Mapping H_2O Transport with Tomographic Absorption Spectroscopy

ABSTRACT

Researchers from the School of Aeronautics and Astronautics in Chengdu, China and the Chinese University of Hong Kong have developed a jet flow, tomographic absorption spectroscopy (TAS) platform to study H_2O transport in a non-reactive jet flow with various conditions. By combining tomography and absorption spectroscopy techniques with a laser with center wavelength of 1368.598 nm, two-dimension (2D) contour imaging was created to display H_2O mole fraction distribution from the laminar jet into ambient air. The reconstructed distributions at different heights above the jet flow nozzle, as well as the 2D contour, matched well with and were validated with computational fluid dynamics (CFD) simulations. This research shows the great potential that TAS has in the field of mass transfer and scalar field of gaseous flows.

GASEOUS PROCESSES

With the concern of the changing climate and the rise of pollutants in the air, precise and effective monitoring is needed to generate an efficient reduction in emission of greenhouse and hazardous gases in industrial production, transportation, and propulsion. Whether the gas sensing is involved in diffusion or transport, in either reactive or non-reactive flows, the applications are important to both scientific research and many fields of engineering.[1] The need for long-term and accurate monitoring apparatuses for gas processes is growing in the advancing technological world.

In the past few decades, the development of laser sensors and detection systems have pushed gas monitoring and sensing to extreme levels of accuracy and precision. Laser detection systems have the ability to obtain and collect data for gas states of temperature, concentration, pressure, and more by observing the interactions between gas molecules and laser photons. Often times, this is achieved by line-of-sight (LOS) setups where the laser beam passes through a specific area of gas or ambient air. There are many different techniques for acquiring the desired information of the gas states, and each of these methods are useful in their unique ways.

One of the most popular technologies is tunable diode laser absorption spectroscopy (TDLAS). TDLAS has been a practical method to study gaseous processes in environmental sensing and combustion diagnostics as its *in situ*, fast and highly quantitative measurement capabilities can be designed into a compact and simple optical setup.[1] Another interesting technique is a combined method of using both absorption spectroscopy (in TDLAS) as well as computed tomography to achieve one-dimensional (1D) to three-dimensional (3D) parameter measurements.[1]

PROBLEMS AND GOALS

TDLAS has been crucial for combustion research, however, the LOS nature of this technique also hinders its applications in non-uniform flames. Fortunately, when TDLAS is combined with computed tomography, a new technique is created: tomography absorption spectroscopy (TAS). A large variety of applications have benefited from TAS including creating two-dimensional (2D) imaging of temperature and H_2O concentration fields in aero-engines, measuring temperature and gas contributions in combustion hybrid rocket injectors, and creating 3D imaging of temperature and gas volumetric distributions of two laminar flames.[1] Although TAS has incredible potential in monitoring and detecting gaseous processes, it still has barriers to overcome.

Tomography requires regularized spectral reconstruction and a well-arranged setup of beam grid. When added to absorption spectroscopy, some reconstruction computations can aid in minimizing reconstruction errors. TAS can heavily depend on the selection of the absorption transitions. This transition selection will affect reliability and accuracy of the data collection during spectroscopy.[1]

Calibration is a critical factor for TAS in gaseous processes. There are many parameters that can influence the measurements: flow state (laminar or turbulent), species composition (single or multiple absorption species), and temperature (room or high temperature).[1] Once the influences of these complex conditions are determined, a new method of absorption spectroscopy for combustion diagnostics and other gaseous process applications can be discovered.

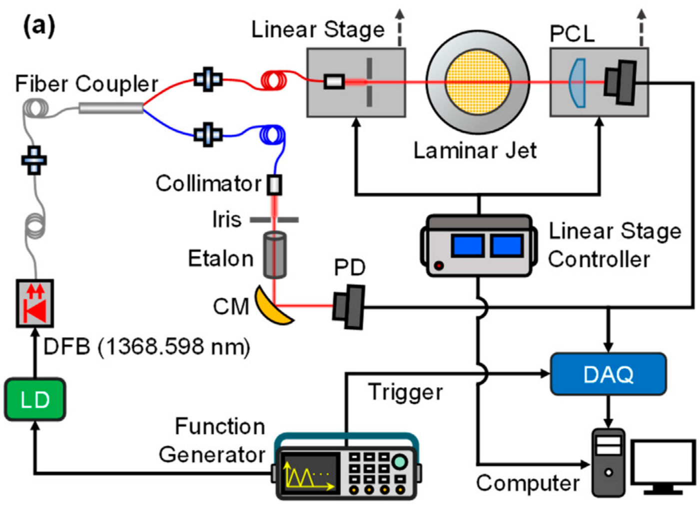

Figure 1. Schematic of the experimental setup: (a) optical system for the present study; (b) schematic of the nozzle and the optical setup. CM, concave mirror; DFB, distributed-feedback laser; LD, laser driver; PCL, plano-convex lens; PD, photodetector; DAQ, data acquisition.[1]

METHOD

Researchers from the School of Aeronautics and Astronautics in Chengdu, China and the Chinese University of Hong Kong have developed a jet flow, tomographic absorption spectroscopy (TAS) platform to study H_2O transport in a non-reactive jet flow with various conditions. In creating this experiment, the influences of these external conditions under a combustion environment can be clarified and recorded. Through this research, absorption spectroscopy can play a major role for combustion diagnostics.

