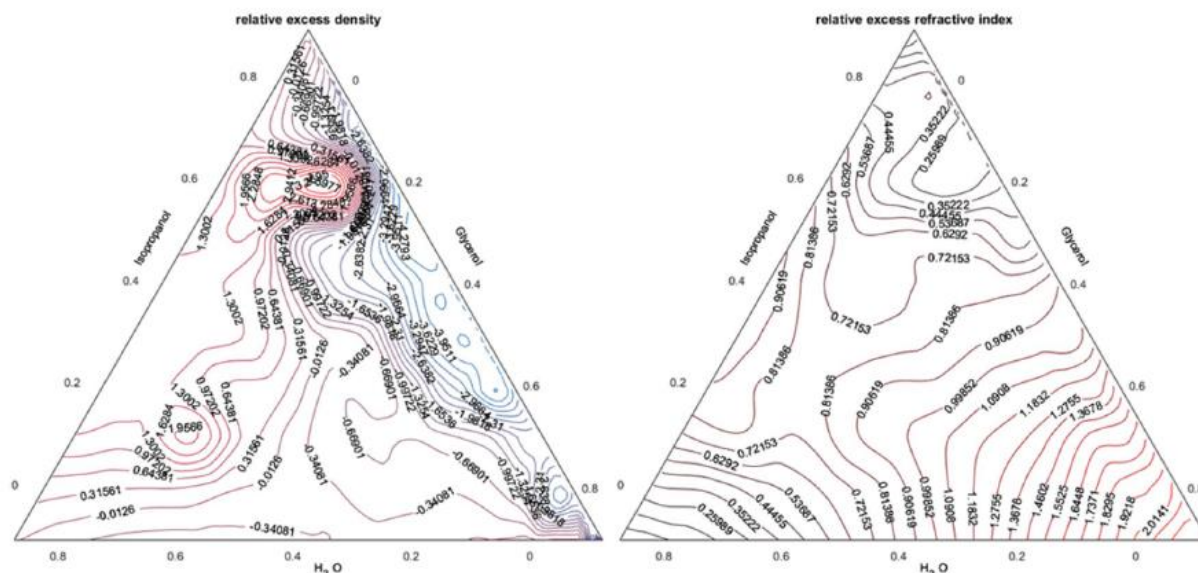
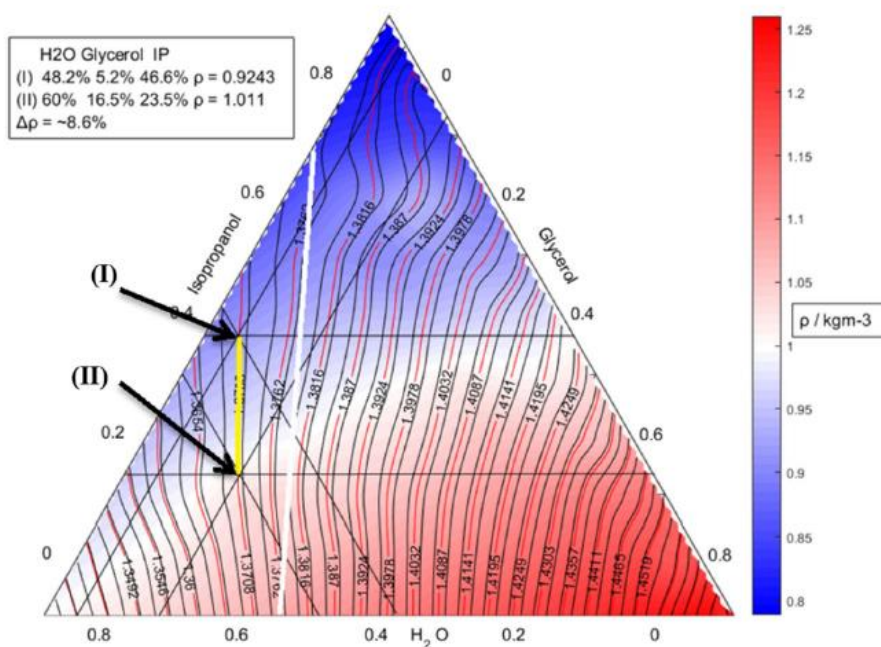


Fig. 1 For the ternary system H_2O –glycerol–isopropanol left: contours of constant relative excess density, right: contours of constant relative excess refractive index

Fig. 2 Contours of constant refractive index in superposition of the density (colormap) for the ternary system H_2O –glycerol–isopropanol



along the connecting line. The white line in Fig. 2 represents a combination of two aqueous solutions with identical refractive index (here $n_D = 1.3762$) and a density difference of about 22.6%.

However, when both liquids begin to intermix, the refractive index changes. In this case light scattered by the seeding particles needed for PIV measurements gets deflected while traveling towards the camera and consequently the

measurements will be biased (i.e., blurred images will be obtained). A constant RI with changing mixing scalar can be achieved instead along the yellow line in Fig. 2, where the refractive index remains at $n_D = 1.3708$ (within a variation less than 1×10^{-4}). It has been pointed out by Alahyari and Longmire (1994), that a variation in the index as small as 2×10^{-4} is sufficient to render PIV images usable. Along this line a density difference of 8.6% can be realized. This

solutions combination is, therefore, selected for the demonstration of the PIV measurements. The mass fractions of the chosen combination of liquids (yellow line in Fig. 2) together with their density at a RI of $n_D = 1.3708$ are given in Table 1. The kinematic viscosity of both ternary solutions was measured by a Cannon–Fenske Routine Viscometer and found to be 4.187 cP for solution (I) and 4.464 cP for solution (II).

3.1 Proof of principle

A small-scale experimental setup was built, that comprises a $10 \times 10 \times 30 \text{ cm}^3$ tank with a stainless steel nozzle of $d_n = 2 \text{ mm}$ and a length of 25 diameters, sealed at the center of the tank such that the nozzle exit is flush with the bottom plate. The jet is created by a piston that is driven by a linear actuator attached to a servomotor. The liquid is injected vertically through the nozzle at a constant nominal inlet velocity of 10.58 m/s to the tank. This corresponds to a jet Reynolds number of $Re = 5300$. A high speed PIV system (particle image velocimetry) is used to measure the flow field in the vertical mid-plane of the jet. It comprises a Phantom Miro LAB 340 camera with a spatial resolution of 2560×1600 pixels, a pixel size of $10 \times 10 \mu\text{m}^2$, 12 bit digital output and a maximum recording frequency of 800 Hz at full scale, as well as a high speed double pulsed Nd:YLF laser with a

maximum recording frequency of 10 kHz at a wavelength of 527 nm and 70 mJ energy/pulse. The walls of the tank are made of glass to gain optical access in the entire jet domain. A combination of two spherical lenses, to focus the laser beam, and a third planar concave lens are used to create a light sheet.

A Kenko Tokina AT-X M100 PRO D macro lens in combination with a Nikon TC-201 Teleconverter is used to perform high spatially resolved recordings. Only qualitative measurements were performed for the proof-of-principle illustrated here. Overall three experiments have been conducted:

1. A reference case with solution I being injected to solution I (no differences in density and RI)
2. A stratified case with the lighter liquid (solution I) being injected to the heavier liquid (solution II) at 8.6% density difference with RIM
3. A stratified case without RIM and a density difference of 8% (here both solutions were slightly altered with a refractive index of $n_D = 1.3712$ for solution I and $n_D = 1.3538$ for solution II)

Figure 3 shows raw images from PIV recordings for the three cases. The jet injects from the bottom and progresses to the top. In image (c) of Fig. 3 particle images are strongly deflected by the mixing interface, especially in the upper part of the image where mixing is more pronounced. This effect is not visible in image if Fig. 3 where the RI is matched and neither in the reference experiment (a), where identical substances are present. It is evident that the light traveling towards the mixing region of the horizontally established density stratification without RIM is heavily deflected. The resulting PIV images cannot be used to obtain velocity measurements.

Table 1 Nominal mass fractions and density of the two liquids with 8.6% density difference

Mixture	H ₂ O	Glycerol	Isopropanol	$\rho \text{ (g/cm}^3\text{)}$
(I)	0.482	0.052	0.466	0.9243
(II)	0.600	0.165	0.235	1.011

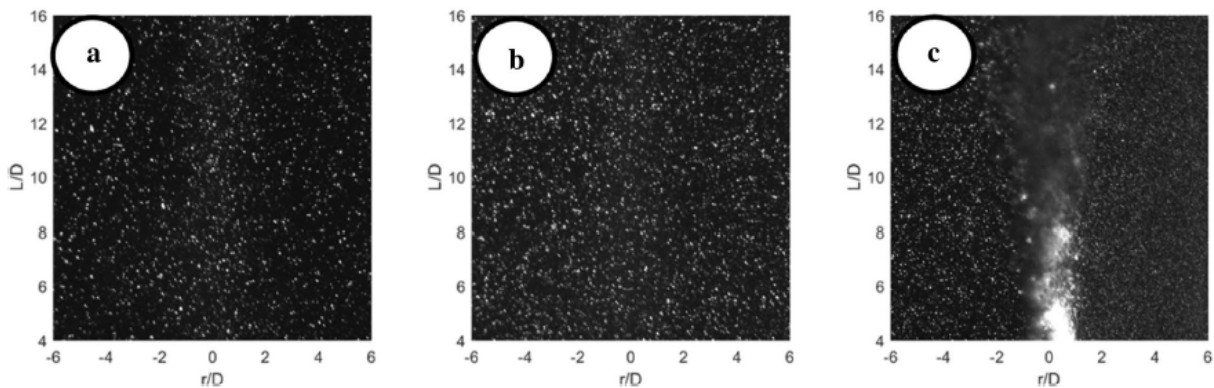


Fig. 3 Raw PIV images for the three test cases. **a** Reference case with solution I being injected to solution I (no differences in density and RI), **b** stratified case with the lighter liquid (solution I) being injected to the heavier liquid (solution II) at 8.6% density difference with

RIM **c** stratified case without RIM and a density difference of 8% (here both solutions were slightly altered with a refractive index of $n_D = 1.3712$ for solution I and $n_D = 1.3538$ for solution II)

3.2 Qualitative comparison between uniform jet and buoyant jet

A total of 1613 Image pairs were recorded. Turbulent statistics were obtained the following way. The ensemble averaged stream-wise velocity component $\bar{u}$ was calculated according to:

$$\bar{u} = \frac{1}{N} \sum_{i=1}^N u_i, \quad (8)$$

where N is the overall number of the recorded instantaneous velocity fields and u_i is the instantaneous stream wise component of the velocity vector. Fluctuations of the velocity were calculated according to the unbiased standard deviation of the velocity vectors:

$$u' = \left[\frac{1}{N-1} \sum_{i=1}^N (u_i - \bar{u})^2 \right]^{1/2} \quad (9)$$

We define the 2D turbulent kinetic energy (TKE) within the assumption that the span wise velocity component is comparable to the cross stream component:

$$\text{TKE} = \frac{1}{2} (u'u' + 2 \cdot v'v'). \quad (10)$$

Figure 4 shows the stream-wise mean velocity of the reference case (left), the stratified case with RIM at 8.6% density ratio (middle) and the stratified case without RIM (right). The jet progresses from bottom to top. When comparing the mean stream wise velocity field of the reference case and the Stratified case with RIM, only slightly different center line velocity decay is observed, where buoyancy causes a slight acceleration of the jet with increased downstream distance. The velocity field without

RIM shows a significant difference. This difference originates by the strong deflection of light when it travels through a region with varying refractive index. Not only the light that is scattered by seeding particles gets deflected on its way towards the camera sensor, but also the Laser light sheet itself gets deflected. The effect is visible on the right hand side of Fig. 3c, where the seeding density appears larger compared to the left hand side (the light sheet enters the facility from the left side!).

