Validation Data Acquisition in HTTF during PCC Events

Reactor Concepts Research Development and Demonstration (RCRD&D)

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  Validation data acquisition in HTTF during PCC events
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Executive Summary

A validation experimental campaign was conducted in an Integral Effect Test (IET) facility of High Temperature Gas Reactors (HTGR), the High-Temperature Test Facility (HTTF) at Oregon State University (OSU). The HTTF simulates Depressurized and Pressurized Conduction Cooldowns (DCC and PCC). This campaign required the development of a new laser spectroscopic diagnostic to measure velocity in the challenging conditions of the HTTF: low speed (~1 m/s) gas flows at HTGR prototypical temperature and 1/10\textsuperscript{th} pressure. This was a collaborative effort between co-PIs at The George Washington University (GW), Oregon State University (OSU), and NASA Langley Research Center. The main accomplishments of this project include the record for dynamic range for velocimetry, highest accuracy obtained with this technique, successful deployment in an IET leading to new validation matrix for CFD. These are detailed below and in manuscript appended to this executive summary.

For this project, we introduced a new class of laser spectroscopic diagnostics to Thermal-Hydraulics to measure velocity of gases; furthermore, the diagnostic was demonstrated in-situ in an IET during DCC events. In such scenarios, particles used in mainstream techniques, like Particle Image Velocimetry (PIV) are not appropriate as they settle down too rapidly and also contaminate the experimental facility. Molecular tracers stay mixed within the working gas and can seed the flow in a technique called Molecular Tagging Velocimetry (MTV). In MTV a molecular tracer is photo-dissociated by a first (write) laser into radicals or molecules. The pattern created by the write laser is then interrogated with planar laser-induced fluorescence (PLIF), the read pulse(s), which are recorded with a camera. The pattern is probed and matched at two times (interval or probe time, \(dt\)), resulting in a time-of-flight velocimetry technique.

This project demonstrated a new application range for MTV in gases. MTV has been extensively used for high-speed gas dynamics: molecules do not suffer from inertia associated with particles in regions of high accelerations (such as shock waves). For high-speed flows, the probe time is on the order of 0.1-10 \(\mu\)s. In time-of-flight techniques, the velocity is reconstructed from the recorded displacement, \(dx\), between time interval \(dt\): \(U = dx/dt\). To first order, the resolution of the pattern matching is typically a (fixed) fraction of a pixel; therefore the resolution of the velocity measurement increases with \(dx\) and, for a given flow velocity, \(dt\). For the low-speed flows of interest here, this requires long probe time, and therefore finding tracers that are stable for a long time. After an extensive literature survey we identified 6 tracers that would be suitable. We also worked with Spectra Physics to design a custom laser system that is flexible enough to probe these various tracers. The final instrument is made of 4 lasers that are integrated into a compact and movable cart to facilitate the deployment of the instrument off-site. One unique aspect of the laser system is the tunable dye laser (needed to do PLIF of the radicals). By being pumped by two Nd:YAG lasers, this laser is able to provide two pulses with any probe time (\(dt\)) for wavelengths between 200 and 900 nm with a linewidth of 3 pm. Accommodating the dual-pulse capability required customizing the pump lasers and the dye laser, making this system unique. Additionally, a custom UV-intensified CCD camera capable of frame-straddling and exposure time as short as 10 ns was acquired. More than two-third of the instrument cost (~$200k) was covered by a cost sharing from the PI’s startup funds.

Of the 6 potential tracers identified, two were tested extensively (H\(_2\)O and N\(_2\)O) at high-temperature and elevated pressure at GW prior to conducting the tests at OSU. For both tracers, an Ar-F laser (193 nm, 10 ns, 10 mJ/pulse) photo-dissociates trace amounts (0.1 – 5% molar fraction) of the gases into OH and NO. OH is probed at 281.905 nm and NO at 226.186 nm (4-30
Validation data acquisition in HTTF

mJ, 10 ns pulse). NO is very stable in inert environment and we could reconstruct velocities precisely with probe delay times as long at 40 ms, compared to 2 ms for OH, resulting in increased precision. Therefore, for the tests in the HTTF, N2O was selected as the final tracer and its optimal concentration was determined to be 0.5% molar. In the GW laboratory, we obtained a velocity measurement precision of 4 mm/s at conditions mimicking the HTTF tests. We also demonstrated the benefit of molecular tracers over particles and the flexibility of our instrument by continuously measuring velocity from 1000 to 0.1 m/s in a blow down test. This represents a dynamic range on velocity of 80 dB, which is unprecedented for velocimetry!

Once the diagnostic was optimized, two two-week campaigns were conducted in the HTTF. This experimental campaign required numerous practical solutions to successfully and rapidly deploy this very sensitive table-top diagnostic in-situ. This was accomplished thanks to very extensive planning from all parties involved in the project. Due to constraints on availability of the HTTF, only adiabatic DCC tests were conducted. Specifically, the velocity was measured at the exit of the hot leg into the Reactor Cavity Simulation Tank (RCST). We were able to record the gas velocity associated with the air ingress for long times (up to one hour). Depending on the initial conditions (density of the gases in the Reactor Pressure Vessel and the RCST) the lock exchange lasted 30-60 s past the valve openings. Large vortices were identified within the shear layer at the interface of the cross flow. These vortices are an indication of shear-driven instability between the counter streams of different density. After the lock-exchange, a small residual flow was still present and its strength decayed exponentially. It finds its source in a buoyancy difference between the gases in both vessels due to the mixing and diffusion of the gases in the cross-over duct and the RPV lower plenum. We did not expect to capture this part of the transient, which would have been less significant (if not negligible) in the presence of a heated core; the precision of our measurement in the HTTF was 6 mm/s, which exceeded our expectations for such a complex test!

Using commercial software (Fluent) we simulated the experiment with Computational Fluid Dynamic (CFD) using Reynolds Averaged Navier-Stokes (RANS) turbulence models. We were not able to accurately reproduce the shear layer instability, mixing, and diffusion captured in our experimental data, even with large 3D meshes (>10 M points). We attributed this to the inadequacy of the RANS models for the flow of interest: our experimental Reynolds number was too low and was outside the applicability range of the RANS models. Instead, we should have employed CFD with less modeling, such as Large Eddy (LES) or even Direct Numerical (DNS) simulations. Unfortunately, we did not have the computational resources to do so.

Finally, it should be noted that this experimental technique holds great promises for measuring velocity in thermalhydraulics. MTV has an application domain (highlighted in the narrative) that is complimentary to more established (and simpler) techniques, such as PIV. It has attracted the attention of several thermalhydraulics researchers and sponsors to measure velocity in harsh environments. The spectroscopic nature of this technique also enables to expand it to measure temperature and concentration simultaneously to velocity.

In lieu of a narrative, 4 detailed journal publications are appended to this executive summary to describe the various development and accomplishments during this project. They include 2 published manuscripts (Experiments in Fluids and Measurement Science and Technology), and two invited contributions following the NURETH-17 conference (Nuclear Science and Technology). Our current Nuclear Engineering and Design draft is not included at this time.
• **Publications:**
  - 5 journal publications (Measurement Science and Technology, Experiments in Fluids, Nuclear Engineering and Design, 2 Nuclear Science and Technology)
  - 5 full length peer-reviewed conference proceedings (2 NURETH 17, Aviation 2016, Lisbon Laser Symposium 2016, PIV 2015 conference)
  - 1 extended abstract ANS proceedings (ANS Winter meeting 2015)

• **Documents:** See below for a copy of the journal articles.

• **Budget:** $800k

• **GWU cost sharing:** $300k

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Characterization of hydroxyl tagging velocimetry for low-speed flows

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1. Introduction

Low-velocity gaseous flows are a difficult class of flow field in which to make robust velocity measurements. Mechanical probes (pitot, hotwire) have significantly reduced sensitivity in such conditions, while more advanced techniques such as particle image velocimetry (PIV) [1] and laser Doppler velocimetry (LDV) [2] are known to experience issues with particle seeding and can have insufficient measurement precision to resolve flow features of interest. Molecular tagging velocimetry (MTV) [2] is an alternative time-of-flight measurement technique that relies on molecular tracers to obtain velocity fields. MTV has been used in both gas and liquid phase fluids. In the gas phase, several techniques exist to tag, or mark, the molecules of interest. The most common measurement scheme involves the creation or excitation of a radical chemical species from a seed gas and subsequently tracking its motion with planar laser-induced fluorescence (PLIF). Examples of seed gas include N2O [3], NO2 [4], Kr [5], acetone [6], biacetyl [7], O2 [8, 9], N2 [10], and H2O [9]. MTV based
on NH tracers created from trace H2O (∼0.1%) or H2 (∼1%) in N2 was also recently demonstrated [11]. Molecular tracers have the advantage over discrete particles of a response time and a settling velocity both equal to zero, which allows them to accurately follow quiescent and hypersonic flows alike [4]. Furthermore, these tracers can also be created in gas flows that are typically challenging to seed for PIV, such as high temperature or reacting flows, and in environments where particles are undesirable. Some of the drawbacks of MTV include lower spatial resolution, limited tracer lifetime, and a more complicated optical setup compared to PIV.

Hydroxyl tagging velocimetry (HTV) makes use of hydroxyl radicals (OH) created from water vapor. Advantages of this scheme are non-toxicity, ease of adding the seed gas (water vapor) to the test gas, and relatively long tracer lifetime at high temperature [12]. H2O is also present at high temperature in most combustion products, which makes HTV a very convenient technique for probing such flows [13]. OH radicals are typically created with a 193 nm argon–fluoride excimer laser (‘write pulse’) through a one-photon photo-dissociation process whose efficiency is temperature-dependent. The dissociation fraction increases by one order of magnitude between ambient temperature and flame temperature [13]. OH offers several vibrational transitions in the ultraviolet (UV) portion of the spectrum, all from the A 2Σg+ – X 2Π electronic transition, that can be excited with planar laser-induced fluorescence (PLIF) to record the tracer locations (‘read pulse’). The wavelengths of such transitions are around 308 nm, 282 nm, 262 nm and 248 nm, in decreasing order of absorption magnitude. It should be noted that when exciting the (0,0) band at 308 nm, the resulting fluorescence occurs in the same spectral region and prevents the use of a filter to remove scattered laser light. Therefore, although the fluorescence signal is stronger under these circumstances, the images are also more likely to be contaminated by scattering from particles and nearby surfaces [14].

Table 1 chronologically lists a selection of HTV measurements with the main parameters of each study. This table confirms that the technique has been successfully applied for very high temperature flows or high speed flows. In particular, the maximum reported delay between write and read pulses (dr) is 30 μs and 50 μs at room temperature and at high temperature (>1400 K), respectively. The most recent studies showed uncertainty (ε) below 2% for hypersonic flows using the (1,0) absorption band at 282 nm, which is the strongest transition that allows spectral filtering [14]. Note that all these studies made use of a single read pulse, the initial tracer location being recorded in a separate step. Write pulse was with a 193 nm excimer laser in all cases.

The present study is part of a wider body of work intending to measure bulk and transient fluid-dynamical processes in a gas-cooled nuclear reactor model (the high temperature test facility, HTTF [18]). Part of the experimental campaign aims at measuring flows of helium and nitrogen in the hot coolant leg of the facility (temperature of 300 to 900 K) during both pressurized conduction cool-down (up to 8 bars) to study passive cooling through natural circulation and depressurized conduction cool-down to understand the phenomenon of air ingress during a loss-of-coolant accident [19]. The timescale of such flows driven by buoyancy and natural circulation can occur over the course of hours, during which gas velocities are reduced to near zero.

In such experiment, the seeding of non-neutrally-buoyant particles would be undesirable due to the potential for settling. Helium filled soap bubbles are the only known neutrally buoyant particles in gas. They are suited mostly for large scale measurements due to their size [20] but have limited lifetime (1–2 min) [21]. Furthermore, they cannot be used in high temperature flows due to evaporation, nor can they be neutrally buoyant everywhere in a fluid presenting density gradients.

These challenges are problematic for investigating many gaseous flows of interest such as buoyant plumes and natural convection phenomena. There is therefore a need for a measurement technique to resolve slow moving gas flows over long timescales which requires long tracer lifetimes. Such a technique could also be used in subsonic wind tunnels to study: boundary layer transition, which requires non-intrusive diagnostics without particles (which could trigger bypass transition [22] if present in sufficiently high density) as well as the resolution of small velocity fluctuations; and the near-wall behavior of turbulent boundary layers [23, 24] where a long probe time can yield information about the secondary flow (spanwise and wall-normal directions).

Velocities down to a few millimeters per second were measured with MTV in liquid buoyancy-driven convective plumes using phosphorescent supramolecules [25]. However, such molecules are not usable in gas flow. In the gas phase, velocities down to about 2 m s−1 have been successfully probed using ozone tagging velocimetry (OTV). However that particular tracer is not suited for high temperature flows because of the reduced lifetime of O3 [9] and the possibility of damage to the test facilities from oxidation by O2. NO is a stable tracer in inert environment and can be used to resolved low-speed flows with high precision, but toxicity and corrosion to the facility can be problematic.

In such cases, HTV can be favored, providing OH tracer lifetime is long enough to achieve the required measurement precision. The goal of the present study is to demonstrate HTV for measuring low velocity flows. To do so, tracer lifetime and measurement precision are evaluated over a wide range of temperature (295 K to 673 K, filling the gap between ambient and flame temperatures) and pressure (1 to 3 atm) in air and N2. Low-speed jets (<10 m s−1) are successfully probed with a dr of up to 3200 μs and effect of tracers diffusion is assessed. HTV results are then compared with PIV results to check the expected precision. This test case of HTV and comparison with PIV are based on advancement and improvement over a preliminary study [26].

2. Experiment

2.1. Experimental apparatus

The HTV system is composed of an excimer laser (write pulse), a dual-pulse tunable dye laser (read pulses) and an intensified CCD camera (imager). The excimer laser, dye
laser, and the two pump lasers are mounted on a cart to permit easy transport to experimental facilities. A diagram of this laser system is shown in figure 1. The excimer laser (GAM EX5A) outputs 10 mJ pulse$^{-1}$ beam at 193 nm (1 nm line-width) to photo-dissociate H$_2$O into OH. Losses in the optics and by O$_2$ absorption in ambient air decreased the energy to 5 mJ pulse$^{-1}$ in the measurement region. The excimer laser operates with a stable resonator that has a measured far-field beam divergence of 2 mrad. A 300 mm focal length spherical lens focused the beam to a measured diameter of 0.7 mm at the waist. Note that excimer lasers with unstable resonators have smaller beam divergence (0.2 mrad), which would allow the beam waist diameter to be decreased for a given focusing lens, and may improve the spatial resolution of the measurement. However, the 0.7 mm diameter beam is suited to the spatial resolution of our application, which is set by the required field of view and the camera sensor resolution.

The outputs of two Nd:YAG lasers (Spectra-Physics Lab-170, 10 Hz, 0.85 J pulse$^{-1}$, 1064-nm) were combined and frequency-doubled to pump a tunable dye laser (Sirah Cobra-Stretch with a 2400 lines mm$^{-1}$ grating). The dual-pulse configuration allowed the recording of initial and displaced tracer locations. This improvement over previous MTV work enables compensation for the potential movement of the write laser beam (from beam wandering or vibration), and hence allowed higher-accuracy measurements in comparison to using only a single read pulse.

Using rhodamine 6G dye and a frequency-doubling BBO crystal, the dye laser can be tuned to wavelengths ranging from 280 to 288 nm, which includes the strongest available transition in the OH molecule that permits non-resonant collection of the fluorescence signal at 281.905 nm. The maximum laser energy was 30 mJ pulse$^{-1}$ and the linewidth was estimated at 5 pm. This beam was then shaped in a 1 mm thick sheet overlapping the excimer beam at a small angle ($\approx$2° in the horizontal plane) in the measurement region.

The fluorescence signal from the read pulses is recorded with a time-gated image intensifier (LaVision IRO25) coupled to a 12-bit CCD camera (QImaging QIClick). The full-frame resolution was 1392 $\times$ 1040 pixels at 10 Hz, but was decreased to 1392 $\times$ 400 pixels in order to record at 20 Hz (2 $\times$ 10 Hz frame straddling mode). The readout time (inter-frame time) of the camera was 200 $\mu$s, which set a limit on the minimum $dt$ between read pulses for independent exposures. A UV-transmitting Nikon 105 mm f/4.5 lens fitted with long-pass filters (Schott WG 295 and WG 305) was mounted on the image intensifier with a 25.4 mm extension tube and provided a magnification of 0.0467 mm/pixel. The gate time of the intensifier was set at 500 ns and temporally centered on the PLIF signal. This gate duration was chosen because it was expected to be much longer than the OH fluorescence lifetime, estimated to be a few nanoseconds [27] while limiting the amount of noise from collection of ambient light. The CCD camera is connected to a workstation through a Firewire interface which allowed images to be written directly to hard drive, enabling the recording of an extended duration of dataset (up to 10 hours at 20 Hz). Instruments were synchronized using a pulse generator (Berkeley Nucleonics 575) with a resolution of 250 ps and were monitored with a high-speed digital oscilloscope (Agilent MSOX-3054A).

### Table 1. Selection of previous HTV studies (in chronological order).

<table>
<thead>
<tr>
<th>Authors</th>
<th>Gas</th>
<th>$\lambda_{\text{read}}$ (nm)</th>
<th>$T$ (K)</th>
<th>$dt$ ($\mu$s)</th>
<th>$U$ (m s$^{-1}$)</th>
<th>$\epsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitz et al (2000) [9]</td>
<td>H$_2$ flame</td>
<td>248</td>
<td>1450</td>
<td>20</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Pitz et al (2005) [16]</td>
<td>H$_2$ flame</td>
<td>308</td>
<td>1400</td>
<td>50</td>
<td>10</td>
<td>N/A</td>
</tr>
</tbody>
</table>

2.2. Flow setup

To investigate the effects of temperature and pressure on the HTV measurement in a controlled manner, a pressure chamber was built and fitted with two UV-transmitting
sapphire windows positioned orthogonally, shown in figure 2. Compressed gas (air or nitrogen) was bubbled through water in a pressurized tank, and exited through a 9.0 mm inner diameter vertical tube located in the center of the chamber. The chamber and tube were wrapped with a 1440 W temperature regulated heating tape, and thermally insulated with mineral wool. The flow exited the test section through a tube at the top of the chamber, was then cooled in a heat exchanger and vented. A thermocouple and a pressure transducer located in the chamber provided gas temperature and pressure measurements. A thermal mass flow controller (Bronkhorst) located before the bubbler supplied the gas at a constant mass flow rate. A pressure controller (Alicat Scientific) located after the heat exchanger regulated the chamber pressure using feedback from the transducer.