There are a few crucial custom design aspects to this new TAS system. The first feature of the TAS setup is the custom laminar jet nozzle seen in **Figure 1**. With the absorption spectroscopy system setup (**Figure 1**), a portion of the laser beam is sent through the dry air injected from the nozzle at different heights above the nozzle to observe the absorption. The flow rate of the dry air, compared to ambient, is 60 L/min. The air flows through a honeycomb straightener and a smooth contraction nozzle to reduce any effects from non-uniform flow and boundary layer on the laminar jet.[1]

One of the biggest factors in this research is the choice of laser and center wavelength. Researchers used a near-infrared distributed-feedback (DFB) laser with a center wavelength of 1.3686 μm. The selection of this absorption transition line is a main concern for accurate and repeatable measurements. Simulated LOS absorption of different transitions were computed and plotted. Absorption lines around 7306.74 cm-1 and 7306.75 cm-1 dominated the contribution to the total absorption. These absorption lines, correlating to a wavelength around 1368.6 nm, were selected for studying H_2O transport in the laminar jet flow.

Another aspect to this developed system is the cross-validation performed by computational fluid dynamics (CFD) simulation. **Figure 2** shows the computational domain and boundary condition setups. Uniform velocity insets were determined for the dry air from the nozzle and the ambient air surrounding the nozzle. The respective set velocities are V_{air} = 0.3537 m/s and V_{amb} = 0.1 m/s with corresponding H_2O mole fractions set at 0.002 and 0.02889. This is why the air from the nozzle is considered "dry" compared to the ambient air. The CFD modeled the mass diffusivity of the H_2O transport model.

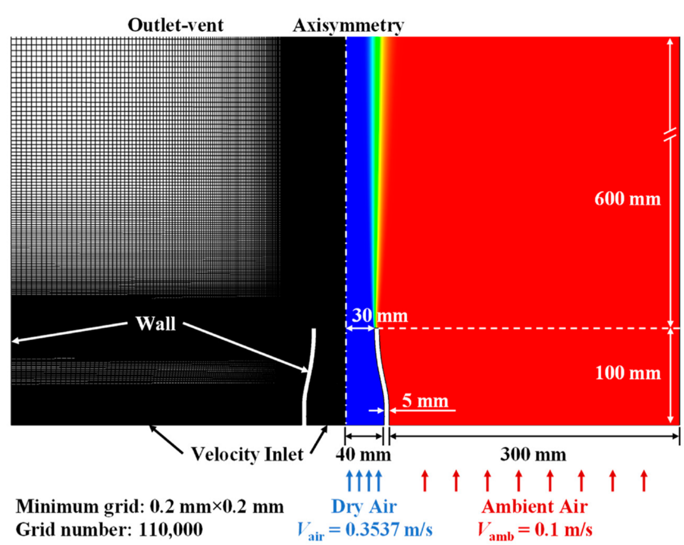

Figure 2. Numerical setup for the CFD simulation of the present laminar jet.[1]

TAS measurements were conducted at specific heights above the nozzle for around four minutes each. The measurements ranged from heights of 1 mm to 10 mm. The change in height, or the resolution, was 1 mm per absorption measurement. The complete TAS measurement took about 40 minutes in total. During the experiment, pressure and temperature were considered constant as any variations had minimal impact on the data collected. Uncertainty analysis of the measurements can be seen in the results section.

In this study, the H_2O molecules are used as the absorption indicator. By mapping and collecting H_2O mole fractions in and around the dry air flow, a new technique is created for scalar transport and mixing of flow fields for asymmetric or turbulent flow research.[1]

RESULTS

To ensure the axisymmetry of the laminar jet, the laser beam was moved from R = -42 mm to 42 mm to cover the ambient air as well as the air from the nozzle. This confirmed the laminar jet was not disturbed by the ambient during the absorption measurement. **Figure 3** shows the symmetric distribution of the LOS integrated absorbance, A_{int}, at different heights above the nozzle. Further steps were taken to reduce the uncertainty before the tomographic reconstruction. The A_{int} was averaged across both sides of the central axis and was smoothed to suppress the uncertainty.