However, when comparing the turbulence level, lower TKE is found in the stratified RIM case, compared to the reference case without stratification, which is visible in Fig. 5. Here the TKE of the reference experiment (left) and the RIM density stratified case (middle) are shown aside of the not index matched case (right). A strong decay of turbulence with increasing downstream distance is observed, that is likely to be originated by suppression of momentum transport normal to the density gradient. The results are strongly biased for the not index matched case, where TKE shows much lower levels compared to the RIM case.

A quantitative comparison of the RIM results with the reference case is done by a comparison of the volumetric flow rate. The nominal volumetric flow rate is given by the cross sectional area of the nozzle and the nominal velocity u_n by:

$$Q_n = \frac{\pi}{4} D^2 \cdot u_n. \quad (11)$$

We then integrated the stream wise mean velocity by:

$$Q_i = \int \int_{-r}^r \bar{u} dA. \quad (12)$$

Figure 6 shows the ratio of the integrated volumetric flow rate and the nominal volumetric flow rate for all three cases as a function of the downstream distance.

The earliest reliable PIV results are obtained at a downstream distance of 4 hydraulic diameters. Here the integrated volumetric flow rate of the reference case and the

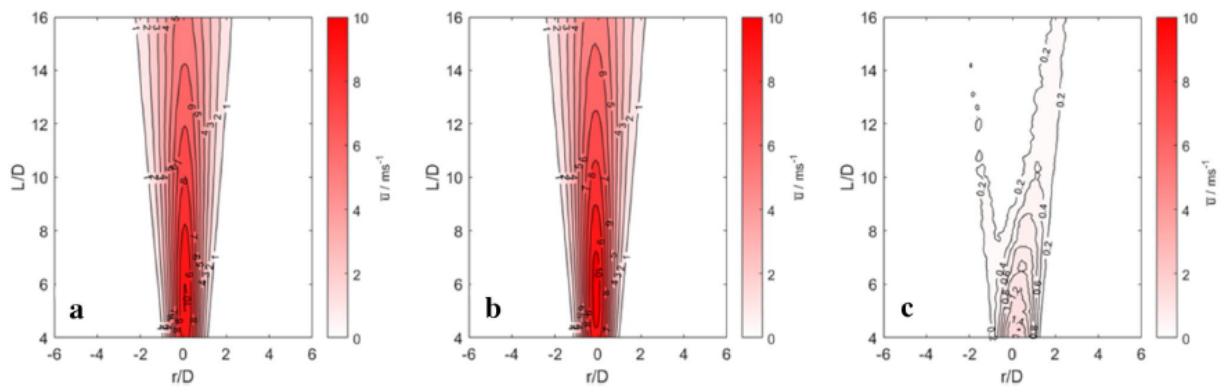


Fig. 4 Stream-wise mean velocity fields. **a** Reference case with solution I being injected to solution I (no differences in density and RI), **b** stratified case with the lighter liquid (solution I) being injected to the heavier liquid (solution II) at 8.6% density difference with RIM **c**

stratified case without RIM and a density difference of 8% (here both solutions were slightly altered with a refractive index of $n_D = 1.3712$ for solution I and $n_D = 1.3538$ for solution II)

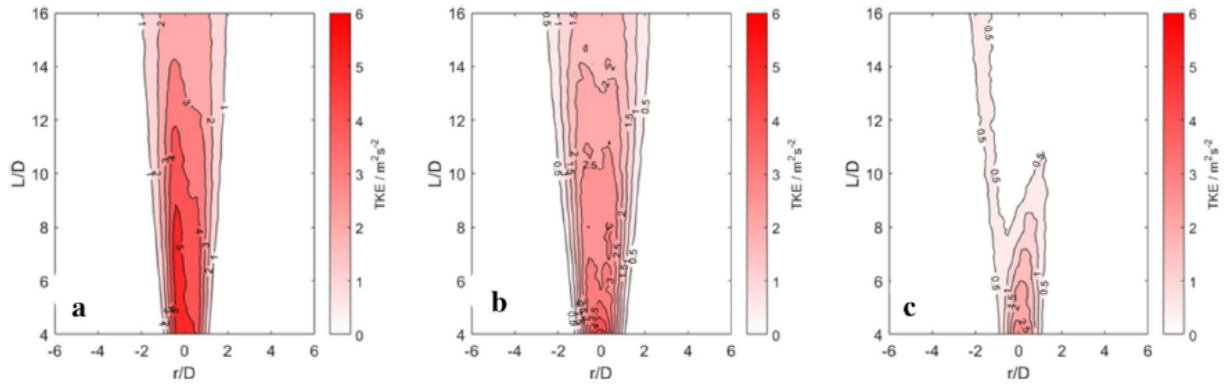


Fig. 5 Turbulence kinetic energy. **a** Reference case with solution I being injected to solution I (no differences in density and RI), **b** stratified case with the lighter liquid (solution I) being injected to the heavier liquid (solution II) at 8.6% density difference with RIM, **c**

stratified case without RIM and a density difference of 8% (here both solutions were slightly altered with a refractive index of $n_D = 1.3712$ for solution I and $n_D = 1.3538$ for solution II)

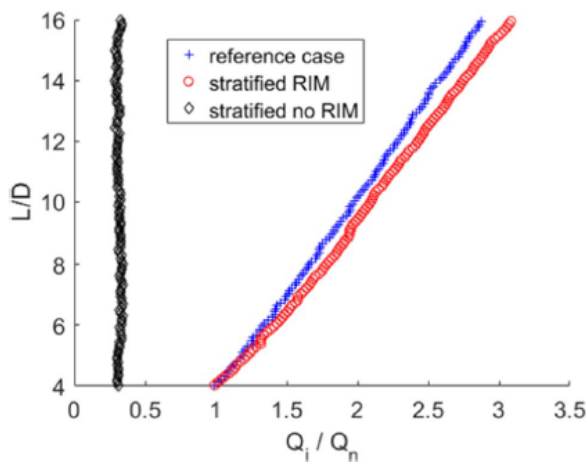


Fig. 6 Integrated volumetric flow rate of the three cases, normalized by the nominal volumetric flow rate

stratified RIM case are almost identical to the nominal volumetric flow rate. This indicates an extremely small entrainment to the jet at this point and demonstrates the applicability of RIM. Both, the reference case and the stratified RIM case show increase in volume flow rate with distance from the jet exit due to entrainment. For the buoyant RIM case, this entrainment appears to be slightly lower compared to the reference case; an effect that is likely in conjunction to the lower levels of turbulence observed for that case. In contrast the volumetric flow rate without RIM deviates significantly from the nominal flow rate. Here the integrated volumetric flow rate appears to be constant with increasing distance from the jet exit, which means there would be zero entrainment and thus demonstrates a strongly biased measurement when refractive index is not matched.

4 Conclusions

In the present work, we present a methodology to systematically identify combinations of two aqueous solutions characterized by constant refractive indices over large density changes, suitable to be used in turbulence research in which optical measurement techniques are employed. The method is based on the prediction of excess properties when three components are intermixing. We successfully achieved RIM with a density difference of 8.6% using the ternary system H_2O –isopropanol–glycerol. To the authors best knowledge this is the highest density difference with RIM reported in the literature. Proof-of-principle measurements were performed on a small scale buoyant jet, using a high temporally and spatially resolved PIV system. Although quantitative measurements were out of the scope of the present work, we observe significant influence of density gradients on the jet turbulence dynamics. While the mean velocity field seems to be affected mostly by viscous effects, we observe a strong suppression of velocity fluctuations with evolving downstream distance that is likely originated by a dampened momentum transport across the density gradient.

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Appendix

See Table 2.

Table 2 Refractive indices, density, excess refractive indices and excess density on mixing H₂O–glycerol–isopropanol at atmospheric pressure and 298.15 °C

H ₂ O x_1	Glycerol x_2	Isopropanol x_3	n_D –	ρ g/cm ³	n^E –	ρ^E g/cm ³
1.0000	0.0000	0.0000	1.3330	0.9980	0.000E+00	0.000E+00
0.9950	0.0050	0.0000	1.3336	0.9994	7.309E–05	8.450E–05
0.9900	0.0100	0.0000	1.3342	1.0005	1.462E–04	–1.310E–04
0.9800	0.0200	0.0000	1.3353	1.0028	1.924E–04	–4.620E–04
0.9700	0.0300	0.0000	1.3365	1.0051	3.385E–04	–7.930E–04
0.9600	0.0400	0.0000	1.3376	1.0074	3.847E–04	–1.124E–03
0.9500	0.0500	0.0000	1.3388	1.0097	5.309E–04	–1.455E–03
0.9400	0.0600	0.0000	1.3400	1.0120	6.771E–04	–1.786E–03
0.9300	0.0700	0.0000	1.3412	1.0144	8.233E–04	–2.017E–03
0.9200	0.0800	0.0000	1.3424	1.0167	9.694E–04	–2.348E–03
0.9100	0.0900	0.0000	1.3436	1.0191	1.116E–03	–2.579E–03
0.9000	0.1000	0.0000	1.3448	1.0215	1.262E–03	–2.810E–03
0.8800	0.1200	0.0000	1.3472	1.0262	1.554E–03	–3.372E–03
0.8600	0.1400	0.0000	1.3496	1.0311	1.847E–03	–3.734E–03
0.8400	0.1600	0.0000	1.3521	1.0360	2.239E–03	–4.096E–03
0.8200	0.1800	0.0000	1.3547	1.0409	2.731E–03	–4.458E–03
0.8000	0.2000	0.0000	1.3572	1.0459	3.124E–03	–4.720E–03
0.7600	0.2400	0.0000	1.3624	1.0561	4.108E–03	–5.044E–03
0.7200	0.2800	0.0000	1.3676	1.0664	5.093E–03	–5.268E–03
0.6800	0.3200	0.0000	1.3730	1.0770	6.278E–03	–5.192E–03
0.6400	0.3600	0.0000	1.3785	1.0876	7.562E–03	–5.116E–03
0.6000	0.4000	0.0000	1.3841	1.0984	8.947E–03	–4.840E–03
0.5600	0.4400	0.0000	1.3897	1.1092	1.033E–02	–4.564E–03
0.5200	0.4800	0.0000	1.3954	1.1200	1.182E–02	–4.288E–03
0.4800	0.5200	0.0000	1.4011	1.1308	1.330E–02	–4.012E–03
0.4400	0.5600	0.0000	1.4069	1.1419	1.489E–02	–3.436E–03
0.4000	0.6000	0.0000	1.4129	1.1530	1.667E–02	–2.860E–03
0.3600	0.6400	0.0000	1.4189	1.1643	1.846E–02	–2.084E–03
0.3200	0.6800	0.0000	1.4249	1.1755	2.024E–02	–1.408E–03
0.2800	0.7200	0.0000	1.4310	1.1866	2.212E–02	–8.320E–04
0.2400	0.7600	0.0000	1.4370	1.1976	2.391E–02	–3.560E–04
0.2000	0.8000	0.0000	1.4431	1.2085	2.579E–02	2.000E–05
0.1600	0.8400	0.0000	1.4492	1.2192	2.768E–02	1.960E–04
0.1200	0.8800	0.0000	1.4553	1.2299	2.956E–02	3.720E–04
0.0800	0.9200	0.0000	1.4613	1.2404	3.135E–02	3.480E–04
0.0400	0.9600	0.0000	1.4674	1.2508	3.323E–02	2.240E–04
0.0000	1.0000	0.0000	1.4735	1.2611	3.512E–02	0.000E+00
0.8985	0.0000	0.1015	1.3419	0.9806	4.410E–03	4.666E–03
0.8009	0.0000	0.1991	1.3511	0.9668	9.292E–03	1.208E–02
0.7027	0.0000	0.2973	1.3583	0.9485	1.215E–02	1.513E–02
0.6001	0.0000	0.3999	1.3638	0.9258	1.311E–02	1.474E–02
0.5064	0.0000	0.4936	1.3679	0.9039	1.306E–02	1.321E–02
0.3948	0.0000	0.6052	1.3718	0.8772	1.203E–02	1.077E–02
0.3076	0.0000	0.6924	1.3742	0.8566	1.057E–02	9.124E–03
0.2213	0.0000	0.7787	1.3760	0.8361	8.550E–03	7.385E–03
0.1016	0.0000	0.8984	1.3774	0.8069	4.655E–03	4.208E–03
0.0009	0.0000	0.9991	1.3772	0.7808	–1.840E–07	–6.555E–07
0.7997	0.1000	0.1003	1.3530	1.0060	5.023E–03	3.502E–03
0.6997	0.2000	0.1003	1.3655	1.0320	6.985E–03	3.192E–03
0.5997	0.3000	0.1003	1.3780	1.0560	8.947E–03	8.820E–04