Comparative PIV and HTV measurements were performed with a different flow setup. For simplicity, the PIV/HTV tests were run at atmospheric pressure. The gas flow was passed through a TSI 6-jet atomizer (Model 9306A) allowing the generation of 0.35 μm diameter droplets in addition to bubbling the flow through water. The flow was then exhausted to ambient air through a 7.9 mm inner diameter copper pipe. The pipe was coiled (eight loops with a diameter of 10 cm, followed by a straight section of 15 cm) and wrapped with heat tape. No particular care was taken to condition the flow, as it was only intended as a demonstration of the technique. A thermocouple affixed to the tube exit provided feedback to regulate the temperature set point.

2.3. Acquisition and processing

2.3.1. OH spectra, lifetime, diffusion, and measurement precision. Excitation spectra of OH in N2 were recorded by scanning the wavelength of the read laser pulse. A single read pulse was used, with a delay of 5 μs after the write (excimer) pulse. The scan range was determined using preliminary simulations with LIFBASE 2.1.1 [28], which indicated strong absorption lines between 281.8 and 283.2 nm. 20 images were recorded every 2.5 pm, then averaged. The lasers power was kept constant over the scan (5 and 10 mJ pulse−1 for the excimer and the dye laser, respectively). The excitation spectra were then constructed using the peak intensity in each averaged image.

The lifetime of OH in N2 was obtained by measuring the signal intensity at different delays (δt = 5, 10, 20, 50, 100, 200, 400, 800, 1600, 3200, and 6400 μs) after the write pulse. The read pulse was tuned to the Q1(1) absorption line at 281.905 nm, which was found to exhibit the strongest absorption. Fifty images were recorded and averaged for each δt, and the maximum signal intensity was reported. The full width at half maximum (FWHM) of the tag line was also measured to estimate tracer diffusion. These data were also used to test the precision of the processing algorithm for a large range of δt and signal-to-noise ratio (SNR). The measurements were performed on a jet in order to ensure the probed volume was continuously renewed. The jet velocity was kept low enough to ensure the tag line remained within the field of view for as long as possible.

Figure 2. Photograph of the test section. Lasers enter the left viewport and the camera images through the right viewport. The jet is vertical in the center of the chamber.

2.3.2. HTV. At δt = 0 s, the excimer laser was pulsed to create a horizontal line of OH radicals located 3 mm downstream of the jet exit. The HTV laser system was tuned to 281.905 nm, corresponding to the Q1(1) absorption line. The tracer positions were recorded twice using the two dye laser pulses: once after a short delay δt and again after a longer delay at δt = δt + dt.

For each run, several hundred image pairs were recorded, and these images were processed to measure vertical displacements with an in-house code. A 20 pixels horizontal binning (the FWHM of the PLIF line is about 20 pixels) with 50% overlap was applied to reduce noise. A Gaussian curve-fitting routine was employed around the peak signal in each vertical intensity profile to obtain sub-pixel accuracy in the displacement measurements. Outliers were then detected and rejected if the measured displacement was larger than twice the mean displacement of the four neighboring data-points. In such cases, outliers were replaced by that mean value. For the results presented in section 3.4, 6 to 7% of the data-points were rejected as outliers.

Averaged velocity profiles and standard deviations were then computed. Note that since only one tag line was used, only one component of velocity was measured. For the flow under study, making the measurements close to the jet exit ensured that the flow could be approximated as unidirectional.

2.3.3. PIV. To perform PIV, the long pass filters were removed from the camera, and only the dye laser is used in dual pulse mode to provide an illumination at 281.905 nm. Pulse separation, δt, was kept identical to that of HTV. Water droplets were generated by the atomizer while keeping the flow rate identical between PIV and HTV. A similar number of samples as in each HTV run (≈300 vector fields) were recorded. Image pairs were processed using the software Davis 8.0.8 from LaVision, Inc [29]. An iterative, multi-pass, cross-correlation scheme was used. The initial interrogation window size was set to 96 × 96 pixels and then reduced through three passes to 32 × 32 pixels with 50% overlap. An outlier detection and removal scheme based on differences with neighboring vectors was employed in post-processing. Mean and RMS vector fields were extracted. When comparing to HTV results, the
vertical velocity component was extracted from the 2D PIV vector field where the HTV tag line was created. PIV results also showed that the transverse velocity component was very close to zero (<0.05 m s$^{-1}$), thus verifying the assumption of unidirectional flow.

3. Results

3.1. OH excitation and fluorescence

Excitation spectra were recorded for two pressures ($P$): 1 ± 0.025 atm (ambient pressure) and 3 ± 0.025 atm; and two temperatures: 295 ± 2 K (ambient temperature) and 673 ± 2 K. These spectra are shown in figure 3 overlaid with LIFBASE simulations at the same conditions. The experimental and simulated spectra compare favorably. The absorption peak locations and linewidths match closely. The amplitudes show some small discrepancies. Such error is not uncommon and can be attributed to transition saturation effects [12, 16]. Pressure broadening can be distinguished between 1 atm and 3 atm, particularly in the peaks near 282.9 and 283 nm. Though the overall peak magnitudes are reduced with increased pressure, the relative magnitude of the individual peaks within a given spectrum were not visibly affected by the change in pressure. However, temperature acts to redistribute the relative strength of the absorption peaks. No significant shift of the peaks is observed with any change in the thermodynamic conditions. The maximum absorption occurs at 281.905 nm ($Q_1(1)$ line) for all cases, which is the wavelength used for the HTV study that follows. However, it should be noted that several other peaks approach a similar magnitude to this line as temperature is increased. Simulations at up to 1000 K indicate that the relative strength of these peaks depends mainly on the laser linewidth. For a linewidth in the range of 2 to 10 pm, the strength of $Q_1(1)$ absorption peak is either the maximum or at least 80% of that of the highest peak magnitude.

The strength of the OH fluorescence signal depends on the density of OH in the probe volume, which in turn depends on the initial density of H$_2$O and the efficiency of the photo-dissociation process induced by the write laser pulse. Thus, to understand the OH-LIF signal dependence on the thermodynamic state of the gas, these two parameters must be examined. Calculation of the H$_2$O density can be achieved by examining the vapor seeding process. To a first approximation, it is assumed that N$_2$ was saturated in water vapor (vapor pressure $p_v$) in the bubbling tank, which results in a number density of H$_2$O independent of the pressure and equal to $6.7 \times 10^{17}$ cm$^{-3}$ ($1.1 \times 10^{-3}$ mol l$^{-1}$) at ambient temperature $T_0$. Since the H$_2$O mole fraction is equal to $p_v/P$ while the number density of N$_2$ is proportional to $P$, the molar ratio of H$_2$O to N$_2$ is then 2.7% and 0.9% at 1 and 3 atm, respectively.

Since the gaseous mixture was heated after the bubbling tank, the ideal gas law specifies that the density at a temperature $T$ will change by a factor of $T_0/T$. Therefore the amplitude of the spectra is normalized by $(T_0/T)$ in order to compare signal strength at equivalent vapor number density in the probe volume. This plot is shown in figure 4, which illustrates the effect of temperature on OH production.

To understand the thermodynamic dependence of the photo-dissociation process, the photo-physics of the excitation process need to be considered. In effect, photo-dissociation efficiency increases with temperature as the H$_2$O molecules get vibrationally excited to levels with higher absorption cross-sections. Population fraction versus temperature can be found in [9]. For the $i$th vibrational level, the dissociation ratio is equal to $\sigma_i E/\hbar\nu A$, with $\sigma_i$ the corresponding cross section [30], $E$ the beam energy, $\hbar$ Planck’s constant, $\nu$ the photon frequency, and $A$ the beam cross sectional area. Note that if

![Figure 3](image-url)
The observed pressure dependence of the fluorescence signal is attributable to collisional quenching. At a given temperature, the quenching rate is proportional to the pressure signal is attributable to collisional quenching. At a given temperature effect is small as it is a balance between lower the pressure significantly decreases the signal, while the net number density in the probe volume but higher OH pro-

3.2. OH lifetime and diffusion

Measurements of OH lifetime were made for three pressures: 1 ± 0.025 atm (ambient pressure), 2 ± 0.025 atm, and 3 ± 0.025 atm; and three temperatures; 295 ± 2 K (ambient temperature), 473 ± 2 K, and 659 ± 2 K. The plots in figure 6 show the decay of the signal intensity as the time delay is increased. The tag line is no longer in the field of view for the longest delay of 6400 µs, thus the corresponding data-point represents the background noise level, which is subtracted from the reported measurements. At small delay, the same trends as for the spectral measurements of figure 3 are observed; the pressure significantly decreases the signal, while the net temperature effect is small as it is a balance between lower H2O number density in the probe volume but higher OH production. However, the beneficial effect of temperature on OH lifetime is visible at longer delay where the decay of the signal is not as marked at high temperature.

Molecular diffusion is another factor that affects the quality of a MTV signal. For a Gaussian profile line, the line width (defined as the FWHM) as function of time \( d_t \) is given by equation (1) [32]:

\[
w = \sqrt{8dwD_{PT}\ln2 + w_0^2}
\]

where \( w_0 \) is the line FWHM at \( d_t = 0 \) s and \( D_{PT} \) is the binary diffusion coefficient of OH in N2. The latter scales with \( T^{3/2}/P \) [33] and is calculated according to equation (2). The reference value used here is \( D_{1 atm,1450 K} = 4.5 \text{ cm}^2 \text{ s}^{-1} \) [9].

\[
D_{PT} = D_{ref,ref} \left( \frac{T}{T_{ref}} \right)^{3/2} \left( \frac{P_{ref}}{P} \right)
\]

The tag line FWHM is measured from the same data as the lifetime measurements and plotted in figure 7. The FWHM increases with \( d_t \) and is similar in all cases at short delay. For \( d_t > 1 \text{ ms} \), the line width appears to increase further for the high pressure cases (3 atm). However, inspection of the data and processing shows that this apparent increase is a result of poor image quality due to a low SNR in these conditions. Figure 6 illustrates the very low signal intensity for long delay and elevated pressures. The theoretical diffusion from equation (1) is plotted in dotted line (diffusion decreases with an increase in pressure) for each temperature and pressure. The observed diffusion of the line is much larger than predicted by the theory. Such large discrepancy has been reported in previous studies and is partly attributable to the formation of additional OH by the photo-product H reacting with H2O. Before such reaction, H diffuses at a faster rate than OH [9, 15], thus increasing the width of the tag line. However, it was realized during data processing that the tag line was not located across the centerline of the jet but in a plane parallel to the jet centerline. This offset resulted in spread of the tag line due to shearing because the front of the line is advected at a lower speed compared to the back of the line. Assuming a laminar pipe flow, the jet velocity is written \( V(r) = V(1 - r^2/R^2) \) with \( V \) the centerline velocity and \( R \) the pipe radius. The line spread caused by shearing is then equal to \( 2Vw_0\pi dr/R^2 \).

Based on the tag line length compared to the jet diameter, it is estimated that measurements are made at \( r = 0.85R \), which corresponds to a shear of about \( 7.6 \times 10^2 \text{ s}^{-1} \) with \( V = 2 \text{ m s}^{-1} \). The dashed line in each plot of figure 7 shows the predicted FWHM including diffusion for \( P = 1 \text{ atm} \) and differential advection, and is in good agreement with the data. The spread is therefore dominated by this shearing effect, which explains why the pressure or temperature dependences are not clearly visible. The effect of velocity gradients can therefore...
be a limiting factor when probing at long $dt$. Conversely, the spread of the tag line could serve as an indicator of out-of-plane gradient of in-plane velocity.

3.3. Optimization of measurement precision

An important aspect of making velocity measurements in low-speed flows is ensuring the measurement precision is sufficient. To this end, the processing algorithm described in section 2.3.2 is applied to the OH lifetime data examined in the previous section with the goal of characterizing the precision of the displacement calculations. For each set of parameters ($P$, $T$, $dt$) the location of the tracers aligned with the jet centerline (where the tracer displacement is maximum) was computed for each single shot image. No outlier detection based on neighboring points was applied since only one point per profile was calculated. The mean of this location was calculated over 50 samples, then the standard deviation of the location, $\sigma_x$, was obtained. This displacement standard deviation was converted to standard deviation in the velocity measurement $\sigma_v = \sigma_x / dt$ and plotted in figure 8 as a function of $dt$. The three plots for various temperatures follow the same trend. $\sigma_v$ increases with $P$ as the signal gets weaker. For all cases, the lowest $\sigma_v$ is between 0.1 to 0.2 m s$^{-1}$, and is obtained for $dt = 200$ to 1000 $\mu$s. This value is slightly lower at $T = 473$ K as the signal gets stronger with temperature, but is worse at $T = 659$ K due to the increase in noise. At low $dt$ ($<100 \mu$s), the decrease in $\sigma_v$ is linear in log–log scale, which is consistent with a high SNR. In such cases the algorithm has a constant precision [34], estimated here at 0.2 pixels (68% confidence level), and the velocity standard deviation scales with $1/dt$. The dashed line in the log–log plots of figure 8 has a slope of $-1$ to illustrate this scaling. At large $dt$ (>1000 $\mu$s), the SNR becomes poor and the precision of the algorithm deteriorates. The larger values of $dt$ are not enough to balance the loss of algorithmic precision, and the resulting velocity standard deviation increases until the signal is completely lost.

As expected the increase in $dt$, to some extent, is beneficial for increasing the velocity precision and allowing to resolve low velocity flows. On the other hand, this increase in precision comes at the cost of a lower spatial resolution. The latter can be expressed $\delta x = Ud_t$, the SNR becomes poor and the precision of the algorithm deteriorates. The larger values of $dt$ are not enough to balance the loss of algorithmic precision, and the resulting velocity standard deviation increases until the signal is completely lost.

As a result, a trade-off between spatial resolution and velocity dynamic range must be found.

3.4. HTV velocity measurements

Velocity profiles are measured 5 mm downstream on the centerline of the jet described in the second part of section 2.2 for four different cases which differ either in gas, temperature, or
delay between read pulses. As mentioned earlier, these tests are run at ambient pressure without the pressure chamber, which makes it easier to check that the measurement were taken on the centerline of the jet in these PIV/HTV tests. Table 2 summarizes these parameters. $E_i$ is the laser pulse energy of the $i$th pulse. The power of the second read pulse was decreased for Case #3 because the PLIF signal was deemed strong enough, and lower power would reduce background noise, thus increasing the SNR.

The PLIF images obtained with the first read pulse $10 \mu s$ after radicals formation, are averaged over 300 samples and shown in figure 9 for all four cases, with identical gray map scaled linearly between (400–3000). The jet is located between $x = -4$ and 4 mm. The higher vapor content there leads to a better signal compared to ambient air on both sides of the jet. The ambient air in which the jet discharges is identical in all four cases, thus the signal is similar in that region. All other things being equal, the signal is stronger in N$_2$ (Case #3) than in air (Case #1), a consequence of the lower quenching of N$_2$ than that of O$_2$ and H$_2$O (3 Å$^2$ versus 20 and 90 Å$^2$, respectively at 300 K [35]). The averaged PLIF images for the second read pulse are shown in figure 10 for all four cases. The gray scale is different from the previous figure, but constant within these four images (400–2000).

Table 3 presents the average SNR for single-shot images for all four cases for the jet region (hot gas seeded with H$_2$O) and surrounding flow (air at ambient temperature and 45% relative humidity). Following [36], the SNR was calculated by dividing the difference between maximum and minimum signal counts within a 31 x 31 pixels window centered on the peak value of the tagged gas line by the standard deviation of the signal counts within a 5 x 5 pixels window centered on the location of the peak signal count. In all cases, the SNR of the jet decreases between the first and second read pulses as OH molecules recombine. The signal of Case #2 is slightly better than Case #1 as a result of more efficient OH photodissociation but also more diffuse because molecular diffusion increases with temperature. The increase of temperature also results in an increase in jet velocity (gas is fed a constant mass flow rate). The use of nitrogen (non-reactive gas) in Cases #3 and 4 also increases the lifetime of the tracers, and thus the signal is better compared to air in Cases #1 and 2. The SNR of the ambient air is similar in all cases, as the composition and temperature of the gas is identical there.

In these measurements, the displacement of the tagged line is about 65 pixels for Case #1, and up to 130 for Case #4, which is quite large by MTV standards. This is because $dt$ could not be decreased below 200 $\mu s$ (camera readout time). Displacement calculations have an accuracy typically below 0.2 pixels, thus a tracer displacement of about 20 pixels is enough to obtain an accuracy of 1% of the calculation of the displacement. A larger displacement will result in a better precision. However, increasing the time delay has other consequences in terms of spatial and temporal resolution. The spatial resolution of MTV scales, to first order, with the recorded distance traveled by the tracer molecules. Hence, increasing the temporal delay improves the precision, but decreases the spatial and temporal resolution as was demonstrated in the previous section.

About 300 image pairs were recorded for each case and the velocity profiles were computed following section 2.3.2. The mean velocity profiles and standard deviation are shown in figure 11. Case #2 stands out as its velocity differs from
the 3 other cases because of the higher temperature. Using the ideal gas law, the increase factor in mean velocity is estimated at $T_2/T_1 = 473/373 = 1.27$. The measured increase ratio is between 1.25 and 1.34 in the $-2 \text{ mm} < x < 2 \text{ mm}$ region, which agrees with the calculated temperature ratio.