Using the LOS integrated absorbance A_{int} measured equidistantly, the mole fraction of H_2O, X_{H2O}, can be reconstructed radially as displayed in **Figure 4**.[1] Water vapor concentrations for both the compressed air and ambient air were also measured. As seen in **Figure 4**, there were a few discrepancies in the shear layer of the laminar jet when comparing the reconstructed mole fraction and the CFD simulation values. When the height was increased from 1 mm to 9 mm, the variations in the X_{H2O} gradients within the shear layer of the laminar jet were correctly detected by the TAS measurements in **Figure 4**b,c.

The confirmed axisymmetry of the laminar jet as well as the overall reconstructed distributions of H_2O mole fraction at different heights align well with CFD simulation and theoretical measurements. The final step to complete the TAS measurements is combining the reconstruction at different heights to create a 2D contour of the H_2O mole fraction distribution. Both the CFD simulation and the TAS measurement of the 2D contour of H_2O mole fraction distribution are shown in **Figure 5**.

The TAS measurements are in relatively good agreement with the CFD simulation. Although the contour lines are not a 100% match and do not have exactly the same smooth curves, the overall 2D contour is similar enough to have further research potential. This shows that in the fields of mass transfer and scalar field of gaseous flows, tomography absorption spectroscopy has great potential. This would enable research to advance in complex reactive flows in applications of combustion and unsteady flow systems.[1]

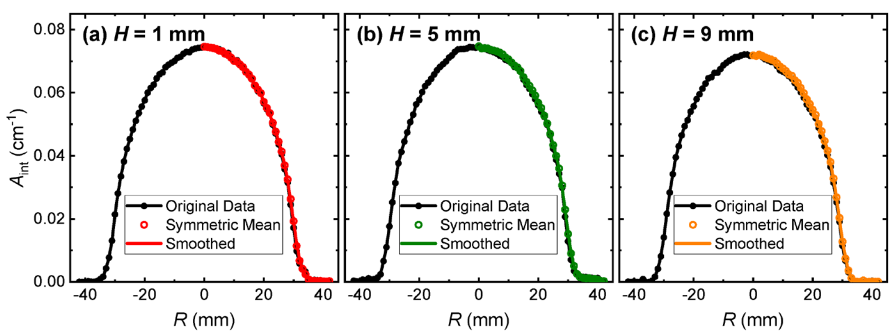

Figure 3. LOS integrated absorbance A_{int} at different heights above the nozzle.[1]

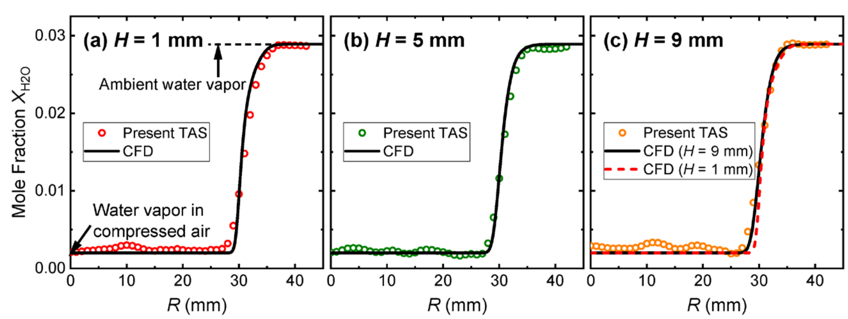

Figure 4. Reconstructed distributions of H_2O mole fraction X_{H2O} at different heights above the nozzle.[1]

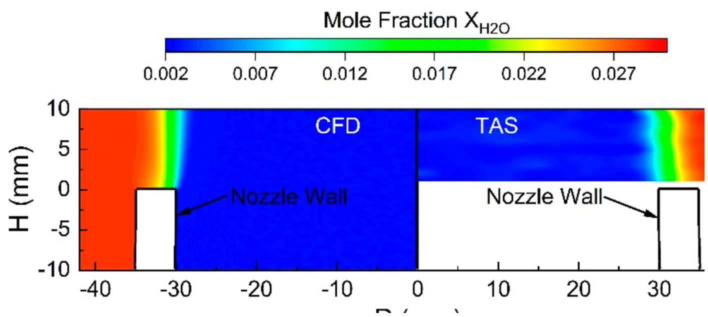

Figure 5. Two-dimensional contour of H_2O mole fraction distribution. Left, CFD simulation; right, present TAS measurement.[1]