Table 2 (continued)

H ₂ O x_1	Glycerol x_2	Isopropanol x_3	n_D —	ρ g/cm ³	n^E —	ρ^E g/cm ³
0.4997	0.4000	0.1003	1.3910	1.0800	1.141E-02	-1.428E-03
0.3997	0.5000	0.1003	1.4052	1.1040	1.507E-02	-3.738E-03
0.2997	0.6000	0.1003	1.4190	1.1280	1.833E-02	-6.048E-03
0.1997	0.7000	0.1003	1.4333	1.1560	2.209E-02	-4.358E-03
0.0997	0.8000	0.1003	1.4487	1.1760	2.696E-02	-1.067E-02
0.6993	0.1000	0.2007	1.3633	0.9920	1.088E-02	1.131E-02
0.5993	0.2000	0.2007	1.3728	1.0280	9.846E-03	2.100E-02
0.4993	0.3000	0.2007	1.3859	1.0380	1.241E-02	4.694E-03
0.3993	0.4000	0.2007	1.3982	1.0560	1.417E-02	-3.616E-03
0.2993	0.5000	0.2007	1.4108	1.0780	1.623E-02	-7.926E-03
0.1993	0.6000	0.2007	1.4235	1.1040	1.839E-02	-8.236E-03
0.1020	0.7000	0.1980	1.4383	1.1260	2.277E-02	-1.313E-02
0.5990	0.1000	0.3010	1.3677	0.9720	1.085E-02	1.313E-02
0.4990	0.2000	0.3010	1.3786	0.9920	1.121E-02	6.816E-03
0.3990	0.3000	0.3010	1.3906	1.0160	1.267E-02	4.506E-03
0.2990	0.4000	0.3010	1.4016	1.0320	1.313E-02	-5.804E-03
0.1990	0.5000	0.3010	1.4142	1.0560	1.519E-02	-8.114E-03
0.1030	0.6000	0.2970	1.4263	1.0600	1.693E-02	-3.129E-02
0.5010	0.1000	0.3990	1.3723	0.9520	1.111E-02	1.443E-02
0.4010	0.2000	0.3990	1.3819	0.9760	1.017E-02	1.212E-02
0.3010	0.3000	0.3990	1.3931	0.9920	1.083E-02	1.811E-03
0.2010	0.4000	0.3990	1.4051	1.0120	1.230E-02	-4.499E-03
0.1040	0.5000	0.3960	1.4165	1.0080	1.329E-02	-3.546E-02
0.4007	0.1000	0.4993	1.3755	0.9280	9.871E-03	1.224E-02
0.3007	0.2000	0.4993	1.3855	0.9460	9.333E-03	3.933E-03
0.2050	0.3000	0.4950	1.3973	0.9500	1.079E-02	-1.932E-02
0.1050	0.4000	0.4950	1.4081	0.9660	1.105E-02	-2.963E-02
0.3060	0.1000	0.5940	1.3788	0.9100	8.983E-03	1.482E-02
0.2060	0.2000	0.5940	1.3896	0.9100	9.245E-03	-1.149E-02
0.1060	0.3000	0.5940	1.4000	0.9240	9.107E-03	-2.380E-02
0.2070	0.1000	0.6930	1.3794	0.9000	5.203E-03	2.634E-02
0.1070	0.2000	0.6930	1.3875	0.9340	2.765E-03	3.403E-02
0.1080	0.1000	0.7920	1.3838	0.8480	5.224E-03	-4.133E-03
0.0090	0.1000	0.8910	1.3886	0.8180	5.644E-03	-1.261E-02
0.0080	0.2000	0.7920	1.3914	0.8500	2.286E-03	-2.844E-02
0.0070	0.3000	0.6930	1.4001	0.8940	4.827E-03	-3.228E-02
0.0060	0.4000	0.5940	1.4089	0.9320	7.469E-03	-4.211E-02
0.0050	0.5000	0.4950	1.4206	0.9840	1.301E-02	-3.794E-02
0.0040	0.6000	0.3960	1.4287	1.0300	1.495E-02	-3.977E-02
0.0030	0.7000	0.2970	1.4407	1.0800	2.079E-02	-3.760E-02
0.0020	0.8000	0.1980	1.4518	1.1430	2.573E-02	-2.244E-02
0.0010	0.9000	0.0990	1.4626	1.1800	3.038E-02	-3.327E-02
0.0100	0.0000	0.9900	1.3765	0.7860	-2.976E-04	3.221E-03

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APPENDIX IV –GWU ARTICLE #1

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RESEARCH ARTICLE



Options for refractive index and viscosity matching to study variable density flows

Simon A. Clément¹ · Anaïs Guillemain¹ · Amy B. McCleney² · Philippe M. Bardet¹

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Abstract

Variable density flows are often studied by mixing two miscible aqueous solutions of different densities. To perform optical diagnostics in such environments, the refractive index of the fluids must be matched, which can be achieved by carefully choosing the two solutes and the concentration of the solutions. To separate the effects of buoyancy forces and viscosity variations, it is desirable to match the viscosity of the two solutions in addition to their refractive index. In this manuscript, several pairs of index matched fluids are compared in terms of viscosity matching, monetary cost, and practical use. Two fluid pairs are studied in detail, with two aqueous solutions (binary solutions of water and a salt or alcohol) mixed into a ternary solution. In each case: an aqueous solution of isopropanol mixed with an aqueous solution of sodium chloride (NaCl) and an aqueous solution of glycerol mixed with an aqueous solution of sodium sulfate (Na_2SO_4). The first fluid pair allows reaching high-density differences at low cost, but brings a large difference in dynamic viscosity. The second allows matching dynamic viscosity and refractive index simultaneously, at reasonable cost. For each of these four solutes, the density, kinematic viscosity, and refractive index are measured versus concentration and temperature, as well as wavelength for the refractive index. To investigate non-linear effects when two index-matched, binary solutions are mixed, the ternary solutions formed are also analyzed. Results show that density and refractive index follow a linear variation with concentration. However, the viscosity of the isopropanol and NaCl pair deviates from the linear law and has to be considered. Empirical correlations and their coefficients are given to create index-matched fluids at a chosen temperature and wavelength. Finally, the effectiveness of the refractive index matching is illustrated with particle image velocimetry measurements performed for a buoyant jet in a linearly stratified environment. The creation of the index-matched solutions and linear stratification in a large-scale experimental facility are detailed, as well as the practical challenges to obtain precise refractive index matching.

1 Introduction

Variable density flows are studied experimentally by two main means: varying the temperature of a fluid (Ogino et al. 1980; Ezzamel et al. 2015), or mixing aqueous solutions of different densities (Alahyari and Longmire 1994; Daviero et al. 2001; Xu and Chen 2012). To obtain velocity, temperature, and/or concentration fields at high spatial and temporal resolutions, non-intrusive optical diagnostics, such as particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF), have become increasingly popular in the

past decades. However, density variations generate changes in refractive index, which can make optical measurements challenging. The laser beam or sheet used to illuminate the flow will bend as it passes through a fluid of varying refractive index. Furthermore, Mie scattered light by seeding particles or emitted by fluorescent dye through a non-uniform refractive index media will result in blurred or distorted images. In large facilities, where the laser beam must travel long distances, refractive index variations as small as 2×10^{-4} can cause significant image distortions and errors in spatial measurements (Daviero et al. 2001). When variable density flows are obtained by varying the temperature of the fluid, refractive index changes are typically negligible in gases, but not in liquids, which makes optical diagnostics challenging in those fluids. Instead, it is necessary to use solutions that are refractive index matched and with appropriate density difference.

✉ Simon A. Clément
simon.clement.pro@gmail.com

¹ Department of Mechanical and Aerospace Engineering, The George Washington University, Washington, DC, USA

² Southwest Research Institute, San Antonio, TX, USA

Refractive index matching of two miscible fluids was first introduced by McDougall (1976), where a process was developed for creating index matched liquids using Epsom salt and sugar solutions. He was able to obtain two fluids with a density difference of 2.8% while maintaining an equivalent refractive index. Others have followed suit using binary solutions of water and various salts and alcohols, which are mixed into a ternary solution. Hannoun et al. (1988) used ethyl alcohol and Epsom salt solutions, resulting in a 2% density difference, to study grid induced turbulence on a sharp-density interface. For large-scale stratified experiments, sodium chloride (NaCl) and ethanol were used to obtain a density difference as high as 2.6%, with a refractive index difference of only 1×10^{-4} (Daviero et al. 2001; Roberts et al. 2001). Past a certain concentration, the ethanol solution behaved non-linearly; therefore, creating a density difference above 2.6% with index-matched fluids was more challenging. Isopropanol (Isopropyl alcohol) and NaCl have been successfully used in PIV and PLIF experiments with a range of density differences up to 4.5% (Lowe et al. 2002; Troy and Koseff 2005). Isopropanol is less dense than water, making it an ideal candidate for creating a larger density difference between index-matched solutions. Horner-Devine (2006) used NaCl and isopropanol solutions for conducting index-matched experiments, but limited the density difference to 0.71%, with an alcohol concentration of 1.8%, because of the increase in viscosity by 10%.

Differences in viscosity between index matched fluids are not often taken into account, as most studies only consider matching refractive index for a chosen density difference. However, it was shown by Chhabra et al. (2005) that variations of viscosity have a strong effect on a neutrally buoyant jet. Matching the dynamic viscosity of the fluids is attractive and allows for the suppression of viscosity variations and the study of buoyancy effects alone. Alahyari and Longmire (1994), while studying microbursts using PIV, were able to match the refractive index of aqueous solutions of glycerol and potassium dihydrogen phosphate (KH_2PO_4), with a 3% density difference. With this fluid pair, they reduced the difference in dynamic viscosity between the two aqueous solutions to 2%. This study by Alahyari and Longmire (1994) is the only reference found by the authors on simultaneous refractive index and viscosity matching.

Although several fluid pairs have been used in the past, as detailed previously in this section, the dependency of their properties with temperature and wavelength has not been fully characterized. In Alahyari and Longmire (1994), the values of density, dynamic viscosity, and refractive index are obtained from chemistry handbooks (see Haynes 2015). The data reported in such handbook were first reported by Wolf (1966), where the temperature used is 293.2 K and the refractive index is given at 589.1 nm (wavelength of the sodium D-line). To fully understand and control the

properties of the index-matched fluids under specific experimental conditions, it is important to know the temperature dependence of density and viscosity, as well as the refractive index dependency with temperature and wavelength. For instance, most reference data are given at 589.1 nm, but diagnostics are performed at lower wavelengths: Nd:YAG at 532 nm, Nd:YLF at 527 nm, or argon-ion at 514.5 nm, to cite a few lasers commonly used in optical diagnostics for fluid mechanics.