The mean profiles of the other three cases are very similar with a maximum velocity of $V_{\text{max}} = 6.5 \text{ m s}^{-1}$, corresponding to a Reynolds number based on the jet diameter of 2690. This similarity was expected since the pressure and temperature of the gas were identical. The velocity profile is asymmetrical, which results from the lack of flow

**Figure 10.** Averaged PLIF images of the second read pulse for Case #1, 2, 3, and 4, from top to bottom, with $dt = 250, 250, 250,$ and 500 $\mu$s, respectively.

**Table 3.** Average SNR for single shot PLIF images.

<table>
<thead>
<tr>
<th>Case</th>
<th>Jet $t_0$</th>
<th>Jet $t_0 + dt$</th>
<th>Ambient air $t_0$</th>
<th>Ambient air $t_0 + dt$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>12.1</td>
<td>10.5</td>
<td>8.6</td>
<td>8.3</td>
</tr>
<tr>
<td>#2</td>
<td>14.3</td>
<td>12.3</td>
<td>8.5</td>
<td>8.2</td>
</tr>
<tr>
<td>#3</td>
<td>19.4</td>
<td>15.6</td>
<td>8.5</td>
<td>8.4</td>
</tr>
<tr>
<td>#4</td>
<td>20.8</td>
<td>13.0</td>
<td>8.9</td>
<td>8.8</td>
</tr>
</tbody>
</table>

**Figure 11.** (a) Mean velocity profiles. (b) Standard deviation.

**Figure 12.** Comparison between PIV and HTV. (a) Mean profiles. (b) Difference from PIV in percent. (c) Standard deviations.
conditioning and curvature in the coiled pipe prior to the jet exit. For this steady flow, the standard deviation is strongly related to the precision of the measurement. Near the center of the jet, where the SNR is the highest, the precision is 0.12 m s\(^{-1}\) (1.8\% \(V_{\text{max}}\)), 0.08 m s\(^{-1}\) (1.2\% \(V_{\text{max}}\)), and 0.10 m s\(^{-1}\) (1.5\% \(V_{\text{max}}\)) for Case \# 1, 3, and 4 respectively, consistent with the results of figure 8. In the regions away from the jet where the ambient air is assumed stagnant, the mean velocity and the precision are both measured to be between 0.10 and 0.15 m s\(^{-1}\). The standard deviations are higher in the shear layer of the jet, especially for Case \# 4, likely as a result of laminar oscillations in the jet shear layers or buoyant instabilities. Careful observations of the downstream flow in the raw images of Case \# 4 showed that the jet slightly oscillates from left to right, as the Reynolds number of the jet is at the limit of the transitional domain (\(Re = 2690\)). This effect is less marked close to the jet exit (probed at shorter \(dt\)), which explains the difference in standard deviations in this region of the jet.

### Table 4. Single shot velocity uncertainties at 68\% confidence level.

<table>
<thead>
<tr>
<th></th>
<th>Jet core</th>
<th>Ambient air</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIV (Air, (T = 373) K, (dt = 250) (\mu s))</td>
<td>0.06 m s(^{-1}) (0.85%)</td>
<td>Not resolved</td>
</tr>
<tr>
<td>Case #1 (Air, (T = 373) K, (dt = 250) (\mu s))</td>
<td>0.14 m s(^{-1}) (2.2%)</td>
<td>0.16 m s(^{-1})</td>
</tr>
<tr>
<td>Case #2 (Air, (T = 473) K, (dt = 250) (\mu s))</td>
<td>0.19 m s(^{-1}) (2.3%)</td>
<td>0.15 m s(^{-1})</td>
</tr>
<tr>
<td>Case #3 (N(_2), (T = 373) K, (dt = 250) (\mu s))</td>
<td>0.10 m s(^{-1}) (1.5%)</td>
<td>0.14 m s(^{-1})</td>
</tr>
<tr>
<td>Case #4 (N(_2), (T = 373) K, (dt = 500) (\mu s))</td>
<td>0.12 m s(^{-1}) (1.9%)</td>
<td>0.13 m s(^{-1})</td>
</tr>
</tbody>
</table>

3.5. Comparison with PIV measurements

HTV measurements are now compared with those obtained with PIV in the same flow conditions as Case \# 1 (air at 373 K and \(dt = 250\) \(\mu s\)). In this configuration, described in section 2.3.3, the camera imaging and calibration, investigation plane (dye laser sheet dimensions and location), and pulse timing are virtually identical.

Figure 12(a) shows PIV results for the mean velocity profile compared to the results obtained with HTV. Because only the fluid issued from the nozzle is seeded with water droplets, the entrained flow and ambient air velocity cannot be resolved with PIV here, which results in erroneous measurements near the boundaries of the seeded domain. The velocity profiles are in good agreement in the jet core, where the flow is adequately seeded. The relative difference in mean velocity between PIV and HTV is shown in figure 12(b). It is less than 2\% in the center region, and the standard deviation of the difference is 1.2\%, 0.8\%, and 1.0\%, for Cases \# 1, 3, and 4, respectively. Comparison cannot be made with Case \# 2 since the jet velocity is different. PIV precision is measured at 0.04 m s\(^{-1}\) (0.6\% \(V_{\text{max}}\)) on average in the center jet region, see figure 12(c), which is half the precision of the best HTV case, Case \# 3.

The agreement between PIV and HTV is very good, a consequence of using the same setup (camera, laser sheet, calibration) for both measurements. This experimental arrangement cancels out any systematic errors that could arise from these components, and shows that for a given setup, HTV is almost as good as PIV for resolving low mean 1D velocities. The accuracy of each measurement is calculated based on estimation of the error on calibration (0.5%), timing (negligible), and displacement measurement. For the latter, an accepted guideline is 0.2 pixel for PIV [1]. For HTV, a conservative choice is to use the standard deviation of the difference between PIV and HTV by assuming PIV is more accurate than HTV. Accuracy and precision are combined to calculate the measurement uncertainty, which is presented at 68\% confidence level in table 4.

The best uncertainty in the jet is obtained for Case \# 3, which combines the advantages of hot and inert gas, with moderate \(dt\). The increased of \(dt\) in Case \# 4 leads to a lower SNR, which decreases accuracy, but would otherwise be beneficial for studying slower flows, as shown by the low uncertainty in the ambient air.

### 4. Conclusions

The present work demonstrates HTV measurements in low-speed (few m s\(^{-1}\)), ambient- or modestly-elevated temperature and pressure flows. Velocity measurement precision is improved by more than one order of magnitude compared to existing literature through optimization of the tracer lifetime.

The effects of gas temperature and pressure on the absorption spectrum of OH have been studied and it has been shown that the Q\(_1(1)\) absorption line at 281.905 nm is suited for the present range of thermodynamic parameters. Diffusion and lifetime of OH tracers were investigated in order to characterize the measurement precision as a function of \(dt\). It was found that molecular diffusion of tracers is not a main concern even at \(dt\) up to 1 ms, but that out of plane velocity gradients could negatively affect the width of the tag line. No useful signal was obtained for \(dt\) larger than 2 ms because of OH recombination.

A velocity measurement uncertainty of 0.1 m s\(^{-1}\) (1.5\% relative) was reported for \(dt = 250\) \(\mu s\) on a heated nitrogen jet. These results were checked against PIV measurements which agree within 2\% with the HTV velocity profiles. When put in context with previous studies, this work shows that low uncertainty velocity measurements can be obtained with HTV over a very wide range of velocity (<1 m s\(^{-1}\) to Mach 2) and temperature (300 K to 2000 K) provided an inert gas such as nitrogen or helium is used as a medium.
Acknowledgments

This project was supported by a DOE NEUP grant to PMB.

References

[29] LaVision 2012 FlowMaster Davis 8.0.8 Product Manual
Development of N$_2$O-MTV for low-speed flow and in-situ deployment to an integral effect test facility

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Abstract
A molecular tagging velocity (MTV) technique is developed to non-intrusively measure velocity in an integral effect test (IET) facility simulating a high-temperature helium-cooled nuclear reactor in accident scenarios. In these scenarios, the velocities are expected to be low, on the order of 1 m/s or less, which forces special requirements on the MTV tracer selection. Nitrous oxide (N$_2$O) is identified as a suitable seed gas to generate NO tracers capable of probing the flow over a large range of pressure, temperature, and flow velocity. The performance of N$_2$O-MTV is assessed in the laboratory at temperature and pressure ranging from 295 to 781 K and 1 to 3 atm. MTV signal improves with a temperature increase, but decreases with a pressure increase. Velocity precision down to 0.004 m/s is achieved with a probe time of 40 ms at ambient pressure and temperature. Measurement precision is limited by tracer diffusion, and absorption of the tag laser beam by the seed gas. Processing by cross-correlation of single-shot images with high signal-to-noise ratio reference images improves the precision by about 10% compared to traditional single-shot image correlations. The instrument is then deployed to the IET facility. Challenges associated with heat, vibrations, safety, beam delivery, and imaging are addressed in order to successfully operate this sensitive instrument in-situ. Data are presented for an isothermal depressurized conduction cooldown. Velocity profiles from MTV reveal a complex flow transient driven by buoyancy, diffusion, and instability taking place over short (<1 s) and long (>30 min) time scales at sub-meter per second speed. The precision of the in-situ results is estimated at 0.027, 0.0095, and 0.006 m/s for a probe time of 5, 15, and 35 ms, respectively.

1 Introduction
Molecular tagging velocimetry (MTV) is a time-of-flight velocity measurement technique that relies on locally creating and tracking molecular tracers (Falco and Chu 1988; Gendrich and Koochesfahani 1996; Koochesfahani and Nocera 2007). A first laser pulse (or write pulse) creates these tracers with a predetermined spatial pattern, then one or several second laser pulses (read pulse), illuminate a cross section of the flow with a controlled time interval. The location of the displaced tracers is recorded for each read pulse with a camera, ultimately leading to velocity profiles. In gas flows, radicals are typically created through photo-dissociation of specific seed molecules and are tracked with planar laser-induced fluorescence (PLIF). MTV has been demonstrated in gas with a variety of tracers created from seed gases such as N$_2$O (ElBaz and Pitz 2012), NO (Danehy et al. 2003), NO$_2$ (Orlemann et al. 1999), O$_2$/N$_2$ [APART technique, Dam et al. (2001), Kr (Parziale et al. 2015), acetone (Lempert et al. 2002), biacetyl (Stier and Koochesfahani 1999), tert-butyl nitrite (Krüger and Grünefeld 1999), O$_2$ [RELIEF, Miles et al. (1989), OTV, Pitz et al. (1996)], N$_2$ [FLEET, Michael et al. (2011)], and H$_2$O (Boedeker 1989). Hall et al. (2017) also demonstrated a technique relying on trace H$_2$O (~0.1%) or H$_2$ (~1%) in N$_2$ to create NH tracers. MTV is a non-intrusive technique applicable to a wide variety of flows ranging from stagnant to hypersonic, from cryogenic to flame temperature, and over a large range of pressure.

Furthermore, MTV does not rely on particle tracers unlike particle image velocimetry (PIV) or laser Doppler velocimetry (LDV). Therefore, it is an attractive technique...
for measurements in facilities which must not be contaminated by solid particles or where particles cannot appropriately seed or follow the flow. For these cases, probes can be deployed, but they are usually point-wise and intrusive (hot-wire, thermocouple, pressure probe, gas composition probe, ...), whereas MTV is non-intrusive and can be extended to resolve 2D velocity or temperature fields (Sánchez-González et al. 2011) even at high repetition rates (Jiang et al. 2010).

However, the in-situ deployment of optical diagnostics into a large experimental facility, or in the field, presents several challenges:

- Optical access must be available. Unless the facility has been specifically designed with optical diagnostics in mind, this is usually not the case. This requires the design and installation of optical viewports suited to the experimental conditions, and transmitting the wavelength of interest for the diagnostics. In most situations, at least two viewports are needed, one for illumination and one for imaging.
- The environment may be challenging for sensitive optical diagnostics. For instance, excessive heat or cold, vibrations, smoke, etc. can be detrimental to the operation of the instruments. Some effects can be mitigated, for instance, heat loading can be addressed with a cooling system. The operating procedures of the facility may force remote operation of the instruments.
- Space can also be a constraint in facilities that were not designed to accommodate external diagnostics.
- The flow of interest or facility may have special limitations, where flow velocities are so low that seed particles might settle out.

The present work demonstrates the development and deployment of MTV for in-situ measurements in the high-temperature test facility (HTTF), an integral effect test (IET) facility located at Oregon State University designed to study the thermal-hydraulics of very high-temperature helium-cooled nuclear reactors (VHTR) (Schultz et al. 2010). The HTTF is an electrically heated scaled down facility (quarter scale) following the General atomic modular high-temperature gas-cooled reactor (MHTGR) design. It operates at reduced pressure (8 versus 64 atm for the MHTGR) and prototypical temperature (up to 1200 K) and aims at simulating depressurized conduction cooldown (DCC) (Reyes et al. 2010).

In a DCC, the pressure boundary has been ruptured through a double ended guillotine of the inlet and outlet cross-over ducts, which are concentric pipes with the hot leg enclosed in the cold leg. At the end of the rapid depressurization, buoyancy drives air into the reactor pressure vessel (RPV) from the cavity where the reactor and auxiliary system sit. The air ingress through the break may lead to oxidation of the graphite in the RPV, and in some conditions, could lead to fire, loss of mechanical integrity of the core, and release of radioactive elements (Oh and Kim 2011; Oh et al. 2011). Numerical simulation of the buoyancy phase of the DCC event showed that the expected velocities are very low, typically below 2 m/s and that the flow stops quickly (~ 2 min) (Gutowska 2015; Utberg 2013).

Because MTV is a time-of-flight technique, the velocity is obtained by measuring a displacement over a period of time:

\[ U = \frac{M \Delta x}{\Delta t} \]  

with \( \Delta x \) the tracer displacement in pixels recorded by the camera, \( \Delta t \) the probe time delay, and \( M \) the magnification. To obtain a high precision for low-speed flow and low magnification, a long probe time is needed in order to measure a significant tracer displacement. Therefore, the tracer must have a long lifetime. Hydroxyl tagging velocimetry based on \( \text{H}_2\text{O} \) seed gas was investigated (André et al. 2017) and was shown to have a useful lifetime of up to 500 \( \mu \text{s} \) in \( \text{N}_2 \) at 1 atm and 373 K, yielding a precision of about 0.1 m/s at a magnification of 0.0467 mm/pixel. While this technique would work in the HTTF conditions, concerns were raised about the water vapor condensing on the electric heaters and short-circuiting them. Oxidation of graphite at high temperature was also a concern. Therefore, an alternate tracer, nitric oxide (NO) was investigated for this work. Both \( \text{NO}_2 \) and \( \text{N}_2\text{O} \) can be used as a seed gas. However, the latter is much safer (\( \text{N}_2\text{O} \) is also used as aerosol propellant and anesthetic) than the former (\( \text{NO}_2 \) is classified as extremely hazardous in the US), and thus \( \text{N}_2\text{O} \) was chosen as the seed gas.

The first part of this paper presents the application of \( \text{N}_2\text{O} \)-MTV to low-speed flows in the aforementioned conditions. The second part details the deployment of the diagnostics in the HTTF and how the practical challenges are addressed. Finally, sample results are presented and the performance of the technique is discussed.

## 2 Characterization of \( \text{N}_2\text{O} \)-MTV for low-speed flows

This section focuses on NO tracers obtained from \( \text{N}_2\text{O} \) seed gas and demonstrates their use in thermodynamic conditions approaching that of the HTTF. The velocity measurement precision, dynamic range, and other aspect aspects of this technique are discussed.

### 2.1 \( \text{N}_2\text{O} \) photo-chemistry

The NO tracers are created from the photo-dissociation of the \( \text{N}_2\text{O} \) seed gas according to the following reactions (ElBaz and Pitz 2012):

\[
\text{N}_2\text{O} + h\nu_{193\text{nm}} \rightarrow \text{N}_2 + \text{O}^{(3)D},
\]  

(R1)
\[ \text{N}_2\text{O} + \text{O}^{(1)}\text{D}) \rightarrow 2\text{NO}, \quad \text{(R2)} \]

where \( h \) is the Planck constant and \( v_{193\text{nm}} \) the photon frequency. An excimer laser with a 193 nm wavelength is used for the photo-dissociation (R1). The frequency-doubled Sirah Cobra-Stretch with Coumarin 2 dye) at a wavelength of 226.186 nm (3 pm linewidth) and energy of 4 mJ/pulse is shaped in a 3-mm-thick sheet and excites NO tracers (read pulses). The dye laser is pumped by two Spectra Physics Nd:YAG Lab 170 10 Hz lasers, providing dual-pulse capability with arbitrary pulse separation in time. The Nd:YAG beams are orthogonally polarized and combined in a Z-fold configuration at their fundamental wavelength (1064 nm) with a polarizing plate. The beam polarization is then optimized so that the nonlinear frequency tripling process yields equal energy from both pulses (~180 mJ/pulse at 355 nm). As a consequence of the frequency conversion, the resulting UV pulses are both vertically polarized, which is required for pumping the dye laser. The dye is circulated with high flow rate circulators from a Sirah Credo laser to minimize dye depletion of the second pulse.

The lasers are mounted on a cart shown in Fig. 1, left. Images are recorded with a QImaging QIClick CCD camera coupled with a LaVision IRO image intensifier and a Nikon UV 105 mm f/4.5 lens. The intensifier serves two purposes: convert the UV signal to a wavelength (around green for P46 phosphor screen) that can be recorded by the CCD and raise the intensity of the weak fluorescent signal above the read noise of the CCD (intensifier gain is set at 80% which represents an increase in signal by a factor of 68). The intensifier also has drawbacks: spatial resolution is limited to 20 μm and added noise due to low quantum efficiency of the photocathode (20% at 230 nm for S20 photocathode). Thus, the selected gain was a traded-off to maximize signal-to-noise ratio (SNR). The intensifier also allows gating the signal, to limit the collection of spurious ambient light. The gate time is set at 500 ns here which is long enough to capture the fluorescence signal (a few ns), while blocking most of the stray light during each exposure.