The reconstruction used for the tomography portion in this research is highly sensitive to the error/noise in the integrated absorbance. Any slight fluctuation in the distribution along the radial direction leads to noticeable deviations in the final reconstruction. Obtaining A_{int} accounts for the majority of the uncertainty. In this research the uncertainty in A_{int} is estimated to be ±2.5%. 100 random tests were run at a height of 5 mm were ran with noise-perturbed A_{int} data. Other spectral parameters can contribute to the uncertainty. **Figure 6** shows the 95% confidence interval of the random tests and the ±2.5% uncertainty in linestrength in the shaded area. The uncertainty of the TAS measurement is relatively small at $\Delta X_{H2O} \approx \pm 0.0025$ when considering the ambient H_2O used as the absorbing species in the data collection at $X_{H2O} = 0.02889$.[1]

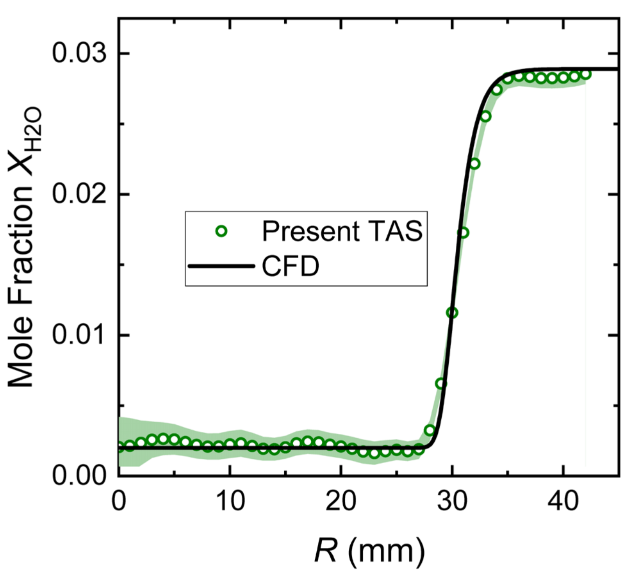

Figure 6. Uncertainty of the present TAS reconstructions of X_{H2O} (H = 5 mm) in the laminar jet.[1]

The combined methods of absorption spectroscopy and 2D tomography allowed researchers to reveal the H_2O transport in a non-reactive laminar jet. The water vapor in the ambient was used as the absorbing species in the TAS measurements, and results were well matched with CFD simulations. Mole fraction of H_2O was mapped in similar fashion to CFD 2D contour distribution, and the experimental data agreed with simulation data. The reconstruction uncertainty of ±0.0025 was considered reasonable and successful.[1] Although further improvements can be made to upgrade the TAS system, TAS has been proven to be a useful tool in the research of mass transfer and the scalar field of gaseous flows. Combustion diagnostics and other non-reactive jets can benefit from the developed TAS technology.

WAVELENGTH'S ROLE

A distributed-feedback (DFB) laser served as the TAS laser source for the investigation of H_2O transport in a dry laminar jet with TAS. The laser required stable current and temperature control in the precision setup. Wavelength Electronics' LDTC0520 laser diode and temperature controller provided the stable drive current and temperature control for the DFB laser with minimal noise and high temperature accuracy. This ensured minimal noise was added to the photodetector after TAS. The LDTC0520 provides up to 500 mA output current to the laser as well as up to ±2.2 A to the thermoelectric cooler or resistive heater.

With low noise of 7.5 µA RMS and current stability as low as 50 ppm at 25ºC for 1 hour, the LDTC0520 delivered constant current to the laser for constant center wavelength for the tomography absorption measurements. The precision temperature stability of the temperature controller at 0.005ºC at 25ºC for 1 hour also provided system stability.

The laser current was modulated with a triangle current scanning signal of 1 kHz using the LDTC0520. The bandwidth of the LDTC0520 can be as high as 500 kHz for a variety of applications. Both the laser driver and temperature controller portions of the LDTC0520 have special safety features and designs for optimal user setup and control.

The LDTC0520 driver and temperature controller enabled sensitive gaseous process characterization with low noise and stable current and temperature output. This makes the developed TAS system a reliable tool for exploring the effects of various conditions on practical applications of combustion and other gaseous processes.

REFERENCES

1. Cheong, K.-P.; Shi, D.; Liu, S.; Wu, J.; Duan, K.; Song, Y.; Ren, W. Tomographic Absorption Spectroscopy for H20 Transport in a Laminar Jet with Inverse Concentration Gradient. *Sensors* **2022**, 22, 5939. https://doi.org/10.3390/s22165939

USEFUL LINKS

- LDTC0520 **Product Page**

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PRODUCTS USED
LDTC0520

KEYWORDS
Tomographic absorption spectroscopy, TAS, tunable diode laser absorption spectroscopy, TDLAS, species transport, diffusion, laminar jet flow, LDTC, temperature controller, laser driver, H_2O, gaseous processes, computed tomography

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REVISION	DATE	NOTES
A	January 2023	Initial Release