To summarize the review given above, Isopropanol (Is) and NaCl are attractive for the high density differences to be reached at a low monetary cost, but they bring high viscosity variations. Glycerol (Gl) and KH_2PO_4 bring dynamic viscosity variations around 2%, but their use can make large-scale tests expensive, as shown in Sect. 2. In Sect. 2, several fluid candidates are compared in terms of refractive index and viscosity matching, while taking their price into consideration. A combination of glycerol and sodium sulfate (Na_2SO_4) allows decreasing viscosity variations below 1%, while keeping costs reasonable.

Density, kinematic viscosity, and refractive index are measured for the fluid pairs Is/NaCl and Gl/ Na_2SO_4 , using methodologies presented in Sect. 3. The results are presented in Sect. 4, and are compared to the values given by Wolf (1966). Moreover, when two index-matched, binary solutions are mixed into a ternary solution, nonlinear variations of density, viscosity, or refractive index with concentration can appear. These effects are investigated by analyzing ternary mixtures of index-matched solutions of Is/NaCl and Gl/ Na_2SO_4 as well in Sects. 3 and 4.

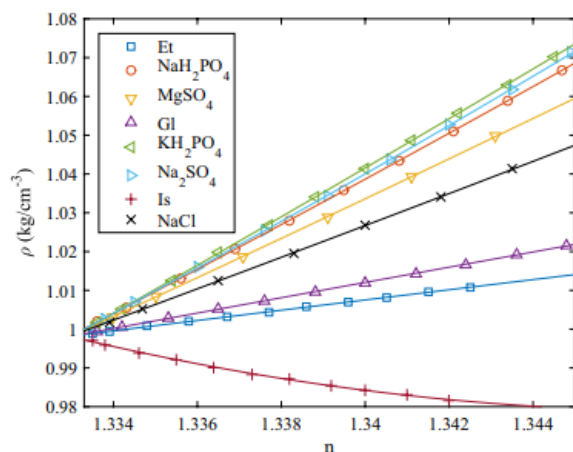
In Sect. 5, the experimental protocol used to study a buoyant jet in a linearly stratified environment is detailed. Several practical challenges are addressed: the precise creation of index matched solutions on a large scale, the formation of the linearly stratified environment, the need to control temperature, and the importance of evaporation when isopropanol is used. Images of a particle seeded flow and instantaneous velocity fields of a refractive index-matched buoyant jet in a linearly stratified surrounding are captured to show the successful use of the characterized fluid solutions in a large scale facility.

2 Fluid pairs for refractive index and viscosity matching

Previous studies have shown that Is/NaCl (Lowe et al. 2002; Troy and Koseff 2005) and Gl/ KH_2PO_4 (Alahyari and Longmire 1994) are attractive to perform index matched experiments. However, the 2017 cost of ACS Reagent grade KH_2PO_4 can discourage experimentalists, and finding alternative molecules can be attractive. From the reference data given in Wolf (1966), three other fluid pairs are identified

Table 1 Fluid pairs for refractive index matching

Light fluids	Heavy fluids
Isopropanol (Is)	Sodium chloride (NaCl)
Ethylene glycol (Et)	Sodium dihydrogen phosphate (NaH_2PO_4)
	Epsom salt (MgSO_4)
Glycerol (Gl)	Potassium dihydrogen phosphate (KH_2PO_4)
	Sodium sulfate (Na_2SO_4)

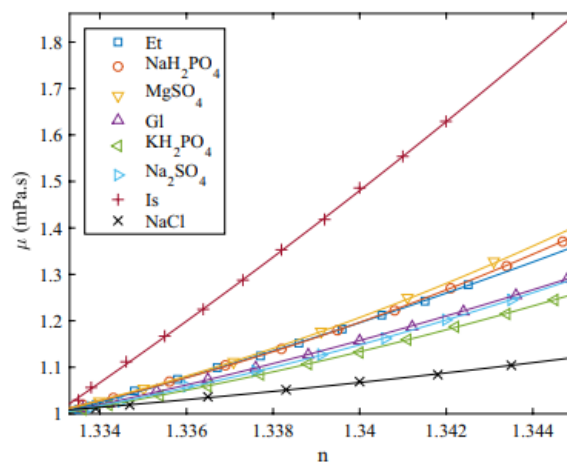
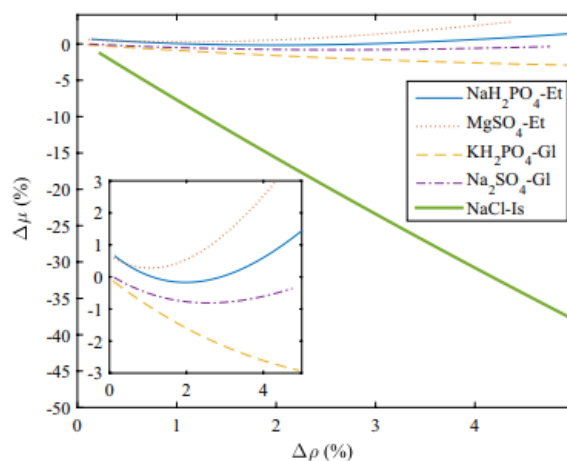
**Fig. 1** Density versus refractive index, at 293.2 K and 589.1 nm. The symbols represent the data points given by Wolf (1966) and the lines are obtained by a second order curve fit

to allow matching refractive index and viscosity simultaneously, while obtaining density differences up to 5%. The fluid pairs investigated in the present manuscript are summarized in Table 1.

From the data by Wolf (1966), the density and viscosity of these aqueous solutions can be obtained as a function of the refractive index, as shown in Figs. 1 and 2. A second-order curve fit is used to obtain the density and viscosity difference for any value of the refractive index.

In Fig. 3, for each index-matched pair, the viscosity difference is given as a function of the density difference. Because isopropanol and NaCl solutions have large viscosity differences, the results obtained for the four other pairs are presented at higher resolution at the bottom left of the figure.

For a 3% density difference, Gl/ KH_2PO_4 has a dynamic viscosity difference of 2.17%, consistent with Alahyari and Longmire (1994). The fluid pairs Gl/ Na_2SO_4 and Et/ NaH_2PO_4 offer an even closer match of the dynamic viscosity, respectively 0.79 and 0.04% for a density difference of 3%. In the perspective of a refractive index and dynamic viscosity-matched experiment, these two fluid pairs are then particularly attractive. Figure 3 also shows that the pair Gl/ Na_2SO_4 has nearly equal dynamic viscosities for a

**Fig. 2** Dynamic viscosity versus refractive index, at 293.2 K and 589.1 nm. The symbols represent the data points given by Wolf (1966) and the lines are obtained by a second order curve fit**Fig. 3** Viscosity difference between index matched solutions, versus their associated density difference. The zoomed figure at the bottom left has a reduced vertical axis to focus on the closely viscosity matched pairs

5% density difference. While in the subsequent manuscript this pair of solutions is tested for a density difference up to 5%, the viscosity difference remains within 1% for a density difference up to 7.3% (Wolf 1966).

For large-scale tests, the monetary cost of the chemicals used is an important parameter. 2017 prices from five large chemicals providers were compared for all the compounds present in Table 1, for laboratory grade (ACS Reagent), and in large quantities (between 50 and 100 kg). Is/NaCl is the cheapest fluid pair, followed by Gl/ Na_2SO_4 . Considering that the fluid pair Gl/ Na_2SO_4 also reduces dynamic viscosity

variations below 1%, it is the most attractive pair for simultaneous refractive index and viscosity matching. Using glycerol and KH_2PO_4 is even ten times more expensive than glycerol and Na_2SO_4 . However, these prices depend on the providers considered and the time at which the search is performed. For instance Alahyari and Longmire (1994) found that potassium dihydrogen phosphate was typically less expensive than Epsom Salt, while during the current price search, Epsom salt was more affordable.

3 Protocol for fluid properties characterization

Density, viscosity, and refractive index of NaCl, isopropanol, Na_2SO_4 , and glycerol aqueous solutions are measured in relation to concentration, temperature, and wavelength. The compounds used are all of ACS reagent quality: sodium chloride (from EK Industries, purity $\geq 99.0\%$), isopropanol (from Avantar Perf Mat-Macron Lab, purity $\geq 99.5\%$), sodium sulfate (from VWR International co., purity $\geq 99.0\%$) and glycerol (from Anachemia Canada co., purity $\geq 99.5\%$).

For each compound, binary mixtures at different concentrations are obtained by creating a mother solution and performing successive dilutions. The concentrations of the solutions studied are given in Table 2. Weight percentage (wt%) is used throughout this article for its universal value, while concentration in g L^{-1} corresponds to a particular value of volume of solution and thus to a particular temperature. In Table 2, the concentrations in g L^{-1} are given as reference for solutions prepared at a temperature of 293.2 K.

3.1 Density measurements

Densities are measured by weighing the fluids in a pycnometer on a precision scale (Intelligent-Lab model PM 100) with a 100 g capacity and a ± 0.003 g uncertainty. The volume of the pycnometer is given as 24.97 ± 0.05 mL, which has a relatively high uncertainty. To decrease this uncertainty, the density of distilled water was measured and compared to the one in Wagner and Pruss (2002), giving a volume of

25.007 mL. The uncertainty on the density is then primarily due to the balance uncertainty, estimated at $\pm 0.12 \text{ kg m}^{-3}$.

To obtain the thermal dependence, the filled pycnometer is heated on a hot plate, shaken to obtain a uniform temperature, and then closed. The temperature is measured before and after measuring the mass of the closed pycnometer and the value recorded is the mean of the two measurements. The temperature is measured using an Acorn Temp 6 RTD Thermometer with a NIST-traceable calibrated probe, with an uncertainty of $\pm 0.2^\circ\text{C}$. This brings an uncertainty on the density of $\pm 0.16 \text{ g/L}$. Therefore, combining the accuracy of both the scale and thermometer results in an overall uncertainty of $\pm 0.20 \text{ kg m}^{-3}$. Four measurements are performed for each temperature and solution to increase the accuracy on the mean value.

3.2 Kinematic viscosity measurements

Kinematic viscosity measurements are carried out with a calibrated Ubbelohde viscometer from Cannon Instrument company. Due to gravity forces, the liquid flows between two marks. The time at which the fluid travels from one mark to the other can be recorded and correlated to the viscosity of the fluid. The time needed for each measurement varies between five and eight minutes for the viscosity range considered here.

A water bath with digital controller is used to control the temperature of the fluid. Temperature is measured at several elevations along the viscometer with a ± 0.2 K uncertainty and no spatial variation is observed. Temperature is recorded after the fluid passes the first mark, and again after it passes the second.

The sections of the tube where the marks are located are narrow and the fluid passes at relatively high speed, making time measurements challenging for the naked eye. To reduce the uncertainty, a Point Grey CM3-U3-13S2M-CS camera coupled with a Nikon 60 mm macro $f/2.8$ lens is used at 10 fps. The starting and ending frames are selected with an uncertainty ± 0.1 s. The thermometer provides a $\pm 0.2^\circ\text{C}$ accuracy, the overall uncertainty on the kinematic viscosity value is then $\pm 0.39\%$. Four measurements are also performed per temperature and solution.