The camera has a full resolution of 1392 \times 1040 pixels at 10 Hz. Resolution was reduced to 1392 \times 400 to operate at 2 \times 10 Hz in frame-straddling mode. Data are recorded straight to a high capacity hard drive which permits several hours of continuous recording. A long-pass filter (230 nm cut-off from Layertec) mounted on the lens transmits the fluorescent signal and rejects the scattered laser light.
For both the laboratory and in-situ measurements, the instantaneous velocity is obtained by measuring the displacement of the tracers using an evolution of standard dual frame cross-correlation scheme, and knowing the time delay between the image pairs as described in Appendix A1.

The optics for shaping and focusing the beams used in the laboratory at GW were selected to be similar to those that would be used in the IET facility in an effort to make the laboratory measurements as representative of the actual in-situ conditions as possible. The camera working distance is also set to match that of the in-situ geometry. The Nd:YAG lasers Q-switches and lamps, excimer laser, image intensifier, and CCD camera are synchronized with a time delay generator (Berkeley Nucleonics Model 575).

### 2.3 Laboratory test section

A stainless steel pressure vessel was built to investigate the performances of the diagnostics in conditions as encountered in a VHTR. This test section, Fig. 1, right, is fitted with two UV-transparent fused-silica viewports to allow transmitting the lasers beam and observing the fluorescent signal. A 9-mm-inner-diameter vertical tube ends in the center of the test section and generates a well-controlled jet of nitrogen or helium seeded by a small fraction of $N_2O$. A National Instruments data acquisition system controls and monitors pressure, temperature, and gases flow rates.

For the in-situ measurements, nitrogen, helium, and possibly a mixture of both are the working fluids. Thus, both helium and nitrogen were considered in the tests. Preliminary data showed that the NO signal is slightly stronger in helium than in nitrogen, which may be explained by the higher fluorescence quenching cross section of the latter [0.012 versus 0.002 Å$^2$ at 300 K, Paul et al. (1993)]. Therefore, in order to have conservative results, the following tests were conducted in $N_2$, with the assumption that the fluorescent signal strength would improve when probed in helium. However, molecular diffusion of NO is larger in helium than in nitrogen; therefore, diffusion of the tracers may make the measurement less precise in helium for long probe times. Tracer diffusion is quantitatively discussed in Sect. 2.4.4.

### 2.4 Laboratory results

#### 2.4.1 Tracer excitation spectrum and wavelength selection

To identify the optimum wavelength for the dye laser (read pulse), the fluorescence excitation spectrum of NO is measured and analyzed. The fluorescent signal is recorded with the MTV system, i.e., the NO tracers are created with the write pulse, while the dye laser scans the read pulse wavelength, all other parameters such as excimer and dye laser powers, $N_2O$ concentration, or probe time being held constant and equal to 5 mJ/pulse, 4 mJ/pulse, 4% molar, and 10 μs, respectively. The dye laser scans between 225.9 and 226.4 nm with a step of 1.25 pm. For each step, 10 frames are recorded and averaged. The maximum intensity as function of wavelength is plotted in Fig. 2 for ambient temperature and three different values of pressure: 1 (ambient), 2, and 3 atm. The excitation spectrum of NO computed by the software LIFBASE 2.1.1 (Luque and Crosley 1999) with the amplitude scaled to the experimental data is also plotted on these figures. The peaks location, width, and relative height show a good agreement with the experimental data.

The strongest signal (highest peak) is obtained at a wavelength of 226.186 nm, which is the Q-branch band head. Note that these spectra are plotted with respect to wavelength in air. The corresponding vacuum wavelength for the strongest peak is 226.255 nm, as reported by ElBaz and Pitz (2012). Figure 2 also shows that the peak height decreases with an increase in pressure due to collisional quenching. The effects of pressure and temperature are discussed in more detail in the next section. While pressure and temperature affects the peak height and width through collisional quenching and broadening, the best signal was still obtained at the same wavelength, which ensured the dye laser would not need to be tuned for each pressure or temperature condition. Therefore, in the remainder of the study, the read pulses are at 226.186 nm.
2.4.2 Effect of temperature, pressure, probe time, and N$_2$O concentration on PLIF signal strength

For the data described in this section the temperature, pressure, and N$_2$O concentration are varied. The tracers are probed at 10 and 1000 µs after being created by the write pulse. The tracers are probed non-consecutively, with only one probe pulse. Diffusion between 10 and 1000 µs is limited, for instance in the most unfavorable case (1000 µs, $P = 1$ atm, $T = 781$ K), the tag line width increases by only 24%, see Sect. 2.4.4.

The results are summarized in the plots of Fig. 3 in terms of the SNR averaged over 100 frames. The SNR is calculated as $(I_{\text{signal}} - I_{\text{bg}})/(4\sigma_{\text{bg}})$, with $I_{\text{signal}}$ and $I_{\text{bg}}$ the signal and background intensity, respectively, and $\sigma_{\text{bg}}$ the background standard deviation, following the definition of Ramsey and Pitz (2011). This definition is quite conservative due to the factor 4 intended to approximate peak-to-peak noise amplitude. As a results, a SNR larger than 4 is considered good and can yield a displacement precision of about 0.1 pixel. Below a SNR of 4, precision is reduced, although a measurement precision of 0.5 pixel can still be achieved for SNR = 1 (Ramsey and Pitz 2011).

Each sub-figure presents a different combination of pressure and temperature with the first row at ambient temperature, and the first column at ambient pressure. Maximum temperature and pressure in this study are 781 K (508 °C) and 3 atm. The N$_2$O concentration is varied between 0.1 and 6% by volume (molar).

The main findings are:

- SNR > 1 at ambient conditions for a concentration of N$_2$O > 0.5%. The SNR increases with temperature, which is convenient for VHTR studies since the gases can be at up to 900 °C. The increase in NO production with temperature was reported by ElBaz and Pitz (2012) for air due to favorable chemical kinetics. The increase of N$_2$O absorption cross section with temperature (Sect. 2.1) likely contributes to this increase as well.

- The fluorescent signal decreases with increasing pressure. ElBaz and Pitz (2012) also showed a decreased NO production with increasing pressure for dry air. Collisional quenching is also a possible factor. This can be problematic at ambient temperature, where the SNR is insufficient at 1% N$_2$O and equal to 0.5 at 6% N$_2$O for $T = 295$ K and $P = 3$ atm. However, a high temperature can offset the detrimental effect of pressure as shown for the $T = 659$ K, $P = 3$ atm plot, where a SNR of 2 is obtained. In this sub-figure, no clear dependence on N$_2$O concentration is observed, which may suggest the N$_2$O concentration was mistakenly held constant for this particular case.
At N$_2$O concentration below 1%, SNR is similar between $\Delta t = 10$ and 1000$\mu$s, which confirms the chemical stability of NO over this duration. SNR seems to decrease for $\Delta t = 1000\mu$s at elevated temperature and ambient pressure. The high temperature may promote recombination of NO tracers. Further study of the lifetime showed successful probing of NO for at least 40 ms with molecular diffusion being the limiting factor, see Sect. 2.4.4.

SNR increases with N$_2$O concentration for low concentration (< 2%). The SNR then plateaus or decreases between 2 to 4%. This is discussed later in more details.

Although the only N$_2$O measurements reported in literature used 4% N$_2$O (ElBaz and Pitz 2012), these results show that data can still be obtained at sub-one percent concentration. Minimizing the N$_2$O concentration is beneficial for cost, safety, and the need to minimally perturb the working fluid (N$_2$O would affect the gas heat capacity and adiabatic index for instance).

N$_2$O is efficiently photo-dissociated by the excimer laser due to its relatively large absorption cross section. However, this also means that the excimer beam will be attenuated as it propagates through the gas mixture (N$_2$ + N$_2$O) in the test section to the measurement region as determined by the Beer–Lambert law. The beam will be mostly absorbed if the optical depth is large, i.e., $\sigma N L \gg 1$. For IET facilities, the distance $L$ can easily be on the order of meters, which put stringent limits on the concentration of N$_2$O to minimize beam attenuation.

The optimal N$_2$O concentration to maximize the amount of dissociated molecules (thus the amount of NO created as explained in Sect. 2.1) for a given path-length is $N_{opt} = 1/(\sigma L)$ (derivation shown in Appendix A.2), and the resulting maximum number density of photo-dissociated N$_2$O molecules is $n_x = E_{0,f}/ehv AL$.

In the present laboratory test, the distance between the window and the jet is $L = 0.30$ m. This results in an optimum N$_2$O molar concentration of 1.5, 3.4, 4.0% for $P = 1$ atm and $T = 295, 659,$ and 781 K, respectively. This is somewhat in agreement with the results of Fig. 3, where the SNR is observed to reach a maximum near these values of N$_2$O concentration. Optimum N$_2$O molar concentrations are 0.5 and 1.1% for $P = 3$ atm and $T = 295$ and 659 K, respectively.

For the in-situ measurements, the beam path inside the facility up to the measurement region is measured at 1.05 m, which translates in an optimum N$_2$O seeding concentration of 0.43% for ambient pressure and temperature.

The present results showed that data can be obtained with concentration as low as 0.2%, which is the optimal concentration for a 2.25 m path-length. Longer path-lengths could still be possible with lasers of sufficient power. Alternatively, the beam could also be enclosed in a N$_2$O-free environment within the test section until it reaches the measurement region (provided this enclosure does not disturb the flow).

### 2.4.3 Velocity measurement precision

The precision of the velocity measurement $\sigma_u$ can be expressed as:

$$
\sigma_u = \sqrt{\left(\frac{\sigma_M}{M}\right)^2 + \left(\frac{\sigma_x}{\Delta x}\right)^2 + \left(\frac{\sigma_t}{\Delta t}\right)^2}
$$

The calibration error, $\sigma_M$, is estimated by taking images of a calibration target in several parallel planes and measuring how $M$ varies with the working distance. Assuming the calibration target can be placed within 2 mm of the laser sheet planes, the corresponding variation of $M$ is 0.4%. The timing unit has a resolution of 250 ps, the lasers have a jitter < 0.5 ns, and each laser pulse has a duration under 10 ns; thus, $\sigma_t/\Delta t$ is negligible considering $\Delta t$ is on the order of milliseconds. The main contributor to the error is the precision on the measured displacement $\sigma_x/\Delta x$ which is a function of the camera, optics, processing algorithm, and SNR. By neglecting magnification and timing errors, and using Eq. 1, the velocity precision can be expressed as $\sigma_u = M \sigma_x / \Delta t$.

MTV data are collected on a steady N$_2$ laminar jet ($U = 0.042$ m/s, $Re = 21$) in the test section described previously at $M = 0.0370$ mm/pixel and at ambient temperature and pressure. The delay between write and read pulses is varied. The initial tracer line location is recorded in a separate step, so that only one read pulse is needed to measure the tracer displacement. For each data point, 100 frames are recorded and the standard deviation of the measured displacement $\sigma_x$ is calculated at the jet centerline. Due to the low $Re$ the flow is stable, and $\sigma_x$ is solely due the precision of the technique. This provides an estimation of the velocity measurement precision $\sigma_u$. The width of the processing window for the data presented in this section is set at 40 pixels (smallest size allowed in the algorithm, Sect. 2.2) so that the calculated precision is conservative. Processing these data with a 160 pixels wide window yields an improvement of precision by a factor of about 2 (not shown), which is consistent with the expected factor of $\sqrt{160/40} = 2$.

Figure 4 presents the measured velocity precision for four cases with different N$_2$O concentration and write beam energy as a function of probe time. As discussed in the previous section, the optimum N$_2$O concentration has been determined to be 0.43% for the beam path-length of the in-situ measurements; therefore, tests are run at concentration close to that value (0.5%). A reduced number of data points are also collected at 1% N$_2$O for comparison.

In order to account for the excimer beam absorption in the IET facility due to the longer beam path than in the
laboratory test section (1.05 versus 0.30 m), the energy delivered by the excimer laser is varied. When operating at full power (15 kV discharge), the excimer laser delivers 10 mJ/pulse at the cavity output, as measured with a powermeter (Ophir F150A-BB-26). This value drops to 3.2 mJ/pulse before the test section window because of losses from the optics (5 mJ) and from O₂ and H₂O absorption in air (2 mJ). Note that transmitted energy can be improved by purging the beam path and using coated optics as described in Sect. 2.4.4, leading to a lower SNR. For Δt > 10 ms, Fig. 5 shows that the SNR drops below 0.25 and the displacement standard deviation increases dramatically, up to almost 10 pixels for the worst-case scenario. However, the increase in Δt still outweigh the increase in σ_u, thus σ_u keeps decreasing slightly. Figure 4 shows that at Δt = 40 ms, the best case scenario (1% N₂O and 1.5 mJ) has a precision down to 0.004 m/s. The worst-case scenario (0.5% N₂O and 0.6 mJ) has a precision of 0.009 m/s. Therefore, the results of Fig. 4 indicate that measurements can be made even at reduced N₂O concentration and write beam energy.

2.4.4 Tracer diffusion

The width of the tag line, w, increases with time due to molecular diffusion according to the following equation assuming a Gaussian profile (Miles et al. 1991):

\[ w = \sqrt{8D\Delta t \ln 2 + w_0^2} \]  

(5)

with \( w_0 \) the initial line width, and \( D \) the binary molecular diffusion coefficient. For NO in N₂, Weissman (1964) reported values of 0.198 cm²/s at 273 K and 0.301 cm²/s at 373 K and 1 atm. As \( D \) scales with \( T^{3/2} / \rho \) (Cussler 2009), \( D_{\text{NO/N}_2} \) is estimated at 0.22 cm²/s at 293 K (ambient temperature).
The diffusion coefficient of NO in helium is here estimated using the Fuller–Schettler–Giddings empirical correlation (Fuller et al. 1966):

\[ D_{AB} = \frac{10^{-3}T^{1.75} \left( \frac{1}{M_A} + \frac{1}{M_B} \right)^{\frac{1}{2}}}{P^2 \left( \sum V_A \right)^{\frac{1}{2}} + \left( \sum V_B \right)^{\frac{1}{2}}} \]  

(6)

with \( M_i \) and \( \sum V_i \) the molecular weight and sum of diffusion volume of component \( i \). Equation 6 gives \( D_{NO/He} = 1.58 \text{ cm}^2/\text{s at } 293 \text{ K} \). This correlation also predicts \( D_{NO/N_2} = 0.23 \text{ cm}^2/\text{s at } 293 \text{ K} \), in agreement with the value extrapolated from Weissman (1964).

Equation 5 is plotted in Fig. 6 for nitrogen and helium with an initial line width equal to the excimer beam waist, \( W_0 = 1.0 \text{ mm} \). The tag line width for each data points from the previous set of experiments is measured as the full width at half maximum (FWHM) and plotted in this figure.

In nitrogen, the increase in the tag line width measured experimentally agrees with the diffusion model, Eq. 5. Effect of diffusion is small for \( \Delta t < 10 \text{ ms} \), with a width increase of up to 50%. It becomes significant at \( \Delta t = 40 \text{ ms} \), where the width increase is on the order of 140%. This is consistent with the observed decrease in precision and SNR for \( \Delta t > 10 \text{ ms} \) in Fig. 4.

In helium, diffusion on the line width is more pronounced. For instance at \( \Delta t = 10 \text{ ms} \), the line width increases by 200%. Therefore, the precision of measurements in helium will benefit from the stronger signal but will deteriorate at long \( \Delta t \) because of diffusion. Thus, there will be an optimal \( \Delta t \) that maximizes the precision. No laboratory data were collected on diffusion of NO in helium; however, results obtained from the preliminary in-situ tests, discussed in Sect. 4, confirm this behavior.

### 2.4.5 Effect of magnification

The displacement error measured in Sect. 2.4.3 is quite large by MTV standard and cannot be explained by the low SNR alone. With a SNR of 1 and 2, a precision of 1 and 0.75 pixels is attained respectively, which is 2 to 3 times larger than the values reported by Ramsey and Pitz (2011). Such discrepancy is attributed to the high magnification and relatively large beam waist of the write laser resulting in a tag line image about 30 pixels across. The cross-correlation Gaussian intensity profile is very wide and shallow; thus, the location of its peak cannot be determined with high accuracy (Gendrich and Koochesfahani 1996). The effect of varying the imaging magnification is here analyzed at constant imaging aperture, i.e., the amount of light collected from a given region is constant, with the data obtained at 0.5% \( \text{N}_2 \text{O} \), \( E_0 = 2.1 \text{ mJ} \), and \( \Delta t = 1 \text{ ms} \). The SNR and \( \sigma_x \) for that data point are 1.36 and 0.96 pixels at a magnification of 0.0370 mm/pix. 100 lower magnification images are numerically simulated by mathematically binning each raw NO-PLIF images and running the same processing scheme. The interrogation window size (initially 40 pixels) is also scaled down according to the binning factor to maintain an equivalent spatial resolution. Results are presented in Table 1. This binning could have also been done directly with the camera chip, with the benefit of reduced read-out noise. However, for consistency and simplicity, the same image datasets were used and binned numerically.

As expected, the image binning improves the SNR and decreases the pixel displacement precision \( \sigma_x \) to values more representative of the performances of cross-correlation MTV algorithms. The equivalent magnification is also given in Table 1, with the resulting displacement precision in millimeters showed in the last column. The precision in millimeters is constant at \( \sim 0.037 \text{ mm} \) as the image is down-scaled down to a \( 6 \times 6 \) binning, where the tag line FWHM is 6.6 pixels. At larger binning factor such as \( 10 \times 10 \), the line becomes too thin and information is lost, leading to a decrease in displacement precision. This analysis was done at \( \Delta t = 1 \text{ ms} \), which yields a measurement precision of \( \sim 0.037 \text{ m/s} \).