Table 2 Concentrations of the solutions in wt% and g L^{-1}

NaCl	wt%	1.95	3.84	5.68	7.48	9.24
	g L^{-1}	19.7	39.4	59.0	78.7	98.4
Is	wt%	1.58	3.17	4.76	6.36	7.97
	g L^{-1}	15.7	31.4	47.5	62.9	78.6
Na_2SO_4	wt%	1.97	3.87	5.71	7.50	9.23
	g L^{-1}	20.0	40.0	60.0	80.0	100
Gl	wt%	2.00	3.98	5.95	7.91	9.87
	g L^{-1}	20.0	40.0	60.0	80.0	100

3.3 Refractive index measurements

The refractive index measurements are performed using a modified Thermo Scientific Abbe-3L refractometer. To test the spectral dependency of the fluids, the original Amici prisms, used to illuminate the solution with sodium D-line light, are removed and the refractometer is illuminated by He-Ne lasers: one at 543 nm (Newport R-30967) and the second at 632.8 nm (JDSU Novette 1508P-1), with an uncertainty of ± 0.1 nm. The temperature is controlled by circulating water through the refractometer measurement cell using a peristaltic pump and insulated tubing, from the digital water bath.

Temperature is measured with the same thermometer as with the viscosity measurement, giving an accuracy on the refractive index of $\pm 0.9 \times 10^{-4}$. The error from the user's ability to read a consistent value due to wondering eye is eliminated by imaging the refractive index display using a camera fixed to the refractometer. This allows for a resolution of 1.0×10^{-4} , giving an overall uncertainty of $\pm 1.7 \times 10^{-4}$ on the refractive index. The offset between measurements of the refractometer and absolute refractive indices is corrected using the values given in Kedenburg et al. (2012) for distilled water. More details about the protocol can be found in Fort et al. (2015).

4 Results of the measurements

The two fluid pairs are studied for different temperature ranges: NaCl and isopropanol between 292 and 301 K, Na_2SO_4 and glycerol between 291 and 296 K. Characterization of the fluids is accomplished with both tap and distilled water. No significant variations are observed within the measurement tolerances. For the refractive index, this result is consistent with Daimon and Masumura (2007), where it was shown that the difference between distilled and tap water is below 5×10^{-5} . Only the results obtained with tap water are presented here, since it is readily and easily obtainable for large-scale experiments.

From the large quantity of data obtained, curve fits are performed using a least-square method to obtain the dependency of density and kinematic viscosity with concentration and temperature, and refractive index with concentration, temperature, and wavelength. The correlations used for the curve fits are detailed below and the values of their coefficients are given in Table 3.

4.1 Density

The density varies linearly with temperature for the range studied here, the correlation is thus of first order with temperature. A second order is used for concentration and a

linear cross term represents the coupling between concentration and temperature dependencies. The temperature is given as $\bar{T} = T - T_0$, where $T_0 = 293.2$ K, and the concentration w is given in weight percentage (wt%).

$$\frac{\rho}{\rho_0} = 1 + \zeta_\rho w + \zeta_{\rho,2} w^2 + \alpha_\rho \bar{T} + \chi_\rho \bar{T} w, \quad (1)$$

The quality of the curve fit (and low spread of the data points) is shown by the R^2 value close to unity, and the root mean square error (RMSE) on the order of the measurement uncertainty ($\pm 0.2 \text{ kg m}^{-3}$). The coefficient ρ_0 corresponds to water at 293.2 K. Its value is 998.2 kg m^{-3} (Wagner and Pruss 2002), which is within the measurement uncertainty.

4.2 Kinematic and dynamic viscosities

The logarithm of the viscosity is usually used for correlations (George et al. 2002), with a second order on both temperature and concentration and a cross term.

$$\ln\left(\frac{\nu}{\nu_0}\right) = \zeta_\nu w + \zeta_{\nu,2} w^2 + \alpha_\nu \bar{T} + \alpha_{\nu,2} \bar{T}^2 + \chi_\nu \bar{T} w, \quad (2)$$

The kinematic viscosity of water at 293.2 K, ν_0 , is also close to the reference value found in the literature, $1.005 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ (Huber et al. 2009). The R^2 is close to unity and the RMSE close to the measurement uncertainty ($\pm 0.39\%$). For glycerol, a slightly higher value of the RMSE indicates a higher spread of the data, but the results shown below are also consistent with the literature.

The dynamic viscosity can then be computed as the product of the density and kinematic viscosity.

4.3 Refractive index

The refractive index of a fluid is linked to its density, thus the correlations also use a first order for temperature and a second order for concentration, with a cross term. The spectral dependency is represented with a classic $1/\lambda^2$ law, and the cross term takes into account spectral variations depending on the concentration.

$$n = n_0 + \zeta_n w + \zeta_{n,2} w^2 + \alpha_n \bar{T} + \chi_n \bar{T} w + \frac{\gamma_n}{\lambda^2} + \gamma_{n,w} \frac{w}{\lambda^2}, \quad (3)$$

The value of n_0 corresponds to water at T_0 , for an infinite wavelength. To compare with the literature, the wavelength $\lambda = 589.1 \text{ nm}$ can be used and at $T = 293.2 \text{ K}$, $n_0 = 1.3333$ for all solutions. The reference value is 1.3332 (Kedenburg et al. 2012), which is within the measurement uncertainty. Again, the R^2 and RMSE show a very good fit and low spread of the data considering the uncertainty of the measurement of $\pm 1.7 \times 10^{-4}$.

Table 3 Coefficients of the empirical correlations

	Units	NaCl	Isopropanol	Na ₂ SO ₄	Glycerol
ρ_0	kg m ⁻³	998.3	998.3	998.2	998.1
ζ_ρ		6.986×10^{-3}	-1.776×10^{-3}	8.976×10^{-3}	2.398×10^{-3}
$\zeta_{\rho,2}$		2.992×10^{-5}	2.422×10^{-5}	3.323×10^{-5}	-4.238×10^{-6}
α_ρ	K ⁻¹	-2.606×10^{-4}	-2.389×10^{-4}	-2.360×10^{-4}	-2.180×10^{-4}
χ_ρ	K ⁻¹	-1.235×10^{-5}	-7.166×10^{-6}	-1.364×10^{-5}	-5.993×10^{-6}
R ²		1.000	0.999	1.000	0.999
RMSE	kg m ⁻³	0.259	0.123	0.168	0.185
ν_0	m ² s ⁻¹	1.004×10^{-6}	1.003×10^{-6}	1.004×10^{-6}	1.004×10^{-6}
ζ_ν		6.205×10^{-3}	4.902×10^{-2}	1.944×10^{-2}	2.065×10^{-2}
$\zeta_{\nu,2}$		3.679×10^{-4}	9.252×10^{-6}	4.694×10^{-4}	3.924×10^{-4}
α_ν	K ⁻¹	-2.519×10^{-2}	-2.518×10^{-2}	-2.484×10^{-2}	-2.562×10^{-2}
$\alpha_{\nu,2}$	K ⁻²	3.132×10^{-4}	3.149×10^{-4}	1.894×10^{-4}	3.451×10^{-4}
χ_ν	K ⁻¹	1.781×10^{-4}	-7.187×10^{-4}	9.918×10^{-5}	-1.700×10^{-4}
R ²		0.998	1.000	0.999	0.999
RMSE	m ² s ⁻¹	2.761×10^{-9}	4.518×10^{-9}	4.630×10^{-9}	1.231×10^{-8}
n_0		1.3241	1.3240	1.3240	1.3240
ζ_n		1.6481×10^{-3}	7.5008×10^{-4}	1.4937×10^{-3}	1.1614×10^{-3}
$\zeta_{n,2}$		2.1561×10^{-6}	6.5668×10^{-6}	-5.3089×10^{-6}	3.6732×10^{-6}
α_n	K ⁻¹	-9.2815×10^{-5}	-9.2148×10^{-5}	-6.0715×10^{-5}	-6.2726×10^{-5}
χ_n	K ⁻¹	-3.1415×10^{-6}	-1.2436×10^{-6}	-3.0317×10^{-6}	-2.0564×10^{-6}
γ_n	nm ²	3.1886×10^3	3.2328×10^3	3.2345×10^3	3.2177×10^3
$\gamma_{n,w}$	nm ²	2.2992×10^1	1.4521×10^1	8.6682	2.297
R ²		1.000	0.999	0.999	0.999
RMSE		8.82×10^{-5}	9.79×10^{-5}	1.13×10^{-4}	1.23×10^{-4}

An important parameter is α_n , which gives the evolution of n with T . Its value is on the order of 10^{-4} , meaning that a difference of temperature as small as 2 K brings refractive index variations of 2×10^{-4} , sufficient to make optical measurements impossible. It is thus crucial to limit temperature differences between the solutions and in the different parts of an experiment.

The different solutes have similar coefficients γ_n , with differences on the order of 1%. The value of the product $\gamma_{n,w}$ is one order of magnitude below the value of γ_n , which shows a low dependence on concentration. This indicates that for each solution pair, the binary mixtures have the same refractive index over a large range of wavelength.

4.4 Comparison with the literature

To assess the pertinence of the measurements performed in the present study, results are compared with published data (Wolf 1966). The density, dynamic viscosity and refractive index are computed using the correlations given above at $T = 293.2$ K and $\lambda = 589.1$ nm, and compared in Fig. 4 to the data by Wolf (1966). The correlation given by Daviero et al. (2001) for density and refractive index are also

represented. A close match can be observed, with the following differences:

- *For density* Glycerol, Na₂SO₄, and NaCl show a maximum difference of 0.6 kg m⁻³. For isopropanol, the density is slightly higher than the reference, with a maximum difference of 1.5 kg m⁻³.
- *For viscosity* Empirical correlations and data by Wolf (1966) are particularly close for Na₂SO₄ and NaCl, with differences lower than 0.5%. For glycerol and isopropanol, differences are below 1.5%.
- *For refractive index* Differences are below 2×10^{-4} for all solutions except isopropanol, for which it reaches 4×10^{-4} .

The differences observed are small and confirm the accuracy of the results obtained and existing datasets. However, assuming a linear relationship between refractive index and concentration, as done in Daviero et al. (2001) for NaCl, overestimates the refractive index by 9×10^{-4} at a concentration of 10 wt%, which would result in large optical aberrations. Therefore, using a second order polynomial is required to ensure an accurate refractive index matching.

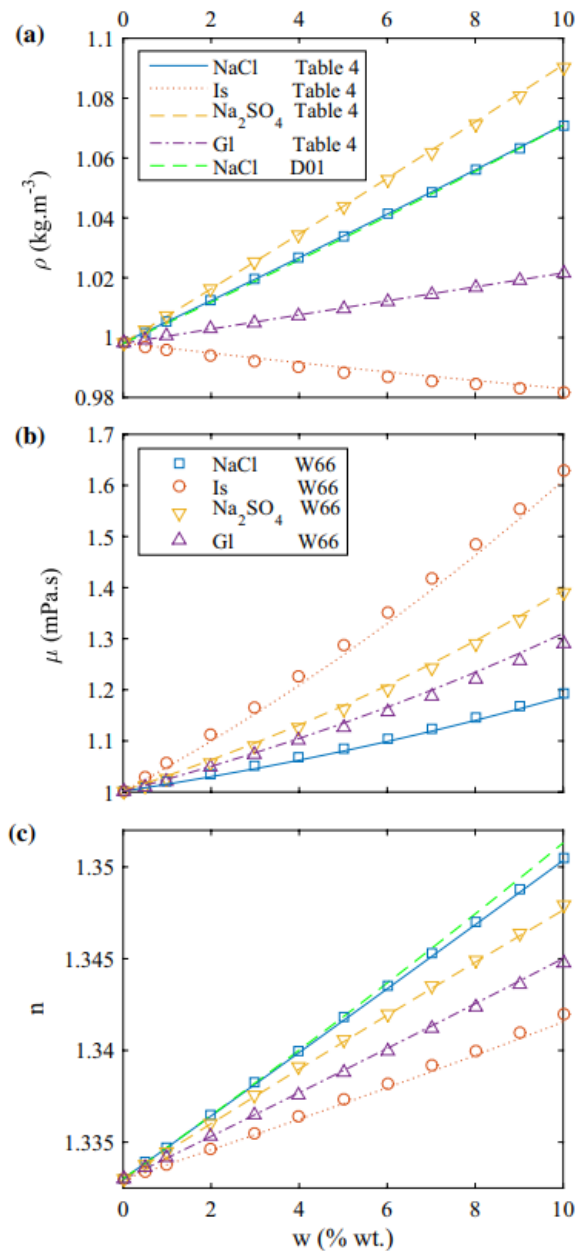


Fig. 4 Comparison between the data by Wolf (1966), noted W66, and the correlations obtained with the present study, at $T = 293.2$ K and $\lambda = 589.1$ nm. The density and refractive index of NaCl by Daviero et al. (2001), noted D01, are also represented

4.5 Practical use of the empirical correlations

The most important parameter of variable density flows is the density difference between the solutions, which is fixed by experiment design. Considering the temperature and wavelength at which tests take place, the concentrations

required for index-matched solutions can be obtained from the correlations in Eqs. (1–3) and Table 3. The viscosity difference between the two solutions can then also be computed.