![Fig. 6 Calculated diffusion of the NO tracer line in N\textsubscript{2} and He at ambient pressure and temperature (solid lines), and measured line width in N\textsubscript{2} (symbols)](image)

<table>
<thead>
<tr>
<th>Binning</th>
<th>SNR</th>
<th>FWHM (pixel)</th>
<th>( \sigma_x ) (pixel)</th>
<th>( M ) (mm/pixel)</th>
<th>( \sigma_x ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>1.36</td>
<td>33.9</td>
<td>0.96</td>
<td>0.037</td>
<td>0.0365</td>
</tr>
<tr>
<td>2 × 2</td>
<td>2.59</td>
<td>17.2</td>
<td>0.52</td>
<td>0.074</td>
<td>0.0382</td>
</tr>
<tr>
<td>3 × 3</td>
<td>3.40</td>
<td>11.7</td>
<td>0.33</td>
<td>0.111</td>
<td>0.0370</td>
</tr>
<tr>
<td>4 × 4</td>
<td>3.93</td>
<td>9.0</td>
<td>0.24</td>
<td>0.148</td>
<td>0.0356</td>
</tr>
<tr>
<td>5 × 5</td>
<td>4.62</td>
<td>7.1</td>
<td>0.20</td>
<td>0.185</td>
<td>0.0370</td>
</tr>
<tr>
<td>6 × 6</td>
<td>4.98</td>
<td>6.6</td>
<td>0.17</td>
<td>0.222</td>
<td>0.0382</td>
</tr>
<tr>
<td>10 × 10</td>
<td>5.72</td>
<td>4.0</td>
<td>0.11</td>
<td>0.370</td>
<td>0.0405</td>
</tr>
</tbody>
</table>
The effect of diffusion was assessed by running the same analysis with the data obtained at 0.5% N₂O, $E_0 = 2.1 \text{ mJ}$, with $\Delta t = 10$ and $\Delta t = 40 \text{ ms}$, yielding a measurement precision of 0.075 mm (0.0075 m/s) and 0.17 mm (0.0043 m/s), respectively, as long as the tracer line is wider than 7 pixels. This velocity measurement precision is consistent with the data reported in Fig. 4, since these correspond to no binning. Thus, this figure can directly be used to estimate velocity measurement precision at lower magnification for each case.

These results demonstrate that the present magnification could be decreased to extend the field of view without loss in actual measurement precision, up to a certain extent (when the line become thinner than about 6 pixels), while also maintaining the same spatial resolution.

It should be noted that the lower magnification lens used for the in-situ measurements (detailed in Sect. 3.2.2) was not available during these laboratory measurements, underlining the importance to predict the effects of magnification on the measurement precision and resolution.

### 2.4.6 Local heating of the gas

Some of the energy of the write beam will be deposited in the probed gas region, thus increasing its temperature locally. ElBaz and Pitz (2012) mentioned that with N₂O-MTV in humid air, a significant amount of laser energy is converted to heat (temperature rise of 50–60 K) because of the quick recombination of the photo-products of O₂, H₂O, and N₂O. The temperature difference between the probed gas and the surrounding gas will give rise to a buoyancy force which may affect the measurement of small velocities. For the present case, the gas medium is inert, thus no O₂ or H₂O dissociation occurs, and recombination of NO is limited. Assuming conservatively that all the energy of the N₂O photo-dissociation goes to heat, i.e., $E = E_0 \sigma n_i dL$ in the weak absorption approximation ($dL$ small), the resulting temperature increase is $\Delta T = E/\rho AdL C_p$. Using the Boussinesq approximation, the fluid acceleration is given by $a = g \Delta \rho / \rho = g \Delta T / T$ which becomes:

$$a = \frac{g E_0 \sigma n_i}{\rho C_p AT}. \quad (7)$$

In the conditions of the laboratory tests (N₂ at 295 K), in the most unfavorable case (1.5 mJ/pulse at the beam waist, and 1% N₂O), the temperature increase is 3 K and one obtains $a = 0.1 \text{ m/s}^2$. At the largest probe time of 40 ms, the gas will reach 0.004 m/s. This conservative estimate is on the order of the measurement precision in the laboratory condition. When the flow is going up or down with a horizontal tag line, as in the laboratory tests, this error directly combines with the other sources of uncertainties. When the flow is horizontal, the tag line is vertical and the buoyancy motion will shift the tracers vertically. In this case, the error in the velocity measurement has to be accounted for according to Eq. 8 as discussed in Sect. 4.2.

### 3 In-situ deployment of N₂O-MTV

#### 3.1 HTTF facility

When simulating a DCC in the HTTF, artificial pipe break and air ingress are simulated with the hot and cold legs discharging from the RPV inside a reactor cavity simulation tank (RCST). Figure 7 presents a schematic of the layout of the facility, with the RPV on the left and the RCST on the right. The RPV is filled with helium (primary coolant for VHTR), while the RCST is filled with nitrogen to simulate air (using air would lead to oxidation of the facility). To vary the gas density ratio between RPV and RCST, helium/nitrogen mixtures are also used instead of pure gases.

The two vessels are connected by the initially annular cross-over duct that splits into two separate pipes (hot and cold leg) that independently enter the RCST. A pneumatically controlled full bore ball valve sits in each leg to simulate a pipe break. The hot leg is a 0.305 m inner diameter straight pipe that spans the 3.5 m between the RPV and the RCST, with the break valve being located 2.0 m from the RPV. It is fitted with a 600-mm-long extension pipe in the RCST so that the outlet is aligned with the imaging viewport, as shown in Fig. 8. In the present work, measurements are made in the RCST at the outlet of the hot leg in order to
characterize the flow of helium from the RPV to the RCST and the flow of nitrogen from the RCST to the RPV.

3.2 Optical arrangement

Due to space constraints around the facility, the only possible location for the laser cart is between the RPV and a loading bay door, on the opposite side from the RCST, as shown in red in Fig. 7. The laser viewport is located on the RCST as shown by the red arrow and is located 7 m from the laser cart. This distance poses challenges in terms of beam steering accuracy, particularly for MTV diagnostics where two laser beams must be precisely overlapped. The main source of beam wandering is thermal expansion: alignment is performed when the facility is cold. As the facility heats up, the various components move with respect to each other. In particular, the RCST mounts are designed to allow such expansion with respect to the RPV. It is also likely that the air surrounding the facility is subject to temperature gradients, resulting in non-uniform refractive index along the beam path causing additional beam wandering. As lasers operate for a long time, their internal temperature also changes, resulting in another source of beam wandering.

An additional concern is the absorption of the excimer beam by ambient molecular oxygen. At 193 nm, the absorption due to Schumann–Runge bands has a cross section of about $3 \times 10^{-22}$ cm$^2$ at standard pressure and temperature (Salby 2012). Using Eq. 3 with molecular oxygen in air ($n = 5.6 \times 10^{18}$ cm$^{-3}$), the beam transmission is 85% over 1 m, and down to 30% over 7 m. Such losses add to losses in the optics and viewport, as well as absorption by N$_2$O before the measurement region. It is therefore essential to maximize the transmitted energy of the write beam.

3.2.1 Laser beam delivery

The overall beam paths and beam profile dimensions are shown in Fig. 9. The path of the lasers was planned using a 3D model of the facility to allow checking the dimensions and making sure the beam path was clear of obstacles. In the laser cart, each beam is directed toward the test section using a periscope made of two first surface mirrors (FSM1 and 4 for the dye laser, and FSM2 and 3 for the excimer) coated for the appropriate wavelength and mounted on computerized linear stages.

The dye laser beam has low divergence (< 0.2 mrad, which can be adjusted with a beam expander integrated to the dye laser before the main amplifier dye cell) and does not require external collimation optics. The beam profile is rectangular and expands by a factor of about two in the long direction over the 7 m, while the short dimension stays almost constant. The excimer laser operates with a stable resonator and has a similar beam profile, but larger divergence (2 mrad), which causes significant beam expansion over the distance. Using an excimer laser with unstable resonator would offer smaller beam divergence (0.2 mrad). To
allow a better control of the excimer beam size and divergence, a 2x beam expander is placed just after the periscope. The beam size in the far field is adjustable with the beam expander.

The beams travel from the cart to the RCST enclosed in PVC pipes for safety. The tube containing the excimer laser beam is purged with helium (nitrogen could have been used as well) to prevent absorption by ambient O₂ and H₂O. The tube is sealed at each end with rubber bellows connected to the beam expander on one side and to the focusing lens (detailed thereafter) on the other side, Fig. 9. These bellows also act as check valves, allowing purge gas to vent from the tube in case of over-pressure. After an initial high flow rate purge, only a very low flow rate of helium is needed to maintain a positive pressure inside the tube and keep the outside air from entering the pipe through residual leaks. Overall, the excimer beam travels through air over 0.6 m between the laser and the beam expander, and 0.3 m between the focusing lens and the viewport.

A frame made of X95 rails is mounted on the RCST to support the beam combining optics and the camera. Each beam is reflected toward the test section by a 50 mm diameter first surface mirror (FSM5 and 6) mounted on that frame. The excimer mirror can be steered vertically and horizontally by piezoelectric actuators (Thorlabs PIAK10) controlling a kinematic mount. Only the horizontal component of the dye laser is motorized on the corresponding mount, the vertical components being controlled by a motorized right angle prism prior to beam combining.

The excimer beam is focused by a plano-convex spherical lens with a focal length of 1500 mm, which corresponds to the distance to the measurement region. The size of the beam at the spherical lens is adjusted to minimize the beam waist diameter at the focal point while maintaining a long enough Rayleigh range. The beam waist is inversely proportional to the input beam size, which in turn is limited by the size of the lens (beam quality decreases away from the center of the lens due to spherical aberration). The beam dimension at the waist is 1.0 mm by 1.5 mm, and the Rayleigh range is 110 and 440 mm, in the streamwise and in the out-of-plane direction, respectively. Despite the long working distance, the beam waist is quite large by MTV standards. The beam quality of the excimer laser (Δw) is the main limitation, and a smaller tag line could be achieved in this geometry with a beam of higher quality. However, it should be noted that according to Eq. 5, for a long enough Δt (such that 8ΔtD ln 2 ≃ w₀²), the width of the delayed tag line becomes almost independent of the initial beam size. For instance for Δt = 15 ms for NO tracers in N₂, w(Δt) = 1.7 mm for w₀ = 1.0 mm, while w(Δt) = 1.4 mm for w₀ = 0.1 mm. Thus, a thinner write beam would improve the spatial resolution for the first read pulse at t, but not significantly for the second read pulse at t + Δt.

The energy of the excimer beam before the viewport is measured at 4.0 mJ/pulse, leading to about 1.1 mJ/pulse in the measurement region, which according to Sect. 2.4.3 ensures a good precision can be expected. The dye laser energy is measured at 3 mJ/pulse at this same location.

The dye laser beam is combined with the excimer beam just after the focusing lens. A right angle prism (P2 in Fig. 9) is used to bring the two beams as close to each other as possible, while avoiding significant beam clipping to maximize the length of the overlap region. Note that the overlap could have been improved by using a dichroic mirror to combine the beams. The dye laser sheet thickness is about 4 mm, which allows overlap over the entire 190-mm-long field of view (field of view is discussed in Sect. 3.2.2). After the combining optics, the beams enter the RCST via a fused-silica viewport and are redirected toward the exit of the hot leg pipe with an uncoated 50 mm right angle prism (P4) mounted on a sturdy dedicated support. This support strut and prism are far from the region of interest; thus, they do not interfere with the flow. The hot leg pipe exit, prism, support, laser viewport, and camera viewport are shown in Fig. 8. This figure shows a small tubing that was used to create a flow seeded with N₂O during the setup of the diagnostics. It was removed for the actual tests.

The write beam (excimer) was carefully aligned to be vertical and intersecting the pipe centerline. It is located 5 mm downstream of the pipe exit to allow measurement of the flow toward the pipe. This alignment process (and camera calibration) is done, while access to the inside of the RCST is possible through a manhole. However, the flange is closed prior to the tests, preventing further access. Therefore, in order to check that the beams are still correctly aligned and overlapping, a right angle prism (P3 in Fig. 9) is mounted on a motorized flip-mount (Thorlabs MFPI101) and permits deflection of the write and read beams after the combining optic, but before the window. The beams are then split with a beam-splitter and projected on two screens located at a distance equivalent to that of the measurement region boundaries. This is shown schematically with dashed line in Fig. 9. Before closing the RCST the location of the beams on each screen is recorded and kept as a reference for correct alignment and overlap. These reference locations are then used for checking the beams alignment and overlap once the RCST is closed. The repeatability of the flip-mount mechanism was assessed by monitoring the beam position over several dozens of actuations and was found adequate. Manufacturer specification for repeatability is 50 μrad, which corresponds to a 60 μm deflection 1.2 m away. Note that this method does not allow monitoring and recording a test simultaneously since the beams are totally reflected by the flip prism. Simultaneous MTV and beam monitoring could be achieved with a low-reflection beam-splitter (i.e., 10:90 or less) instead of a prism. This solution was
not implemented, because it was preferable to maximize the laser energy available for these measurements.

When combined with the linear stages in the laser cart and motorized mounts on the steering mirrors, this system gives the possibility to correct for beam wandering caused by thermal expansion of the facility, or thermal effects in the lasers.

### 3.2.2 Imaging

Due to geometrical constraints (the distance from the region of interest to the window is 480 mm and the window clear aperture is 65 mm), imaging the full hot leg diameter (305 mm) would require a wide angle lens (focal length < 35 mm). For reference, the Nikon 105 mm f/4.5 UV used in the laboratory experiments would result in a FOV of only 45 mm in these conditions. There are only a very limited number of commercially available UV-transmitting lenses, and while a custom lens could be assembled in the laboratory it would not compare in terms of image quality to a commercial lens. The best match for the current application is the Cerco 45 mm f/1.8 lens by Sodern. This lens is chromatically corrected from the UV (200 nm) to the visible, which allows maintaining the correct focus between calibration with a target under visible light, and data collection in the UV. The camera and its housing are mounted on a linear stage to be able to refine the focus during the run if needed. The camera was rotated to have 1392 pixels in the vertical direction, producing a field of view 190 mm in height.

CFD simulations of the flow (Gutowska 2015) indicated that the flow of helium from the RPV would occupy the upper quarter diameter of the hot leg pipe. Since only 190 mm of the 305 mm of the pipe could be imaged, it was decided to tilt the camera slightly up to focus on the flow near the top of the pipe. Figure 10 shows a cross section of the imaging setup. The viewport is recessed into a 250 mm diameter tube which limits the tilt angle of the camera. The maximum angle is 4° up, which is insufficient to give optical access to the top of the pipe. To further increase the vertical viewing angle, two fused-silica wedge prisms (3° wedge) are placed between the lens and the window and each deflects the light by 1.53°. At a distance of 500 mm, this shifts the field of view vertically by about 25 mm and allows imaging the top of the pipe. A third-order polynomial mapping function is used based on a calibration target to correct for the perspective effects induced by the viewing angle.

The large lens aperture limits the depth of field to 6 mm and also causes some vignetting. Due to the camera angle, the top and bottom of the frame will not be perfectly in focus as the distance to the object plane varies by ± 11 mm. This is not too critical for MTV where the image signal is usually spatially averaged during the processing to reduce noise. Nevertheless, this will lead to a decrease spatial accuracy and velocity precision in these regions. Focus could have been improved by using the Scheimpflug principle. This was not attempted as the imaging setup was already quite complex, and time was limited.

The aperture of this f/1.8 lens (45/1.8 = 25 mm) is similar to that of Nikon 105 mm f/4.5 (105/4.5 = 23.3 mm) used in the laboratory test; thus, the same amount of light per area is collected, providing the working distance is identical. Therefore, the change in magnification is approximately equivalent to binning the image. The image resolution with the 45 mm lens is 0.137 mm/pix, which corresponds to a binning factor of 3.7 compared to the data of Sect. 2.4.5. This factor is well within the range where the velocity measurement precision is expected to remain constant, providing the SNR is sufficient.

### 3.3 Thermal management

The temperature of the cart, lasers, and dye is monitored with thermocouples connected to a computerized data acquisition system. The dye circulators and Nd:YAG lasers are water-cooled. The warm air exhaust from the air-cooled excimer laser is vented outside the cart, and an air conditioning unit can provide cold air if necessary. The cart can be operated continuously for several hours while being closed and near a high temperature source.

The camera and image intensifier are located very close to the HTTF during the experimental campaign (Fig. 10). In order to prevent the intense heat from damaging them or inducing excessive thermal noise, a cooling system was implemented. Camera, intensifier, lens, and filter are enclosed in an aluminum box that is actively cooled by circulating chilled water in copper tubings around it. Mineral wool is wrapped around it and covered with fiberglass fabric for further protection. Cooling power
has been measured at more than 5 kW, which should be more than sufficient to protect from the heat from the HTTF and minimize thermal noise. A UV-transmitting hot mirror (Edmund Optics # 46-589) is mounted on the front face of the housing to prevent radiative heating to the filter and lens assembly.

The combining optics are mounted on a water-cooled aluminum breadboard (Thorlabs MBC2412) fixed on the X95 frame.

3.4 Remote control and operation

When the facility operates under pressure and at high temperature, operators have to stay in the control room which is adjacent to the facility. The time required for pressurizing and warm-up is on the order of hours; thus, the diagnostics has to be remotely operated and monitored from this control room. The remote operation is achieved as described below:

- One computer is remotely connected via Ethernet to the workstation located on the laser cart that controls the excimer laser and the dye laser with dedicated software. The dye laser has an integrated pyroelectric powermeter, which allows monitoring the pulse energy and optimization of the tuning of the frequency-doubling crystal.
- The Nd:YAG lasers are operated with a wired controller, whose factory cable is 10 feet (3 m) long. In test conditions, it was possible to operate the lasers with a 50 feet (15 m) cable, which is long enough to reach the control room.
- The cooling water loops for the dye circulators, the camera housing, and the breadboard pass through the control room, allowing adjustment of the flow rate based on the respective temperature readings.
- All the linear stages (2 per laser in the cart, and 1 for the camera), piezo-actuators (2 per beam on the breadboard) and flip-mount are computer-controlled as well. A USB camera is dedicated to monitoring the 2 beam alignment targets.
- A CCTV system is deployed to monitor various locations: one camera for the dye laser and its periscope, one for the excimer laser and its periscope, one for the beam combining optics, and one for the laser viewport.
- The image intensifier and CCD camera have cables long enough to reach the control room, and the images being recorded can be observed in real time.
- The timing unit is also located in the control room, which allows adjusting $\Delta t$ in response to the observed tracers displacement. Time delays due to the long cables are taken into account when synchronizing the instruments.