The results obtained are summarized in Figs. 5 and 6 for Gl/Na₂SO₄ and Is/NaCl, respectively. The density difference, viscosity difference, and refractive index of index-matched solutions are given versus temperature and concentrations. They are given for a wavelength of 532.0 nm as an example, which is often used for PIV measurements with Nd:YAG lasers. Particular points of interest are represented, obtained at 293.2 K: a 3% density difference for Gl/Na₂SO₄ and 5% for Is/NaCl. It can be noted that temperature has a low impact on the density difference, but a large impact on the viscosity difference (especially for the Gl/Na₂SO₄ pair) and on the refractive index.

This representation of the data can be computed for any wavelength and allows for the determination of the concentrations required for any desired temperature, density difference and viscosity difference.

If the viscosity of the solutions needs to be adjusted without modifying the density, it can be done by adding small quantities of sodium carboxymethylcellulose (NaCMC). This compound is used by Chhabra et al. (2005) to vary the dynamic viscosity without modifying the density. However, adding NaCMC changes the rheology of the solution, bringing a non-Newtonian behavior, which would here be undesirable and is beyond the scope of this work (Fujita and Homma 1955; Lohmander and Strömberg 1964).

4.6 Ternary mixtures from index matched solutions

A characterization of the ternary mixture over a wide range of compositions would result in ternary triangles for density, viscosity, and refractive index. To the authors' knowledge, such extensive study was only performed by Saksena et al. (2015) and Cadillon et al. (2016) for two immiscible index-matched binary solutions. Thanks to their thorough analysis these authors were able to also control the viscosity. The data reported in the present manuscript are only in the region of interest, where the experimental facility is employed. They correspond to single lines through the ternary triangles.

Using the results presented above, index-matched binary mixtures are prepared. A 5% density difference is studied for Is/NaCl, and 3% for Gl/Na₂SO₄. The concentrations of the index-matched solutions are given in Table 4. These solutions are characterized using the methodology described in Sect. 3.

The concentration of Gl/Na₂SO₄ to obtain a 3% density difference (6.31 and 5.00 wt%) is slightly different from the ones obtained by Wolf (1966) at (6.57 and 5.08 wt%). This is due to the difference of refractive index and density: a gap

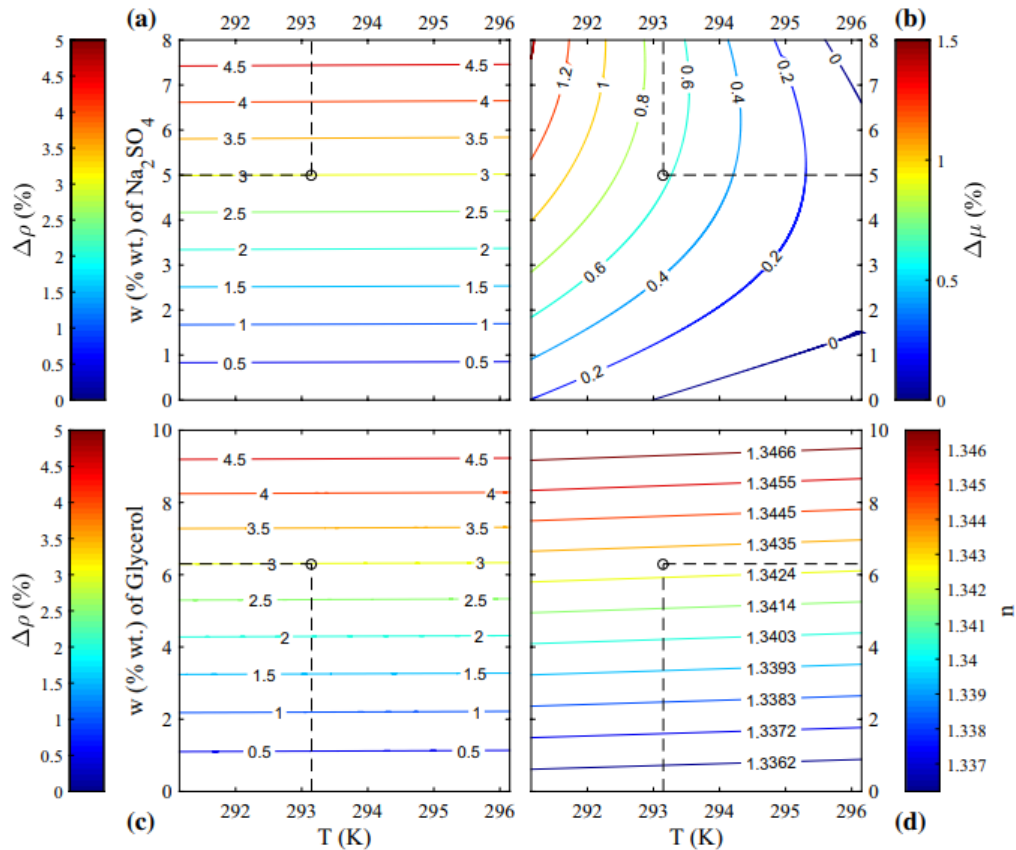


Fig. 5 Difference of density (a, c), difference of viscosity (b) and refractive index (d) of index matched solutions of Gl/Na₂SO₄, versus temperature and concentration of Na₂SO₄ (a,b) and glycerol (c,d). The point corresponding to a 3% density difference at 293.2 K is also represented

in refractive index of 2×10^{-4} corresponds to a concentration difference of 0.2 wt% ($\zeta_n \approx 1 \times 10^{-3}$) and a gap in density of 0.6 kg m^{-3} corresponds to a concentration difference on the order of 0.1 wt% ($\zeta_\rho \approx 2 - 9$).

The density, kinematic viscosity, and refractive index of these solutions are measured as a function of temperatures at both wavelengths. The results agree with the correlations (Eqs. (1–3) and Table 3) within the measurement uncertainty. Considering that the index matched solutions were freshly prepared, the accuracy of the mother solutions and successive dilutions is thus attested.

To investigate non-linear effects when mixing index-matched binary solutions, ternary mixtures are also studied. A simple linear model is often used to compute the density ρ_{tm} and refractive index n_{tm} of the ternary mixture:

$$\rho_{tm} = \phi_1 \rho_1 + \phi_2 \rho_2 \quad \text{and} \quad n_{tm} = \phi_1 n_1 + \phi_2 n_2 \quad (4)$$

where ϕ_i is the volume fraction of each solution. The viscosity ν_{tm} is computed with:

$$\ln(\nu_{tm}) = x_1 \ln(\nu_1) + x_2 \ln(\nu_2) \quad (5)$$

where x_i is the molar fraction of each solution. Because the two solutions mixed contain two compounds each, it is hard to define a molar fraction, and the volume fraction is used hereafter for the viscosity. This model is a simplification of the relationships given by McDougall (1976), where both solutes diffuse independently and separate concentration variables are used for each solute.

The validity of the linear approximation presented above is tested by performing measurements with the ternary solutions, obtained from mixing index matched binary solutions in various proportions. Solutions are created from 0 to 100% salt solution, by 20% volume fraction increment. For each ternary mixture, the density, viscosity, and refractive index are measured versus temperature and for two wavelengths, as done previously.

The measurements can then be compared to the linear laws given in Eqs. 4 and 5, taking the values from Eqs. (1–3) and Table 3 for the index matched solutions. The following results are obtained:

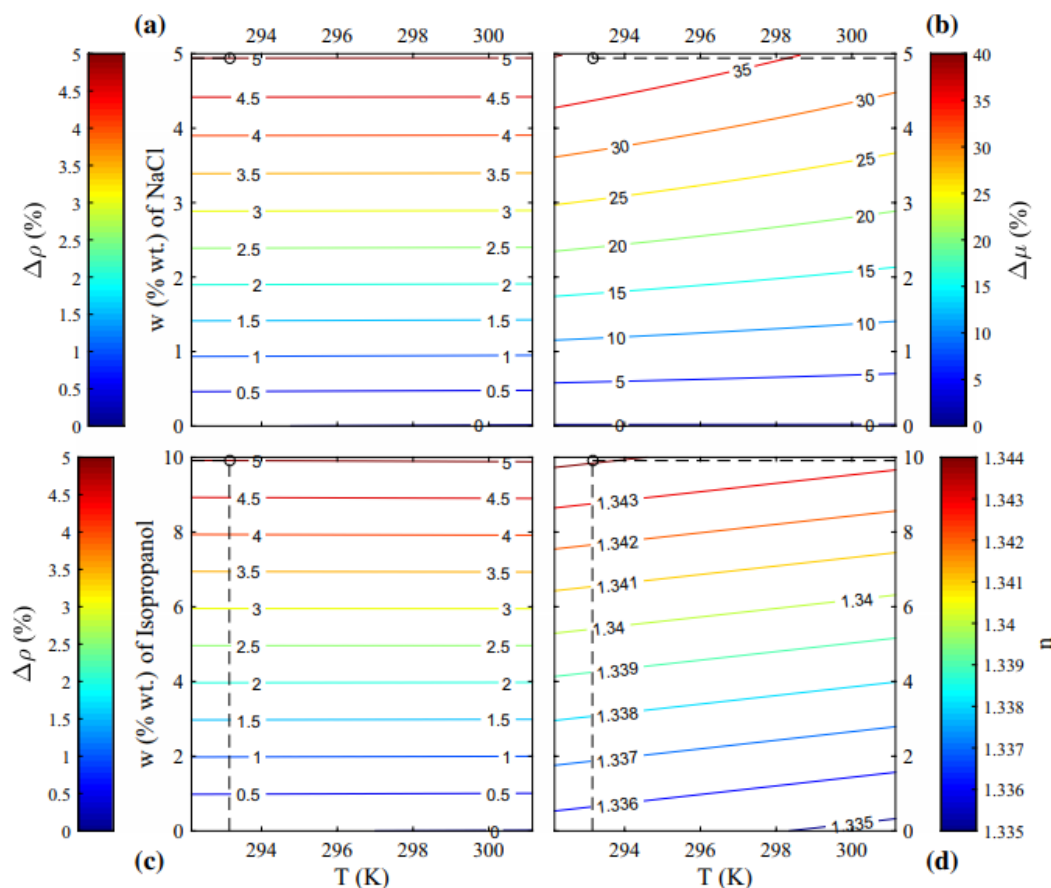


Fig. 6 Difference of density (a, c), difference of viscosity (b) and refractive index (d) of index matched solutions of Is/NaCl, versus temperature and concentration of NaCl (a, b) and isopropanol (c, d). The point corresponding to a 5% density difference at 293.2 K is also represented

Table 4 Concentrations of the index-matched solutions in wt% and g L^{-1}

5 %	NaCl	wt%	4.94
		g L^{-1}	51.1
	Is	wt%	9.91
		g L^{-1}	97.4
3 %	Na_2SO_4	wt%	5.00
		g L^{-1}	52.2
	Gl	wt%	6.31
		g L^{-1}	63.9

The concentrations in g L^{-1} are given for a preparation temperature of 293.2 K

- For density: deviations between linear model and measurements are below 0.2 kg m^{-3} for all temperatures. It can thus be considered to follow a linear behavior.
- For viscosity: deviations from linearity are below 0.2% for the Gl/ Na_2SO_4 pair, which is below the measurement uncertainty. The difference in kinematic viscos-

ity between the glycerol and sodium sulfate solutions is below 1%. Because the measurement uncertainty is 0.39%, it is difficult to estimate with confidence deviation from linear behavior of the Gl/ Na_2SO_4 pair with the current system. For the Is/NaCl pair, the difference between measurements and models is given in Fig. 7 versus temperature and concentration. With a measurement uncertainty of 0.39%, a spread of the measurements can be observed, but a clear deviation from linear behavior appears. For concentrations approaching 60%, a difference as high as 1.2% is obtained at low temperature.