3.5 Seed gas injection

The $\text{N}_2\text{O}$ seed gas is injected independently in the RPV and RCST with the method of partial pressure, and the amount of gas is monitored with a pressure gage with an accuracy of ±0.1 kPa. For 100 kPa tests, this gives a 0.5 ± 0.1% $\text{N}_2\text{O}$ concentration in the RCST. The $\text{N}_2\text{O}$ concentration in the RPV is set at 1.0 ± 0.1% because the lasers will interact with the $\text{N}_2\text{O}$-rich helium only near the top of the pipe, at the far end of the measurement region, thus absorption is not an issue, and a stronger signal can be obtained there. The gas mixture in each vessel is independently homogenized by recirculating the gas; then, each vessel is vented back to the test pressure (atmospheric pressure for the present test).

Finally, because the hot leg on the RPV side of the break valve is not part of the circulating loop, $\text{N}_2\text{O}$ is also injected in this region. This seeded region is not a closed domain and its volume is not known; thus, the $\text{N}_2\text{O}$ concentration in that region is unknown. The first run allowed refining of this filling procedure.

4 Sample results in the IET facility

In this first test, gases were at ambient temperature and pressure, and only the hot leg ball valve was opened. In this test, the initial gas concentration in the vessels was 70 ± 5% He 30 ± 5% $\text{N}_2$ in the RPV and 80 ± 5% $\text{N}_2$ and 20 ± 5% He in the RCST, for a density ratio of 0.48 between the two mixtures. For simplicity, the gas mixtures from the RPV and from the RCST will be referred based on their main component, i.e., helium and nitrogen respectively.

At $t = 0$ s, command to open the valve was issued, which allowed gases to flow through after $t = 5$ s. The valve was fully opened at $t = 14$ s. Data were recorded up to $t = 1800$ s, or 30 min. The initial value of $\Delta t$ was chosen to be 5 ms based on preliminary simulations of the flow that indicated velocity up to about 1 m/s for this density ratio. For such velocity and $\Delta t$, the displacement is 5 mm or 36 pixels and provides sufficient precision on the displacement measurement. It also allows some margin in case the velocity is larger than expected, as the read pulse illuminates the flow over a 10-mm-long region. The tracers displacement was monitored in real-time, and $\Delta t$ was adjusted accordingly.

4.1 NO-PLIF images

Figure 14a, b shows a pair of single-shot images recorded at $t = 12.5$ s and $t = 12.5 + \Delta t$ s, respectively, with $\Delta t = 5$ ms. In the image of the first read pulse, (a) NO tracers initially form a line. This line is displaced by the flow from the RPV, as visible in the top part of the second image. (b) The signal is also brighter there due to the higher concentration of $\text{N}_2\text{O}$. 

\[ t = 0 \text{ ms}, \Delta t = 5 \text{ ms} \]
Diffusion of the tag line is also visible from one image to the next.

The SNR of single-shot images is computed and summarized in Table 2 for the first and second read pulse, and in the helium and nitrogen region of the flow. Four different intervals in time are selected to discuss different seeding and $\Delta t$ configurations. From $t = 10$ to 25 s, $\Delta t = 5$ ms, and the helium flow is seeded with the unknown amount of $\text{N}_2\text{O}$ injected in the hot leg. The signal is very strong (1500 and 900 counts for the first and second pulse, versus a background noise level of about 11 counts), resulting in a very high SNR for the helium flow region as shown in Fig. 14a, b. This bright fluorescent signal slightly increases the background noise. This is not an issue for the helium flow as the signal is strong enough to ensure a high SNR (32.1 and 19.8). However, this causes a visible decrease of the SNR of the $\text{N}_2$ region compared to the $325–335$ s interval (0.57–0.51 for pulse 1 and 0.39 to 0.32 for pulse 2).

After about 60 s, the $\text{N}_2\text{O}$-rich gas from the hot leg has flowed to the RCST, and helium is then flowing from the RPV with a $\text{N}_2\text{O}$ seeding of 1% or less (due to mixing and diffusion occurring in the RPV between helium and $\text{N}_2$). The SNR is then about constant for the first pulse in both helium and nitrogen. It decreases for the second pulse because of diffusion of the tracers.

### Table 2

Average SNR for 100 frames for the first and second read pulses in helium and nitrogen at various times in the run

<table>
<thead>
<tr>
<th>$t$ (s)</th>
<th>$\Delta t$ (ms)</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pulse 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{N}_2$</td>
</tr>
<tr>
<td>15–25</td>
<td>5</td>
<td>0.51</td>
</tr>
<tr>
<td>325–335</td>
<td>5</td>
<td>0.57</td>
</tr>
<tr>
<td>700–710</td>
<td>15</td>
<td>0.54</td>
</tr>
<tr>
<td>1060–1070</td>
<td>35</td>
<td>0.53</td>
</tr>
</tbody>
</table>

The SNR is very high in the helium region during the first 60 s due to the higher concentration of seed gas in this region of the flow. Elsewhere where the seed gas concentration is about 1%, the SNR is relatively low (between 0.4 and 0.6) compared to the laboratory measurements (also at 1% $\text{N}_2\text{O}$). This can be explained by several reasons:

1. The cavity of the excimer laser was misaligned during transportation. While the maximum power was recovered, the beam profile and quality could not be restored back to its previous state, leading to a larger than expected beam waist diameter (about 1.5 mm in the streamwise direction, instead of 1 mm).
2. The wedge prisms and hot mirror were not included during the laboratory measurements which, on the other hand, included a 89% reflection mirror. The uncoated wedges and the hot mirror have a transmission of 83 and 95%, respectively. The resulting transmission for the in-situ data is 12% lower than for to the laboratory tests.
3. The laboratory measurement were performed in a reduced FOV where the write and read beam overlapped ideally. In the in-situ measurements, the overlap is not ideal near the edges of the field of view. Nevertheless, such SNR are high enough for processing the data.

### 4.2 Velocity profiles

For each pair of single-shot images, the instantaneous velocity profile is calculated as described in Appendix A1. The present use of a dual-pulse MTV system prevents errors due to beam drift and wandering and allows their characterization, see Sect. 4.4).

The time history of the velocity is shown in Fig. 11 at three locations: $y = -25$, 85, and 130 mm. The velocity profiles at four different times ($t = 1, 15, 100$ and 1000 s) are plotted in Fig. 12. Dotted lines are indicated to reference the locations/times from one figure to the other.
The flow out of the hot leg appears about 10 s after the valve starts opening. In this buoyancy-driven phase, helium and nitrogen velocities peak at 0.9 and 0.2 m/s at $y = 130$ mm and $y = -25$ mm respectively. The counter flow of helium and nitrogen forms a shear layer in the region 60 mm < $y$ < 90 mm which is characterized by a large velocity gradient and an inflexion point in the velocity profile. This gives rise to a flow instability that manifests itself on Fig. 11 as quick fluctuations of the velocity for the location $y = 85$ mm between $t = 10$ and 50 s. The flow then slowly decays and mixing coupled with diffusion maintain a density difference between RPV and RCST; the helium flow is still measured at 0.2 m/s after 30 min.

The initial $\Delta t$ is 5 ms up to $t = 553$ s, after which it is increased to 15 ms to improve precision as the velocity decreases. The increase in precision at $t = 553$ s is visible in Fig. 11 as a decrease in the fluctuations amplitude. Between $t = 1055$ and 1095 s, $\Delta t$ was set to 35 ms. This value further improves the precision of the measurement in the low-speed regions; however, excessive displacement of the tracers in the helium flow prevents resolving the flow there. According to Fig. 11, the helium velocity at that time is up to 0.24 m/s, corresponding to a tracers displacement of 8.4 mm for $\Delta t = 35$ ms, which is too large to be imaged by the second read pulse. Diffusion would also make the line about 5 mm wide (Fig. 6). Thus, no displacement data can be extracted in helium for $\Delta t = 35$ ms. This leads to missing velocity data, as seen on the curve $z = 130$ mm in Fig. 11 between $t = 1055$ and 1095 s. After that, $\Delta t$ was dialed back to 15 ms for the rest of the run. This was the first run and it was deemed acceptable to lose some data in order to establish the limits of the present diagnostics in term of $\Delta t$. During subsequent runs, $\Delta t$ was kept at 15 ms or less to prevent data loss. The adaptive interrogation window size algorithm refined the window size based on SNR. Final window sizes for this test are presented in Appendix A3.

A small offset on the mean value (< 0.02 m/s) is observed in the time-series of Fig. 11 when the value of $\Delta t$ is changed such as at $t = 553$ s. This shift may be explained by the flow not being truly unidirectional. For instance, the light helium moves upward as it exits the pipe. The error in streamwise velocity is (Hill and Klewicki 1996):

$$e_U = V \frac{\partial U}{\partial y} \Delta t$$

with $V$ the velocity component parallel to the tag line, and thus changes with $\Delta t$. $\partial U/\partial y$ can be estimated from the measured velocity, and is negligible in the nitrogen stream region. $V$ is discussed here based on the densimetric Froude number $Fr = U/\sqrt{g' L}$ with $g' = g(\rho_{RCST} - \rho_{RPV})/\rho_{RPV}$ the modified gravity. The lengthscale $L$ is taken as the tracer displacement during the probe time. $Fr$ gives the ratio of inertial forces (assumed in the horizontal streamwise direction at the pipe exit) to the buoyancy forces (in the vertical direction after the pipe exit), thus $Fr \approx U/V$.

In the helium region in the early stage, $U = 1$ m/s, $\Delta t = 5$ ms, and $L = 4$ mm which gives $Fr = 4.9$, and $e_U \approx 0.02$ m/s. In the late stage, $U = 0.2$ m/s, $\Delta t = 15$ ms, and $L = 2.5$ mm which gives $Fr = 1.2$, and $e_U \approx 0.01$ m/s. These estimates are on the order of the measured offsets (< 0.02 m/s). Flow visualization and numerical model of the DCC will help estimating this vertical component more precisely and correct for it.

The local heating by the write beam will also add a vertical motion to the probed gas. In the most unfavorable case, this drift is estimated using Eq. 7 to be 0.004 m/s in helium and 0.003 m/s in nitrogen.

### 4.3 Estimation of precision

The precision of the in-situ measurement is estimated based on the assumption that after the initial relatively fast helium flow and shear layer instability, the flow is steady, with only a long time scale decay of velocity, as visible in Fig. 11 for $t > 100$ s. This assumption allows setting an upper bound on the measurement precision by calculating the RMS (root mean square) of the fluctuations of the velocity around its mean value, $\sigma_{RMS}$. The time history is first split in three domains based on the value of $\Delta t$: 100–500 s for $\Delta t = 5$ ms, 553–1055 s for $\Delta t = 15$ ms, and 1055–1095 s for $\Delta t = 35$ ms. Data are then filtered with a high-pass Butterworth filter with a time constant of 20 s which isolates the fluctuations of interest against the long time-scale velocity decrease. The RMS fluctuations are finally computed for each domain, and plotted in Fig. 13.
The precision for all cases is deteriorated in the top and bottom 20% of the field of view due to the low SNR there, as explained when discussing the window size.

For $\Delta t = 5$ ms, away from the image edges, the precision is around 0.027 m/s in the nitrogen gas region ($y < 60$ mm). The precision is slightly better in the helium gas region (0.023 m/s) due to the stronger signal there.

For $\Delta t = 15$ ms, the precision in the nitrogen stream velocity improves to 0.0095 m/s. The effect of tracer diffusion in helium becomes visible as the RMS fluctuations are higher there than in the nitrogen stream.

For $\Delta t = 35$ ms, the precision in the nitrogen stream velocity measurement keeps improving, down to about 0.006 m/s. In helium, the signal is lost above $y = 90$ mm, and no meaningful $u_{RMS}$ can be reported there.

The estimated precision for the in-situ velocity measurement in the nitrogen stream is reported in Fig. 4 for these three values of $\Delta t$. The data points show that despite the lower magnification than in the laboratory measurements (0.0370 versus 0.137 mm/pix), the precision of in-situ measurement is comparable. The equivalent aperture of the light collection optics, combined with the lower resolution results in a thinner, brighter image of the tag line image, thus improving the SNR.

The spatial resolution of the in-situ measurement is a function of the window size and tracer displacement. In the $y$ direction, it is 1.37 and 3.43 mm for a 40 pixels windows and a 100 pixels windows with 75% overlap, respectively. In the $x$ direction (streamwise), the measured velocity is the average over the tracer displacement, which is on the order of 1 mm in the nitrogen stream, and up to 4 mm in the helium stream. In the out of plane direction ($z$), the spatial resolution is on the order of the write beam diameter, or 1.5 mm.

The uncertainty on the velocity measurement is computed using Eq. 4. Because $\sigma_u / \Delta x$ dominates this expression by more than one order of magnitude, the results of Fig. 13 can be used as a good approximation of $\sigma_u$. The results in the present form also include the error due to the vertical velocity component caused by the bulk upwards flow of helium ($c_U$) as well as buoyancy effect caused by the write laser beam. The total uncertainties at 63% confidence interval are 0.032 m/s and 0.014 m/s for $\Delta t = 5$ and 15 ms, respectively.

4.4 Laser beams drift

The dual read pulse MTV system has the advantage of accounting for possible wandering of the write beam which is potentially an issue in case of vibrations and thermal effects. Over the 30 min run, the average tag line location imaged by the first read pulse drifts linearly at a rate of 0.7 pixel/h or 0.1 mm/h. For $\Delta t = 5$ ms, this drift would add an bias error of 0.01 m/s in the velocity measurement after 30 min if only one read pulse was used. This drift of the write pulse beam may be attributed to the pointing stability of the excimer laser (20$\mu$rad, which corresponds to 0.2 mm 10 m away. While this test was not heated, there are still...
possible temperature changes within the facility building that could also explain this drift. The standard deviation of the instantaneous tag line location is 0.29 pixels or 0.040 mm, which is smaller than the displacement measurement precision (0.135 mm for $\Delta t = 5$ ms). These fluctuations have a uniform frequency distribution (between 0 and 5 Hz) and a Gaussian amplitude distribution, consistent with the white Gaussian noise that can be expected from the random error (i.e., precision) in the measurement.

5 Conclusions

The successful deployment of N$_2$O-MTV to an IET facility demonstrates a great potential for in-situ velocimetry measurements in such facilities over a large range of pressure, temperature, and flow velocity.

The technique was first characterized in the laboratory to replicate the in-situ conditions. The optimum read pulse wavelength was identified, and data were collected between 295 and 781 K and between 1 and 3 atmospheres with various concentration of N$_2$O seed gas. Signal-to-noise ratio and velocity measurement precision were analyzed to assess the performances of the technique for probing low-speed flows. Diffusion of the tracers becomes the limiting factor for long probe times (> 20 ms), especially in helium where the binary diffusion coefficient is greater. In nitrogen, a precision of 0.004 m/s was achieved with a probe time of 40 ms at a magnification of 0.037 mm/pixel. Absorption of the write and read beams was investigated and showed that the write beam path needs to be purged with an inert gas outside of the vessel and that seed gas concentration must be optimized for a given path-length inside the vessel.

Significant efforts were devoted to anticipate and mitigate potential challenges encountered when operating optical diagnostics in a large test facility, notably delivering the lasers beams to the test section, imaging the flow, avoiding problems caused by thermal loading and vibrations, and operating the diagnostics remotely.

Velocimetry data collected at 10 Hz over 30 min are presented and shed light onto the complex flow encountered during a depressurized conduction cooldown. The flow is driven by buoyancy forces which create a counter-current of helium and nitrogen in the hot leg at velocity up to 0.9 and − 0.2 m/s, respectively. During the first 60 s of the run, shear layer instability is generated at the gases interface, as observed by high velocity fluctuations in this region. The resulting mixing, in addition to diffusion, allows a density difference to persist which sustains low-speed flow (< 0.2 m/s) over long period of time (> 30 min). Such flow has yet to be predicted by numerical models used for gas-cooled reactor design, thus the present data will lead to improvements of the safety of these reactors. Finally, the MTV technique could be invaluable to instrument relevant flows in other facilities.

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Compliance with ethical standards

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Appendix A1: MTV processing algorithm

The pair of single-shot images recorded at $t$ and $t + \Delta t$ and shown in Fig. 14a, b have low SNR in the N$_2$ region, as discussed in Sect. 4.1. Cross-correlating these two single-shot images, referred to as $x_t$ and $x_{t+\Delta t}$, results in weak correlation peaks, producing many outliers. Furthermore, there also exists differences between the two images in term of read pulse intensity and tracer line width (due to diffusion), which are detrimental to cross-correlation.

An attempt at mitigating these effects is performed here by including time-averaged reference images in the processing, as detailed below:

- Prior to the beginning of a run, reference images are recorded at zero velocity (no flow) for the first and second read pulses, and averaged over 300 consecutive samples. These images are recorded with circulators turned off; thus, vibrations are negligible. This acquisition takes 30 s, time over which the beam drift is negligible (drift < 1 pixel/h, Sect. 4.4). Figure 14c, d shows such reference images for the first and second read pulses, respectively. This provides high SNR images of the undisplaced tracer for each read pulse, $X_0$ and $X_{\Delta t}$. This step is performed for each value of $\Delta t$ used in the experiment. Note that diffusion has visibly increased the line width between Fig. 14c, d.
- In order to reduce noise and improve the cross-correlation, each image is binned in the tag line direction using with a 160 pixel-wide window (with an overlap of 75%).
- Every binned row in each single-shot image is cross-correlated with its respective reference image, i.e., $X_0 \otimes x_t$ and $X_{\Delta t} \otimes x_{t+\Delta t}$. Such correlation performs particularly well when diffusion is important because the two correlated images are for the same probe time delay. Furthermore, it is also unaffected by difference in intensity and spatial profile between first and second read pulses.
- The width of the binning window is iteratively refined based on the unscaled cross-correlation value. For instance, a high value indicates a strong signal and well-defined tag line, enabling to decrease the binning window.
size and improve the spatial resolution. The binning window size is bounded between 40 and 160 pixels.

- Once the window size has converged, the correlation peak is curve fitted to a Gaussian function to extract the displacement (cross-correlation lag) to a sub-pixel level between the single-shot image and its reference location for the first and second read pulses. The corresponding lag results for the first and second pulses, \( X_0 \otimes x_t \) and \( X_{\Delta t} \otimes x_{t+\Delta t} \), are displayed in Fig. 15a, b, respectively. Not that Fig. 15a is a direct measurement of the single-shot tracer displacement with respect to the initial reference location, while Fig. 15b is a measurement of the single-shot write beam wandering with respect the initial reference location.

- The lag of \( X_{\Delta t} \otimes X_0 \) is negligible, even at \( \Delta t = 35 \) ms, thus the reference location \((X_0 \text{ or } X_{\Delta t})\) can be assumed identical for first and second read pulses. Therefore, the final tracer instantaneous displacement between the two single-shot images is obtained by taking the difference between the two displacements obtained by cross-correlation as done in Fig. 15c. This requires interpolation because data from the two images are on a different grid as a consequence of the adaptive windowing.

As a dual-pulse technique, this method still accounts for beam wandering as shown in Fig. 15a. A drawback of this method would be that in some experiments, it is not possible to record reference images at zero velocity.

Using the data of Sect. 4, and performing an estimation of the precision as done in Sect. 4.3, the improvement in precision with this method is between 5 and 15% (for \( \Delta t = 5 \) and 35 ms) compared to the usual cross-correlation of single-shot image pairs \((x_t \otimes x_{t+\Delta t})\). As expected, the gain is more significant at longer \( \Delta t \) due to the effect of diffusion.

### Appendix A2

The number density of \( \text{N}_2\text{O} \) molecules dissociated in a control volume of length \( dL \) located at a distance \( L \) is obtained by combining Eqs. 2 and 3, and setting the beam energy entering the control volume to be \( E_0 e^{-\sigma_n L} \).

\[
 n_d = \frac{E_0 e^{-\sigma_n L}}{h \nu dL} (1 - e^{-\sigma_n dL}).
\]  

(9)

The maximum value of \( n_d \) is found by solving \( \partial n_d / \partial n_i = 0 \) for \( n_i \):

\[
 n_i = \frac{1}{\sigma dL} \ln \left( 1 + \frac{dL}{L} \right).
\]  

(10)

\( dL \) can be set arbitrarily small such as \( dL \ll L \), in which case Eq. 10 becomes:

\[
 n_i = \frac{1}{\sigma L}.
\]  

(11)

### Appendix A3

The adaptive interrogation window size algorithm refined the window size in the region of high SNR characterized by a high correlation peak. The window size for the second read pulse as a function of time and spatial location is shown in Fig. 16. The window size is larger near the top and bottom of the frame than near the center for the following reasons: image vignetting, reduced overlap of the read and write beams, larger diameter of the write pulse beam, and depth of field limited by the camera angle. The window size reaches the minimum of 40 pixels in the \( \text{N}_2\text{O} \)-rich helium.

![Fig. 15](image_url) Main steps of the cross-correlation scheme. Single-shot tracer displacement (lag of maximum cross-correlation peak) relative to reference location for first and second read pulses (a, b), respectively. Tracer displacement between the two single-shot images is recovered by taking the difference between the relative displacements (c).

![Fig. 16](image_url) Time-space color plot of the interrogation window size for the second read pulse images, indicated in pixels on the chart. Missing data are in black.
stream from the hot leg pipe after $t = 10$ s. After $t \sim 80$ s, the $N_2O$ concentration of the helium/N$_2$ mixture from the RPV is lower, and the window size increases to a minimum of 100 pixels for the rest of the run, with the exception of the interval where $\Delta t$ was set to 35 ms between $t = 1055$ and 1095 s.

References


NON-INTRUSIVE VELOCITY MEASUREMENTS WITH MTV DURING DCC EVENT IN THE HTTF

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ABSTRACT

Velocity profiles are measured using molecular tagging velocimetry (MTV) in the high temperature test facility (HTTF) at Oregon State University during a depressurized condition cooldown (DCC) event. The HTTF is a quarter scale electrically heated nuclear reactor simulator designed to replicate various accident scenarios. During a DCC, a double ended guillotine break results in the reactor pressure vessel (RPV) depressurizing into the reactor cavity and ultimately leading to air ingress in the reactor core (lock-exchange and gas diffusion). It is critical to understand the resulting buoyancy-driven flow to characterize the reactor self-cooling capacity through natural circulation.

During tests at ambient pressure and temperature, the RPV containing helium is opened via the hot and cold legs, to a large vessel filled with nitrogen simulating the atmosphere. The velocity profile on the hot leg pipe centerline is recorded at 10 Hz with MTV based on NO tracers. The precision of the method was calculated at 0.02 m/s by measuring quiescent flow prior to the tests. A helium flow from the RPV is initially observed in the top quarter of the pipe. During the first 20 seconds of the event, helium flows out of the RPV with a maximum below 2 m/s. The velocity profile then becomes linear and decays slowly over the rest of the recording (down to 0.2 m/s after 30 min). Counter-flow of nitrogen is also observed intermittently at lower velocity (>0.1 m/s).

MTV was implemented here for the first time in a large scale thermal hydraulic facility and shows a very promising potential for both gaining fundamental understanding of such flows and as a validation tools for numerical simulations. The flow patterns and timescales observed indicate that additional flow regimes might be taking place between the predicted lock-exchange and diffusion regimes.
1. INTRODUCTION

Very High Temperature gas cooled Reactor (VHTR) have potential to be an efficient, economical, and safe source of carbon free electricity. High temperature of the core also allows the reactors to serve as source of high quality heat, which can have a multitude of industrial applications. This design is being considered as part of the Generation IV nuclear reactors and is the main reactor under study in the US under the Next Generation Nuclear Plant (NGNP) design. To assist in the development of the NGNP, several integral and separate test facilities (IET and SET) have recently been built in the United States. They aim at developing correlations and benchmark cases for system level codes as well as for validating computational fluid dynamics codes [1]. The requirements for the latter are different than for the former. Specifically, in addition to measuring point-wise temperature and pressure drops necessary for low order models, it is desirable to resolve velocity and temperature fields in the fluid as well. This requires a different class of diagnostics than used for developing correlations. For some conditions, laser-based diagnostics are appropriate for resolving desired quantities, however their deployment in a large IET is rather challenging, which has limited such use to date.

In the present study, a molecular tagging velocimetry (MTV) system was developed by the co-investigators and deployed in-situ in an IET of a VHTR. The facility and accident scenario under study are presented first. Then the experimental measurement system and its in-situ deployment is introduced. Velocity results for several runs in the IET are finally reported.

2. INTEGRAL EFFECT TEST FACILITY

2.1. High Temperature Test Facility

To assist in development of system level codes as well as validation of computational fluid dynamic (CFD) codes, an integral effect test facility has been built at Oregon State University under sponsorships of the US Department of Energy and the US Nuclear Regulatory Commission: The High Temperature Test Facility (HTTF). The HTTF is a scaled down facility of VHTR, following General Atomic Modular High Temperature Gas cooled Reactor (MHTGR) design, for simulation of depressurized conduction cooled down (DCC) [2]. The facility can also be employed for Pressurized Conduction Cooled (PCC) tests. The facility is ¼ height (6.1 m tall), ¼ diameter (1.92 m OD) of the MHTGR and in its current configuration has a prismatic block core. It is a reduced pressure (1:8 ratio or 8 atm) and prototypical temperature facility.

In DCC, the pressure boundary has been ruptured through a double ended guillotine of the inlet and outlet cross over ducts, which are concentric pipes with the hot leg enclosed in the cold leg. At the end of the rapid depressurization, air from the cavity in which the reactor vessel and auxiliary system sit ingresses in the reactor pressure vessel (RPV). The air ingress through the break will lead to oxidation of the graphite in the RPV and in some conditions, could lead to loss of mechanical integrity of the core and release of fission products.

In the HTTF, artificial pipe break and air ingress are simulated with the hot and cold legs discharging from the RPV inside a Reactor Cavity Simulation Tank (RCST). The RCST can be filled with gas mixtures prior to opening pneumatically controlled ball valves that sit in each leg. Figure 1 presents the RPV with the initially annular cross over duct that splits into two separate pipes that independently enter the RCST.
Figure 1. Schematic of reactor pressure vessel. The hot and cold legs are shown at the bottom right, the hot leg being the larger diameter pipe that goes straight inside the RCST. Elements on top of the legs are pneumatic actuators for the valve valves that simulate the double ended cross over duct break

2.2. DCC event description

Air ingress events have been the subject of numerous analytical and numerical studies to, in part, inform design of the HTTF. From these studies, it is assumed that an air ingress event follows several stages [1] that are summarized here along with the main equations relating the main observable quantities. After the depressurization of the RPV, a stratified counter-flow takes place within the hot and cold legs between the RPV and RCST, resulting in air entering the lower plenum of the RPV, stage 1. In a second stage, air within the lower plenum is circulated within the hot core by natural convection. To date, data have only been only acquired with core at room temperature, a more in-depth description of the first stage is given.

Following the work of Oh and Kim, 2011 [3], during the first stage two air ingress mechanisms have been identified: stratified flow and diffusion. In the stratified, or gravity current, mechanism the density difference between the helium on the inside, and the air on the outside (or in the RCST in the HTTF), drives a counter flow through the break. The second mechanism is driven by air concentration gradients between the inside and the outside. The time scale of each mechanism is reproduced:

\[
\Delta t_{gc} = \frac{L_1}{U_s} \\
\Delta t_{d} = \frac{L_2}{D_{AB}}
\]

where \( L_1 \) and \( L_2 \) are the length-scales associated with gravity currents and diffusion, respectively, \( U_s \) the axial velocity scale or the superficial velocity, and \( D_{AB} \) the bimolecular diffusivity coefficient of He into
air. The gravity current length-scale, \( L_1 \), is taken as the distance from the break to the center of the lower plenum. The superficial velocity is related to the current speed \( U \) by:

\[
U_s = U \frac{h}{H}
\]

where \( H \) and \( h \) are the channel and current depths. The current velocity for the density ratio, \( \gamma \), of interest is given by:

\[
U = \sqrt{(1 - \gamma) g H} \left( 1 - \gamma \frac{h}{H} \right) \left( 2 - \frac{h}{H} \right) \left( 1 + \frac{h}{H} \right) \]

where \( g \) is the acceleration of gravity. For two non-reacting non-polar gases, the bimolecular diffusivity coefficient is given by:

\[
D_{AB} = \frac{18.58 T^{3/2}}{P \sigma_{AB}^2 \Omega_D} \left( \frac{1}{M_A} + \frac{1}{M_B} \right)
\]

Where \( T \) is the temperature, \( P \) the pressure, \( M \) the molecular weight, \( \sigma_{AB} \) Lennard-Jones parameter, and \( \Omega_D \) the collision integral. The diffusion length scale varies with time and is calculated by solving the following equation:

\[
\frac{1}{D_{LP}} \int_{z_L}^{1} \left[ 1 - \text{erf} \left( \frac{z}{2 \sqrt{D_{AB} t}} \right) \right] dz = 0.5
\]

where \( D_{LP} \) is the lower plenum diameter and \( \text{erf} \) is the error function. For the MHTGR conditions, Oh and Kim 2011 computed the following values for the gravity current and diffusion timescales. \( \Delta t_{gc} = 19.5 \) s and \( \Delta t_d = 1.29 \times 10^4 \) s which indicate that diffusion was negligible in this stage of the DCC event.

3. DIAGNOSTICS

3.1. MTV technique summary

Molecular tagging velocimetry (MTV) is a time-of-flight velocity measurement technique that relies on locally creating and tracking molecular tracers [4]. A first laser pulse (or write pulse) creates these tracers with a predetermined spatial pattern, and then a second laser pulse (read pulse) or pulses excite a cross-section of the flow with a controlled time interval. The location of the displaced tracers is recorded for each read pulse with a camera, ultimately leading to velocity profiles. The technique was first developed in the lab using \( \text{H}_2\text{O} \) tracers [5] before focusing on NO tracers (due to their longer lifetime) obtained from photo-dissociation of \( \text{N}_2\text{O} \) [6]. In the laboratory, MTV performances and accuracy were assessed in a controlled environment. Velocity profiles were successfully obtained in air, nitrogen, and helium for a large range of parameters: temperature from 295 to 781 K, pressure from 1 to 3 bars, with a velocity precision of 0.01 m/s. Details of the MTV technique and its applicability to VHTR studies are presented in a joint paper and presentation.

3.2. Deployment to the HTTF

The technique was optimized in the lab for the expected conditions of the HTTF. Optical path was adjusted to match the geometry of the HTTF. The laser system was developed on a cart to allow easy transportation.
Another challenging aspect of the instrumentation was to enable remote control of the system. This includes remote operation of the several lasers, control of the laser, camera and dye temperature, remote monitoring and steering of the beams to maintain overlap in the test region. This was accomplished with computer controlled linear stages and data acquisition system, remote connected computers to control the lasers, and CCTV camera system. The layout of the experiment at OSU is shown in Figure 2.

![Figure 2. Floor plan of the HTTF showing laser and camera location](image)

Details of the laser cart are shown in figure 3:

![Figure 3. Laser cart. Left: back of the cart. Right: Front of the cart with the two beams being shot through the tubes.](image)

Details of the breadboard holding the optics and camera section are shown in figure 4:
Once inside the RCST, the beams are redirected towards the exit of the hot leg with a 90° prism, visible on the left image of figure 5. The beams are aligned to overlap in the measurement region, highlighted in purple. Figure 5, right, gives the exact coordinates of the velocity measurements location at the exit of the hot leg. The beam was carefully aligned to be vertical and intersect the pipe centerline.
4. RESULTS

4.1. Isothermal DCC, hot leg break only

In this test, gases are at ambient temperature, and only the hot leg valve is opened. For this first test of the diagnostics in the HTTF, there was large uncertainty on the gas concentration in the vessels. It was estimated (with ±5% uncertainty) that the RPV had 70% He 30% N₂ and RCST had 80% N₂ and 20% He, for a density ratio $\gamma = 0.48$. At $t = 0$ s, the valve starts to open, and is fully opened at $t = 14$ s. Data are recorded up to $t = 1,800$ s, or 30 min.

4.1.1. Short term behavior

Figure 6 shows velocity profiles and time evolution of the velocity for the first 120 seconds to focus on the early stage of this lock exchange.

The qualitative description of the flow obtained from looking at the raw MTV images is clearly seen in the spatial profiles, and the magnitude of the velocity can now be quantified. The peak velocities are approximately 0.95 m/s for the helium flow out of the RPV, and -0.20 m/s for the nitrogen into the RPV, as shown on the left of figure 6. Helium flow occupies the top quarter of the pipe and nitrogen flow the rest. The corresponding current velocity calculated using the equation from section 2.2 is 0.9 m/s, in agreement with the measured value.

The flow magnitude then decreased as time goes. This time evolution is better visualized in figure 6, right, where temporal evolution for a few selected points is plotted. The flow starts about $t = 10$ s into the run due to the slow opening of the valve. Purple and green curves are near the inflexion point (where He and N₂ mix) and show more fluctuations than in the initially pure helium stream (top curve) or in the N₂ stream (bottom 3 curves). This region of mixing is characterized by large velocity gradient and an inflexion point in the velocity profile, which can give rise to flow instability, most likely of the Kelvin-Helmholtz type. These instabilities are visible in figure 6, right, as quick fluctuations of the velocity.

Figure 6. Velocity results for isothermal hot leg only DCC, zoomed in the early stage. Left figure shows velocity versus location (spatial profiles) at the instants marked by a dotted line on the right figure. The right figure shows velocity versus time (temporal profiles) at the location indicated by dotted lines on the left figure.
4.1.2. **Long term behavior**

Figure 7 shows the late stage of the flow for the same run. The discontinuity around $t = 550$ s and $t = 1,100$ s are artifacts resulting from the change of $dt$, which allowed probing slower speed more accurately. As shown in these curves, the velocity profiles maintain the same trends, and decrease in magnitude. Unlike predicted by numerical simulations, there is still a significant flow for a long period after the valve opened (~0.2 m/s after 30 min). This can be attributed to assumptions and implications made when modeling the flow in the HTTF.

![Figure 7](image)

**Figure 7.** Same as figure 6, for the full run showing the late stage flow

4.3. **Isothermal DCC, hot leg + cold leg break**

The setup of this test was similar, and the gas content was estimated at 100% He in the RPV and 70% N$_2$, 30% He in the RCST for a density ratio $\gamma = 0.19$. Both hot and cold legs were opened at the beginning of the run to simulate a realistic DCC break. The camera was slightly pointed upward and raised to fully capture the He flow at the top of the pipe. This was previously unresolved partly because of image vignetting near the edges of the frame. Figure 8 shows the observed flow. The jump at $t = 500$ s is also an artefact due to the change of $dt$. It has some similarity with the previous hot leg only DCC, but also exhibits differences. Notably, the maximum velocity is around 2.1 m/s, which is explained by the higher Helium concentration in the RPV as the calculated current velocity is 1.8 m/s.

Another interesting phenomenon is the increase of velocity around $t = 150$ s. This was not observed in the previous test when only the hot leg was opened. It could also be due to the different gas composition. Balance of the flow between hot and cold legs could create some feedback loop that increases the hot leg flow for a short duration. Work to understand this is still ongoing. At $t = 600$ s (10 min), hot and cold legs were closed, which is visible on the graph: Velocities drop to zero after that event.
5. CONCLUSIONS

Velocity profiles have been successfully measured using molecular tagging velocimetry (MTV) in the high temperature test facility (HTTF) at Oregon State University during a depressurized condition cooldown (DCC) event. The technique was developed in the lab then deployed at OSU. The challenges associated with implementing an advanced optical technique to an IET have been overcome and valuable results were obtained.

A helium flow from the RPV is initially observed in the top quarter of the pipe. During the first 20 seconds of the event, the velocity profile seems parabolic with a maximum current velocity of 0.9 and 1.7 m/s, depending on the initial RPV gas composition, in agreement with the theory. The velocity profile then becomes linear and decays slowly over the rest of the recording (down to 0.2 m/s after 30 min). Counter-flow of nitrogen is also observed intermittently at lower velocity (0.1 to 0.01 m/s).