- For refractive index: the solutions are initially index matched, and do not show any change in refractive index when mixed in different proportions for both wavelengths.

For the density and refractive index, a linear behavior can be assumed. However, the viscosity of the Is/NaCl pair shows a non-linear behavior, particularly present at low temperature. If concentration measurements are

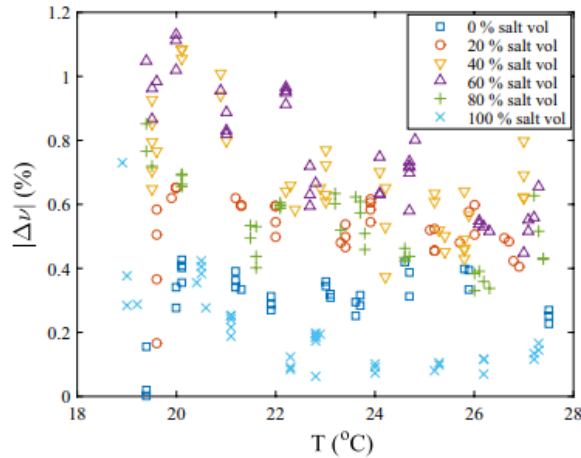


Fig. 7 Deviation from linear behavior for the Is/NaCl pair. The difference in kinematic viscosity between the measurements and a linear model is given as a function of the temperature and salt concentration (in volume %)

performed, this non-linear behavior should be taken into account to relate viscosity of the mixture to concentration.

The density and refractive index of ternary mixtures of isopropanol and NaCl are given by Bagrovskaya et al. (1996) for a molar concentration of NaCl of 1 M. The viscosity of ternary mixtures of isopropanol and NaCl are given by Bald and Kinart (2017) over a wide range of compositions. The results are used to extract the Jones–Dole viscosity coefficients, but the units used and the absence of density values make it hard to compare their results with the values obtained in the present manuscript.

5 Application to a buoyant jet in a linearly stratified environment

Buoyant plumes and jets interacting with stratified environments are fundamentally studied for industrial, geophysical, and environmental applications. The turbulent mixing of hydrothermal plumes in ambient sea-water is used to characterize sea-floor hydrothermal discharge, and is capable of sustaining deep sea life (Sysoev and Kantor 1995). Dispersion of pollutants and exhaust plumes in oceans and lakes can be controlled by discharging wastewater as turbulent buoyant plumes that rapidly dilute the effluent and by utilizing ambient stratification to maintain a submerged plume (Brooks 1996). Finally, in accident scenarios, these jets are responsible for mixing and transport of gaseous species in containment buildings of nuclear reactors (IAEA 2010).

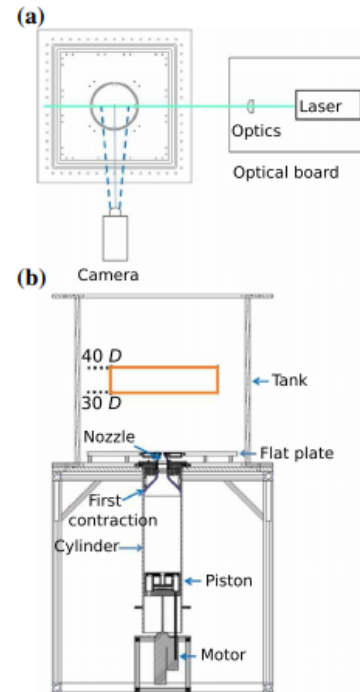


Fig. 8 **a** Optical configuration, **b** vertical jet facility with location of PIV image frame, indicated by orange box

5.1 Highly repeatable vertical round jet facility

The test facility shown in Fig. 8 produces a round, axisymmetric, incompressible jet with controlled velocity. The vertical jet discharges into a cubic tank (0.77 m^3); the nozzle is centered on the bottom surface of the tank and is connected to a large cylindrical chamber initially filled with liquid. A linear motor drives a piston through the 203 mm diameter cylinder (located under the tank). At the top of the cylinder, the fluid goes through a first contraction followed by a second contoured nozzle, with exit diameter, D , of 12.7 mm (or 6.35 mm), into the experimental cubic test section. Since the fluid in the cylinder is initially at rest, the issuing flow has little to no initial disturbances. The test section has a width to nozzle diameter ratio of 72 (or 144 for the 6.35 mm nozzle), which minimizes interaction between the jet and the side walls. The tank is made of clear acrylic and allows for visual access to the flow. Full details of the experimental facility design can be found in McCleney (2012).

To conduct PIV measurements, the jet is seeded with $10\mu\text{m}$ or $30\mu\text{m}$ diameter hollow glass sphere particles, depending on the magnification desired. The camera and laser are positioned perpendicular to each other (Fig. 8a), with the laser illuminating a plane in the center of the jet. The PIV processing is performed with LaVision, Inc. DaVis 8.3.0.

5.2 Creation of index-matched fluids and stratification

The stratified environment is created with a two-tank method (Hill 2002). This method allows for density profiles of any shape to be constructed and offers substantial savings in terms of labor and time. It requires establishing and maintaining controlled flow rates between three different containers: two storage tanks, Tank A and Tank B, and the test section. The setup is illustrated in Fig. 9. Tank A is filled with the light solution (isopropanol or glycerol), while Tank B is filled with the heavier salt solution (NaCl or Na_2SO_4). To create a linear stratification, fluid is pumped from Tank A into Tank B at a flow rate Q and from Tank B into the facility tank at a flow rate $2Q$. To minimize mixing during the filling process of the test section, the liquid is poured over a thin floating diffuser plate made of Styrofoam. This plate can be removed once the tank is filled or left in place to provide a moving rigid boundary at the top of the tank. From Tank B, only a small portion of the exit flow is sent to fill the test section; the rest is recirculated back into Tank A, creating a jet inside the tank that mixes the solutions. A similar recirculation is used to mix the solution in Tank A.

Before any fluid is admitted to the test section, the cylinder, which encases the piston, is filled with the light solution, from a small dedicated reservoir. This reservoir contains sufficient light solution for several runs. A small aspect ratio plug is placed over the nozzle exit and removed before initiating the jet, while providing minimal disturbance to the flow. Once filled, the test section is isolated from the air in the laboratory to prevent evaporation. After each run, the plug is repositioned over the nozzle exit, so that when the piston is slowly moved back to its original position, the light solution is drawn into the cylinder from the reservoir. Before each run, a conductivity probe (Model 125MicroScale from Precision Measurement Engineering, Inc.) travels the tank elevation to measure the initial conductivity, and therefore density profile.

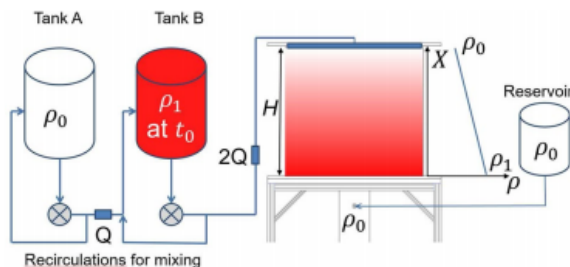


Fig. 9 Two-tank method to create the linear stratification. The time t_0 refers to the beginning of the facility tank filling

Particular care must be paid when creating large quantities of solutions with precise concentrations. First, filtered, deionized, and degassed tap water is poured into the storage tanks at a fixed flow rate, measured with a rotameter (king instrument) with a $\pm 2\%$ full scale accuracy. With the water density known, the flow is stopped when the adequate mass of water has been poured in the tanks. When preparing the salt solutions, volume variations take place when dissolving the salt in water and it is more accurate to use concentrations in weight percentages than mass per volume. The solutes are then added, with their weight measured on an Arlyn industrial bench scale, which has a 68 kg weight limit and a 0.01 kg resolution. Using this technique, the overall uncertainty on the index of refraction is 1.2×10^{-4} , which is sufficient to enable optical diagnostic here.

When using isopropanol, prevention of evaporation is of paramount importance. Both storage tanks and the reservoir are sealed after the solutions are added to prevent evaporation. They possess pressure gages and vacuum release valves to allow the vacuum created by emptying the tank to be filled by air.

5.3 Experimental precautions and limitations

Because a refractive index difference as low as 2×10^{-4} can be sufficient to make optical measurements impossible, the environment conditions must be controlled carefully. During calibration tests, two sources that cause distortions of this order were identified; temperature variations and evaporation at the free surface of the test section.

If fluid located in different parts of the experiment have different temperatures, their refractive indices can change and cause optical aberrations when mixing. Temperature variations in the room are recorded for several days, showing variations up to 2°C over periods of 2–3 h. In these conditions, the temperature of the light solution contained in the reservoir, the cylinder, and the hose that connects the two can fluctuate, whereas the test section remains at nearly constant temperature due to its large thermal inertia. To minimize this problem, thermal insulation and thermocouples are added around the reservoir, the cylinder, and the housing. With this installation, temperature variations are kept below 0.2°C and refractive index discrepancies are avoided. Minimizing the temperature fluctuations of the fluids and the room is also important to prevent natural circulation in the tank, which would disturb initial conditions and mix the vessel.

The dilution of isopropanol in water is exothermic. An increase of temperature of several degrees is observed when preparing the isopropanol solution in Tank A. A cooling system is used to efficiently bring the tank back to room temperature. This heating effect was neglected during the run of the jet considering the low alcohol concentration,

but detailed data are given by Peeters and Huyskens (1993) for the exothermic/endothermic mixing of several alcohols with water.

The test section was originally designed to be temporarily and partially open, for operations such as conductivity measurements or moving the plug on top of the nozzle. However, evaporation of isopropanol will then occur, and a thin layer of fluid at the surface with a lower concentration and temperature will form. If the top of the jet reaches this layer and entrains the fluid into the field of view, optical distortions appear. This is minimized by performing all operations while keeping the tank closed and vaporizing isopropanol into the test section before filling. When glycerol and Na_2SO_4 are used, water evaporates first because of its higher vapor pressure. Its concentration decreases, but at a much slower rate than isopropanol, which is a significant practical advantage.