Two interesting features were observed and would deserve more scrutiny: -the persistence of a significant flow past several minutes, and -a temporary increase of the current velocity after about 2 minutes into the DCC.

In summary, MTV was implemented here for the first time in a large scale nuclear facility and shows a very promising potential for both gaining fundamental understanding of such flows and as a validation tools for numerical simulations. The flow patterns and timescales observed indicate that an additional flow regimes might be taking place between the predicted lock-exchange and diffusion regimes.

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ABSTRACT

$\text{N}_2\text{O}$ molecular tagging velocimetry ($\text{N}_2\text{O}$-MTV) is developed for use in very-high-temperature reactor environments. Tests were carried out to determine the optimum excitation wavelength, tracer concentration, and timing parameters for the laser system. Using NO tracers obtained from photodissociation of $\text{N}_2\text{O}$, velocity profiles are successfully obtained in air, nitrogen, and helium for a large range of parameters: temperature from 295 to 781 K, pressure from 1 to 3 bars, with a velocity precision of 0.01 m/s. Furthermore, by using two read pulses at adjustable time delays, the velocity dynamic range can be increased. An unprecedented dynamic range of 5,000 has been obtained to successfully resolve the flow during a helium blowdown from 1000 m/s down to 0.2 m/s. This technique is also applied to the high-temperature test facility (HTTF) at Oregon State University (OSU) during a depressurized condition cooldown (DCC) event. Details of these measurements are presented in a companion paper. This technique shows a strong potential for fundamental understanding of gas flows in nuclear reactors and to provide benchmark experimental data to validate numerical simulations.

KEYWORDS

Molecular tagging velocimetry, validation data, gas cooled reactors
1. INTRODUCTION

Molecular tagging velocimetry (MTV) is a time-of-flight velocity measurement technique that relies on locally creating and tracking molecular tracers [1]. A first laser pulse (or write pulse) creates these tracers with a predetermined spatial pattern, and then a second laser pulse (read pulse) or pulses excite a cross-section of the flow with a controlled time interval. The location of the displaced tracers is recorded for each read pulse with a camera, ultimately leading to velocity profiles. In gas flows, radicals are typically created through photo-dissociation of specific seed molecules and are tracked with planar laser-induced fluorescence. MTV has been demonstrated in gas with a variety of tracers. Examples of seed gas include N$_2$O [3], NO$_2$ [4], Kr [5], acetone [6], biacetyl [7], O$_2$ [8, 9], N$_2$ [10], and H$_2$O [2, 9]. This non-intrusive technique is applicable to a wide variety of flows ranging from stagnant to hypersonic, from cryogenic to flame temperature, and over a large range of pressure.

These characteristics make MTV attractive for experimental studies of very-high-temperature gas-cooled nuclear reactor (VHTR). In both the stratified and natural circulation flows that occur in these facilities, which typically have low velocities (below 1 m/s), MTV requires tracers that persist for a long duration to obtain resolvable displacements. This is typically not possible with particle-based methods because settling would be an issue, in addition to contamination of the facility.

The present work focuses on NO tracers obtained from N$_2$O (nitrous oxide) seed gas and demonstrates their use in thermodynamic conditions similar to that of VHTR. The velocity measurement precision, dynamic range and other aspect aspects of this technique are discussed.

2. EXPERIMENTAL TECHNIQUE

2.1. N$_2$O Photo-chemistry

The NO tracers are created from the photo-dissociation of the N$_2$O seed gas according to the following reactions:

\[
\begin{align*}
    \text{N}_2\text{O} + h\nu &\rightarrow \text{N}_2 + \text{O} \\
    \text{N}_2\text{O} + \text{O} &\rightarrow 2\text{NO}
\end{align*}
\]

where \( h \) is Planck’s constant and \( \nu \) the photon frequency. An excimer laser with a 193 nm wavelength is used for the photo-dissociation, as detailed in the following section. The first reaction relates to the photo-dissociation ratio, given by the equation:

\[
\frac{n_d}{n_i} = \frac{\sigma E}{h\nu A}
\]

\( \sigma \) is the photo-dissociation cross section, equal to $8.95 \times 10^{-20}$ cm$^2$ for N$_2$O. The cross section slightly increases with temperature. \( E \) and \( A \) are the beam energy and cross sectional area, respectively. NO is stable in inert environment such as helium or nitrogen, which is useful for increasing the probe time to reach high velocity measurement precision. Molecular diffusion of the tracers limits the probe time by spreading the tag line. The latter increases proportionally to \( dt \) to the first order.

2.2. Molecular tagging velocimetry system

The diagnostics rely on several lasers and a camera synchronized together. The seed gas is initially dispersed in the flow being probed. A first laser beam (the write pulse) is from an excimer laser (GAM Laser EX5) at 193 nm. This beam is gently focused by a 1.5 m focal length lens and photo-dissociates the N$_2$O in its path. The NO molecules are created nearly instantaneously (<10 ns) and form a line, the location of which is to be measured subsequently using fluorescence. Two laser pulses shaped in a 3-mm
thick sheet (read pulses) are then emitted from a tunable dye laser (Sirah Cobra-Stretch) at a wavelength of 226.1929 nm to illuminate the NO tracers and induce fluorescence. An intensified camera (QImaging QIClick CCD camera coupled with a LaVision IRO intensifier) records the fluorescent signal and rejects the laser light with a long pass filter (280 nm cut-off), informing on the location of the tracers at two different instants in time. The velocity is then obtained by measuring the displacement using cross-correlation techniques and knowing the delay between the two images. Since only a single tag line was used in these studies, only a single component of velocity can be resolved.

2.3. Test Section

A stainless steel pressure vessel was built to investigate the performances of the diagnostics in conditions as encountered in a VHTR, namely high pressure and high temperature. This test section is fitted with two UV-transparent fused-silica viewports to allow the lasers beam to enter it and the fluorescent signal to be observed. A 9-mm diameter jet is located vertically in the center of the test section to generate a well-controlled flow of nitrogen or helium containing a small fraction of N₂O that can be probed with N₂O-MTV. A National Instruments data acquisition system controls and monitors pressure and temperature in the chamber, as well as jet flow rate and N₂O molar fraction.

![Figure 1. Laser system (left). Test section with laser viewport (right)](image)

3. RESULTS

3.1. Tracer Spectrum and wavelength selection

The fluorescence excitation spectrum of NO is first measured and analyzed to identify the optimum wavelength for the dye laser (read pulse). The MTV signal is recorded while the dye laser scans the wavelength, all other parameters (laser power, N₂O concentration, probe time) being held constant. The scan is run between 225.9 and 226.4 nm and results are presented in Figure 2 for ambient temperature and pressure. The emission spectrum of NO computed by the software LIFBASE [11] is also plotted on this figure and shows a good agreement with the experiment. The strongest signal (highest peak) is obtained at a wavelength of 226.1929 nm which is the Q-branch band head.
Tests were also performed at higher pressure (up to 3 bars) and temperature (up to 500 °C). While pressure and temperature affects the peak height and width through collisional quenching and broadening, the best signal was still obtained at the same wavelength, which ensured the dye laser would not need to be tuned for each pressure or temperature condition. Therefore the rest of the study was done with the read pulses at 226.1929 nm.

3.2. Effect of temperature, pressure, probe time, and N₂O concentration

For the data described in this section the NO signal is measured by keeping the wavelength of the read pulse constant (where the signal is maximum) and the temperature, pressure, and N₂O concentration are varied. The tracers are probed at two different times of 10 and 1000 µs after being created by the write pulse. The tracers are probed non-consecutively, with only one probe pulse. The results are summarized in the plots of figure 3. Each sub figure presents a different combination of pressure/temperature with the first row at ambient pressure, and the first column at ambient temperature. Maximum temperature and pressure in this study are 781 K (508 °C) and 3 bars, respectively. The N₂O concentration is varied between 0.1 and 6% by volume. Note that the only previous study on N₂O-MTV was done at 4% [3].

The main findings are:

- Signal increases with temperature, which is convenient for VHTR studies since the flow can be up to 900 °C.
- Signal decreases with an increase in pressure. This can be problematic at low temperature (lower left subfigure has the lowest signal of all), but this detrimental factor can be offset by the gain obtained from temperature increase, as shown for the 659 K, 3 atm plot.
- Signal intensity is similar between 10 and 1000 µs, which confirms the chemical stability of NO over this duration. Further study of the lifetime showed successful probing of NO for at least 20 ms with molecular diffusion being the limiting factor. The effect of the probe time delay on the velocity measurement is discussed in the following section (3.3).
- Signal increases with N₂O concentration for low concentration (<2%). Above 2%, the signal either plateaus or decreases. This is discussed in more details in section (3.3).
- Although the only N₂O measurements reported in literature used 4% N₂O, these results show that data can still be obtained at sub-one percent concentration.
3.3. Velocity measurement precision

MTV is a time-of-flight technique, where the velocity is obtained by measuring a displacement over a period of time according to the equation \( V = \Delta x / dt \) with \( \Delta x \) the tracer displacement, and \( dt \) the probe delay time. Since the resolution of the displacement measurement is limited by the camera resolution (discretized in pixels), larger \( dt \) are required to probe slower flows for a given magnification (magnification being set by the size of the field of view, which is largely determined by the lens used, distance of the lens from the CCD, working distance and CCD sensor size). The precision of the velocity measurement is then expressed as

\[ \sigma_v = \frac{\sigma_x}{dt} \]

The precision on the measured displacement is a function of the camera, optics, and processing algorithm, as well as signal quality (typically characterized by the signal-to-noise ratio –SNR). The following figure presents the measured precision for 4 cases with different pressure, temperature and \( \text{N}_2\text{O} \) concentration as a function of probe time.
The dashed line on Figure 4 has an arbitrary height and a slope of -1 (in log-log plot) to represent the aforementioned theoretical relationship between velocity precision and probe time. At low probe time (<100 µs), the SNR is high and diffusion is negligible, thus the precision of the displacement is constant, and the experimental data follow the -1 slope trend line. As \( dt \) increases further, the precision keeps decreasing (i.e. improves), but departs from the theoretical trend. This is because the jet in this test was convecting the tracers out of the probe sheet. Precision down to 0.1 m/s are obtained for this set of experiments. Improvement of the setup (reducing jet velocity and enlarging probe laser sheet height) yielded precision down to 0.01 m/s at probe time of 10 ms. This precision is for a given magnification and field of view, which limits the maximum displacement that can be measured. This corresponds to about 1 m/s, and thus the technique has a velocity dynamic range of 100:1, which is similar to that of particle image velocimetry (PIV).

3.4. Optimization and Outlook

To be deployable to VHTR experiments, additional challenges must be addressed concerning the N\(_2\)O-MTV technique.

3.4.1. Seed Gas Concentration

Because N\(_2\)O has a relatively large absorption cross section, it is easily photo-dissociated by the excimer laser. However, this also means that the excimer beam will be attenuated as it travels through the gas mixture (nitrogen+N\(_2\)O). The transmission efficiency is:

\[
\frac{E}{E_0} = e^{-\sigma n_i L}
\]

with \( L \) the path-length of the beam in a gas containing a concentration \( n_i \) of N\(_2\)O. The exponential nature of this equation indicates that the beam will be quickly absorbed if the quantity \( \sigma n_i L \) is large. \( \sigma \) is a physical constant, and \( L \) is geometrical constraint which correspond to the distance the laser beam has to
travel in the experiment between the viewport and the measurement region. For integral effect test facility, this distance can easily be on the order of meters, which put strong limitations on the concentration of N₂O to avoid beam attenuation. Other considerations in wanting to reduce the N₂O concentration include cost, safety and the desire to minimally perturb the flow system.

By combining the equation for the photo-dissociation efficiency and beam attenuation, the optimal N₂O concentration to maximize the amount of dissociated molecules for a given path-length is \( n_{opt} = \sigma L \). For \( L = 30 \text{ cm} \), the optimum N₂O concentration is 1.5%. For \( L = 100 \text{ cm} \), it is 0.45%. The previous results showed that data can be obtained with concentration as low as 0.2% with the present setup, which corresponds to a path-length of 225 cm. Longer path lengths could still be acceptable with lasers of higher power. Alternatively, the beam could also be enclosed in a N₂O-free environment within the experiment until it reaches the measurement section (provided this enclosure does not disturb the flow).

### 3.4.2. Velocity Dynamic Range

The velocity measurement relies on the displacement of the tracers between two instants in time. In the present work, this is accomplished by two consecutive read pulses. However, most MTV studies to date have used only one read pulse. The initial location of the tracers is recorded in a separate step by firing the read pulse within a few nanoseconds of the write pulse. The assumption that the initial tracer location is constant is usually reasonable when doing measurements in the laboratory, where the environment is well controlled. Factors potentially affecting the position of the write beam are vibrations, beam steering through turbulent flow and thermal expansion. Therefore, it is preferable to rely on two probe beams when doing field measurements where such issues may occur.

In more controlled experiments where the initial tracer location is constant, the two probe pulses can be taken advantage of to increase the velocity dynamic range. For instance, a first pulse can be fired after a short delay, allowing measurement of high speed flows, and then a second pulse is fired after a longer time, enabling the measurement of lower velocities with high precision. But this approach could be susceptible to the previously mentioned error factors (vibration, etc.).

The velocity dynamic range of the MTV system was investigated. This test was performed with HO tracers created from H₂O seed gas. This technique, called hydroxyl tagging velocimetry (HTV) [2], is similar to N₂O-MTV, though HTV generally has a weaker signal at long \( dt \). Similar tests would work even better with N₂O-MTV. In this test, a small chamber (5.7 liters) is pressurized at 3.5 bars with Helium and a 1/4” diameter valve is then quickly opened to vent the chamber to the atmosphere. Such flow would be similar to a blowdown, as is experienced during the depressurization phase of a DCC. Velocity is measured with MTV at the valve exit. The first read pulse is 3 µs after the write pulse and is used for resolving high speed flow (~100 m/s). For low flow speed (order of 1 m/s), the displacement is very small, and the precision is poor. The lower speed part of the flow is precisely resolved with a longer \( dt \), of 253 µs. The initial tracer location is obtained from measurements before the opening of the valve, when the flow is quiescent and the line is not convected.

The jet mean velocity as a function of time is plotted in figure 5. The valve opens at \( t = 1.5 \text{ s} \). The flow is initially fast (limited by the speed of sound in the gas, \( \sim 1,000 \text{ m/s} \) for helium), and is correctly captured by the first pulse at \( dt = 3 \text{ µs} \). The second pulse at \( dt = 253 \text{ µs} \) is not visible because out of the camera FOV. When the flow is slow enough (< 20 m/s), the second pulse becomes visible and is then used to calculate the velocity.

The first pulse is still visible, but the very small displacement makes the measured velocity very imprecise (on the order of 10 m/s). The precision on the second pulse measurement is about 0.2 m/s. Overall, the flow is resolved from 1000 m/s down to 0.2 m/s, which corresponds to a dynamic range of 5,000:1. Using a single pulse allow a dynamic range of only 100:1. Uncertainties due to calibration and
timing are negligible compared to the precision, thus the aforementioned measurement precision provides an estimation of the overall uncertainty, i.e. 10 m/s for $dt = 3 \, \mu\text{s}$ and 0.2 m/s for $dt = 3 \, \mu\text{s}$.

![Figure 5. Jet velocity versus time for a helium blowdown](image)

4. **DEMONSTRATION OF THE DIAGNOSTICS ON THE HTTF AT OSU**

The diagnostics described were designed to be deployed to the High Temperature Test Facility (HTTF) at Oregon State University (OSU) to perform velocity measurements during a depressurized conduction cooldown (DCC) in this Integral Effect Test (IET) facility. The implementation of this technique to the HTTF and detailed results are presented in a companion paper and presentation. Sample results are presented here to illustrate the capabilities of the N$_2$O-MTV method for VHTR investigations.

The HTTF replicates a DCC by opening both hot and cold leg of the primary to a large cavity (RCST) simulating the ambient atmosphere surrounding the reactor. Velocity profiles are measured at the exit of the hot leg at a frequency of 10 Hz for 30 minutes. In a DCC scenario, simulations predict helium to flow out of the reactor, and air (here nitrogen is used as a surrogate) to ingress into the reactor, in a buoyancy-driven flow. Figure 6 shows velocity profiles and time evolution of the velocity during an isothermal DCC. These results are the first detailed velocity data obtained from an IET, and they reveal the complexity of the evolution of the flow during such events.

The high measurement precision was crucial in these experiments because of the low velocities experienced in the HTTF (< 2 m/s). The laboratory investigation of the effect of temperature/pressure of the NO signal, N$_2$O concentration, and timing parameters of the tests that is detailed in this paper made the *in-situ* measurements successful.
Figure 6. Velocity result for isothermal DCC. Left figure shows velocity versus location (spatial profiles) at the instants marked by a dotted line on the right figure. The right figure shows velocity versus time (temporal profiles) at the location indicated by dotted lines on the left figure. Thick black lines are locally averaged profiles.

5. CONCLUSIONS

A non-intrusive velocity measurement technique based on molecular tagging has been investigated to determine its suitability for gas flow measurements in VHTR conditions. NO tracers obtained from N2O seed gas allow precise measurements over a large range of temperature (295 to 781K) and pressure (1 to 3 atm). We also demonstrate that the required concentration of seed gas can be significantly lower than in previous studies (0.2% vs 4%), which minimizes the change of the thermo-physical properties of the flow under investigation. The probe time of NO can be at least 10 ms which is much longer than used in previous work. This long delay gives adequate precision (0.02 m/s) when measuring low speed flows (<2 m/s).

On the other hand, high-speed flow such as during a blowdown can also be probed by using a shorter probe time. High and low speed flows can be simultaneously probed by taking advantage of the dual-probe pulse capacity of the current system since vibration, beam steering and thermal expansion do not appear to be significant in the current tests. A dynamic range of 5,000:1 is demonstrated by measured the velocity of a blowdown jet from 1,000 m/s to 0.2 m/s.

The N2O-MTV technique is readily implementable on VHTR-type facility. Data have been recorded during a DCC on the HTTF at OSU, and are presented in more details in a companion paper.

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REFERENCES