The use of glycerol also requires precautions; when glycerol is mixed with tap water, the solution becomes cloudy after a few days due to the formation of a precipitate, making optical diagnostic impossible. Proteins and/or bacteria are probably at the origin of this precipitate and advanced filtering could suppress this effect. The addition of a general $1\text{ }\mu\text{m}$ filter and a $0.2\text{ }\mu\text{m}$ anti-bacteria filter only slowed down the precipitation process in this case. The precipitate was essentially prevented by also adding de-ionizing filters to the water treatment system. Another alternative would have been to use antimicrobial food preservatives in minute concentrations, such as benzoic acid or sorbic acid. These have very small effects on the thermos-physical properties of the solutions. The water is also deaerated to prevent air bubbles from forming on solid surfaces.

6 Particle seeded images and velocity fields

In this section, sample results are shown for both Is/NaCl and Gl/ Na_2SO_4 . Characteristics of the tests are given in Table 5, using the parameters shown in Fig. 9.

Obtaining index matched solutions is more challenging with the Is/NaCl pair because of evaporation and this pair is considered first in this section.

An image of the particle seeded jet obtained during initial tests is shown in Fig. 10a. Before the run, the fluids prepared in the two storage tanks are index matched; however, due to temperature variations and evaporation at the top of the facility tank, a refractive index mismatch develops, sufficient to cause optical aberrations and make the particles indistinguishable.

By controlling the temperature variations and evaporation, refractive index matching is achieved; in Fig. 10b,

Table 5 Characteristics of the tests, with U the exit velocity, D the nozzle diameter, H the height of the stratified environment

Fluid pair	Is/NaCl	Gl/ Na_2SO_4
U (m/s)	2.57	3.66
D (mm)	12.7	6.35
H (m)	0.81	0.81
$\Delta\rho = \frac{2(\rho_1 - \rho_0)}{\rho_1 + \rho_0}$	0.05	0.03
$Re_D = \frac{UD}{\nu_0}$	20,000	20,000
$Fr = \frac{U}{\sqrt{g\Delta\rho D}}$	32.6	84.7
$N = \sqrt{\frac{g\Delta\rho}{H}}$	0.778	0.603

Re and Fr are the Reynolds and Froude numbers, and N is the Brunt-Väisälä frequency, also called buoyancy frequency. ρ_0 is the density of the light aqueous solution (isopropanol or glycerol) and ρ_1 the density of the dense aqueous solution (NaCl or Na_2SO_4)

three successive images of the jet are superimposed to aid in visualizing the direction of the flow. Since the fluid inside the tank is not seeded before jet initiation, the particle concentration in the field of view varies. An example of this is seen on the right hand side of the image, where fewer particles are visible.

The images observed in Fig. 10b are analyzed using Davis 8.3, with a 50% overlap, 2 passes with circular windows containing 96×96 pixels and 2 passes with circular windows containing 32×32 pixels. In Fig. 11, the instantaneous velocity and vorticity fields are shown at two different time instances: t_1 (a), the first frame captured of the jet, and $t_1 + 25\text{ ms}$ (b), ten frames after t_1 .

Even with the Is/NaCl pair, which is more challenging than Gl/ Na_2SO_4 , a fine control of the experimental conditions allows creating a 5% density difference stratification (see Table 5) while remaining refractive index matched. For the Gl/ Na_2SO_4 pair, tests were performed successfully with a 3% density difference, for which two sample velocity fields are given in Fig. 12. The resolution and field of view differ from the images shown for the Is/NaCl pair because the experimental apparatus was modified.

In both cases, although the flow moves upward in average over the field of view, with high velocities in the bulk of the jet and velocities close to zero in the ambient fluid, strong velocity fluctuations are noticeable in this turbulent jet. The vorticity is mostly positive on the left side of the image, where vortices are rotating counter-clockwise, and negative on the right side. Two main vortices (v_1 and v_2) can be followed on the images, with their approximate centers marked by black disks. Detailed results will be presented in future publications.

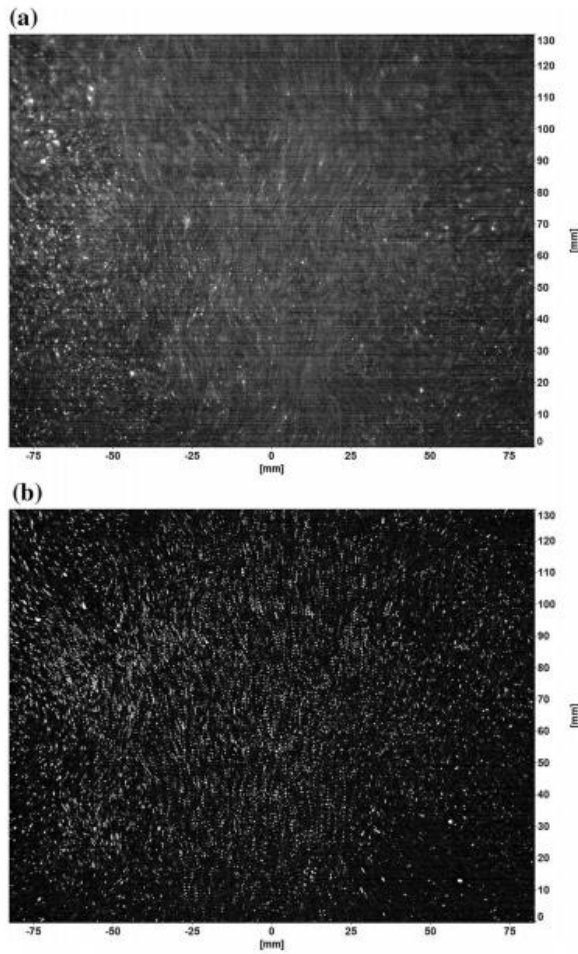


Fig. 10 **a** An image of the buoyant jet with a mismatch of refractive index. **b** Three successive images of the particle seeded flow field are superimposed, with the first obtained at $t = t_0$, at a frame rate of 400 Hz and an exposure of $400 \mu\text{s}$ (the laser was CW). They are taken between 30 and $40 D$, and are centered on the jet centerline

7 Conclusion

A new fluid pair, glycerol and sodium sulfate solutions, is identified to study variable density flows with dynamic viscosity differences below 1% and density differences up to 7.3%. The fluid pair isopropanol and sodium chloride is also attractive for the high density difference it enables, although it brings large viscosity variations. Depending on the constraints of the experimentalist in terms of viscosity variations, both fluid pairs enable large scale tests at reasonable costs.

The density, viscosity and refractive index of the four solutions are measured versus temperature and concentration, and the refractive index spectral dependency is characterized for a density difference up to 5%. Correlations are

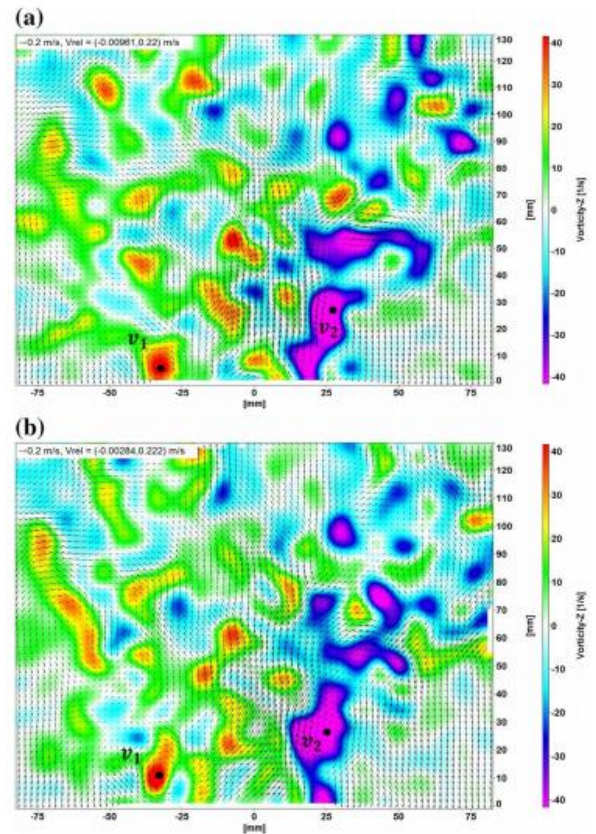


Fig. 11 For a test with isopropanol and NaCl with a 5% density difference, velocity fluctuations and out of plane-vorticity fields at the time **a** t_1 and **b** $t_1 + 25 \text{ ms}$. The values of the radial and vertical averaged velocities are given at the top left of the images. Two vortices, v_1 and v_2 , can be followed

provided to enable the selection of fluid mixtures for given experimental conditions for that range of density differences, while keeping dynamic viscosity variations below 1%. For these two fluid pairs, if fluids are index matched for one wavelength, they remain index matched for any wavelength, simplifying the simultaneous deployment of optical diagnostics, such as PIV and PLIF, which rely on different regions of the spectrum. However, temperature has a large impact on the refractive index of the solutions and on the viscosity difference between index matched solutions. It is also shown that refractive index varies non-linearly with concentration and that a second order polynomial must be used to ensure refractive index variations below 2×10^{-4} .

Ternary mixtures composed of index matched solutions mixed in different proportions are studied for varying temperatures and show that a linear behavior can be assumed for density and refractive index, simplifying equation of state for numerical simulations of such flows. However, it is important to note that viscosity does not vary linearly

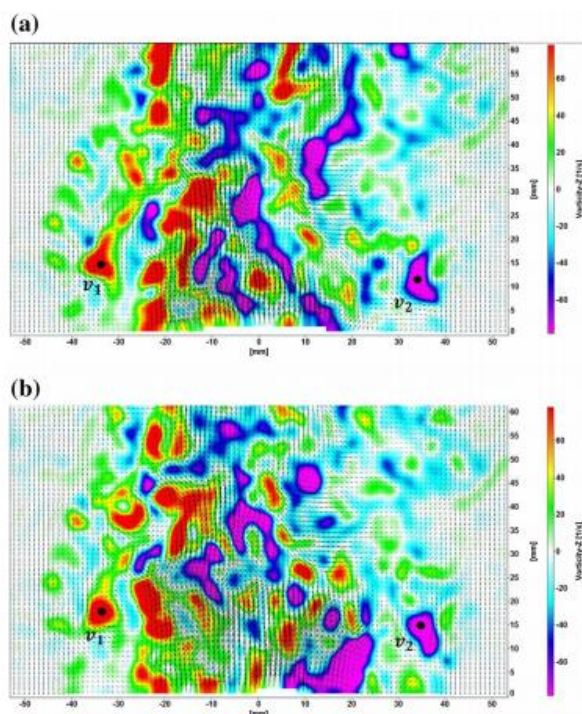


Fig. 12 For a test with glycerol and Na_2SO_4 with a 3% density difference, velocity fluctuations and out of plane-vorticity fields at the time **a** t_2 and **b** $t_2 + 25$ ms. The values of the radial and vertical averaged velocities in the horizontal and vertical directions are given at the top left of the images. Two vortices, are v_1 and v_2 , can be followed

with concentration when ternary mixtures are formed. Matching dynamic viscosities is then particularly attractive to circumvent this effect; for example, non-linear viscosity variations must be accounted for if the Is/NaCl pair is used.

The practical use of these fluids is illustrated with a buoyant jet in a linearly stratified environment. Several practical challenges are detailed such as the preparation of the solutions on a large scale and the creation of the linear stratification. It is shown that a particular care must be paid to the control of temperature and evaporation. Images of the particle seeded jet are clear and observable, where the flow structures can easily be followed. Instantaneous velocity fields show the capability of accomplishing quantitative analysis using these refractive index matched fluids.

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