

Measurements of water mole fractions using Laser-Induced Grating Spectroscopy in a turbulent duct flow

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ABSTRACT

The precise, non-intrusive determination of fluid properties in highly dynamic environments remains a key challenge in experimental fluid mechanics. This study utilizes Laser-Induced Grating Spectroscopy (LIGS), an optical technique that allows for spatially resolved, pointwise measurements of speed of sound, which subsequently allows for temperature determination in gas mixtures of known composition. Here, LIGS is deployed in a turbulent flow channel, marking the first application of this diagnostic technique in such an environment. By analyzing the signal composition, a correlation between the water mole fraction ψ and the amplitude ratio R , which comprises the thermal and electrostrictive signal contributions, was derived. While supplementary experimental data is missing for calibration, the current measurement framework needs to rely on supplementary sensors for temperature, pressure, and humidity. Turbulent flows inherently induce significant statistical signal fluctuations. Consequently, an in-situ calibration point in dry air was introduced to precisely determine the fringe spacing. This approach enabled the successful evaluation of the speed of sound, demonstrating good agreement with NIST reference data. However, pronounced variance in the experimental data currently precludes the reliable derivation of absolute temperatures from the speed of sound measurements. These limitations underscore the necessity for a reference calibration under controlled, stationary conditions. Establishing such well-defined boundary conditions will facilitate the derivation of a robust mapping function from R to ψ and enable accurate temperature calculations, ultimately closing the system of equations required to simultaneously retrieve the water mole fraction and temperature solely from the LIGS signal at a known pressure.

Motivation

Turbulent flows are ubiquitous in both natural phenomena and engineering applications and play a central role in processes governed by the transport of momentum, heat, and mass. Characterized by highly nonlinear, chaotic flow dynamics, turbulence manifests across a broad spectrum of spatial and temporal scales, from large, high-energy macroscopic vortices to microscopic dissipative structures. The experimental characterization of such highly dynamic environments presents

a significant metrological challenge. Traditional intrusive probes are often inadequate, because not only do their finite dimensions limit spatial resolution, but their physical presence inherently disturbs the sensitive flow field, that they are intended to measure.

The objective of the present study is therefore to investigate the feasibility of spatially resolved, pointwise measurements using Laser-Induced Grating Spectroscopy (LIGS) for non-intrusive, in-situ measurements of fluid dynamics. To this end, a flow channel was developed that enables the application of LIGS to determine the species concentration inside a turbulent two-phase flow. The strong potential of LIGS for measuring gas-phase properties such as temperature, pressure, velocity, and mixture composition has been demonstrated in combustion and flame environments [1, 2, 3], as well as for fuel concentration measurements in high-pressure reacting flows [4, 5]. In the present work, the LIGS technique is extended to a low-pressure turbulent flow environment. Although LIGS generally provides a high signal-to-noise ratio, its signal intensity scales with the local gas density [6], which makes measurements in low-density regions, such as turbulent channel flows, particularly challenging. Consequently, this study assesses the sensitivity and accuracy of the LIGS method for detecting small water vapor concentrations under these conditions.

Experimental Setup and Methods

Theoretical Background

Laser-Induced Grating Spectroscopy (LIGS) is a non-intrusive diagnostic technique that can be classified as a four-wave mixing method exploiting opto-acoustic and acousto-optic interactions [7]. During the excitation phase, two short-pulsed, linearly polarized laser beams of identical wavelength λ_{exc} are crossed at an angle Θ . Their interference within the intersection volume produces a spatially periodic intensity distribution, commonly referred to as a laser-induced grating. The spacing of the grating Λ , is determined according to

$$\Lambda = \frac{\lambda_{\text{exc}}}{2 \sin(\Theta/2)} \quad (1)$$

which defines the characteristic length scale of the induced modulation. The interaction of the fluid under investigation with the interference pattern gives rise to both non-resonant and resonant processes.

The non-resonant mechanism is driven by electrostriction and leads to Laser-Induced Electrostrictive Grating Scattering (LIEGS). Electrostriction describes the displacement of molecules in response to spatial gradients of the electric field, causing molecules to accumulate in regions of higher field intensity. This results in a localized pressure modulation, which relaxes by launching two counter-propagating acoustic waves. The superposition of these waves forms a temporally oscillating density grating [1].

In contrast, the resonant mechanism occurs when the excitation wavelength λ_{exc} coincides with an absorption transition of a molecular species present in the medium. In this case, Laser-Induced Thermal Grating Scattering (LITGS) is generated. Energy absorption followed by collisional quenching produces localized heating, giving rise to spatially periodic temperature and density variations. This thermal grating persists in addition to the counter-propagating acoustic waves induced by the associated density and pressure wave. The latter are normally orders of magnitude weaker than the thermal grating and require much higher energy pulses (more than 100 mJ) to generate detectable scattered signals [1].

The induced density and thermal gratings are interrogated using a continuous-wave (CW) probe laser, which is aligned at the appropriate Bragg angle. Scattering of the probe beam occurs only when the phase-matching condition is fulfilled, resulting in constructive interference from successive grating planes and producing a coherent, highly directional signal beam. The temporal oscillation of the detected LIGS signal provides direct access to the acoustic response of the fluid. Specifically, the oscillation frequency of the signal corresponds to the propagation frequency of the induced acoustic waves. In quiescent gases, these waves propagate at the local speed of sound c_s , yielding the fundamental LIGS frequency relation

$$f = n \frac{c_s}{\Lambda} \quad (2)$$

where $n = 1$ for thermal gratings (LITGS), and $n = 2$ for electrostrictive gratings (LIEGS) [8]. Once the oscillation frequency is determined via Fourier analysis, the local speed of sound can directly be obtained. Since the signal amplitude of the thermal grating depends on resonant absorption and subsequent collisional quenching, its strength contains information about the local absorption coefficient and thus the molar fraction of the absorbing species.

The preceding theoretical considerations provide the framework for quantifying water vapor concentration in turbulent boundary layers. This approach relies on the simultaneous acquisition of LIEGS and LITGS measurements, facilitated by high-energy laser pulses that generate electrostrictive and resonant signals of comparable magnitude. At specific given pressure and temperature conditions, the water vapor concentration is determined by normalizing the LITGS signal amplitude against the LIEGS reference intensity.

Experimental Setup

For this study, a turbulent flow channel has been developed that enables precise control of the flow temperature, pressure, and mass flow rate, thereby providing well-defined boundary conditions within the channel. The water content of the flow is regulated by an upstream evaporator and accurately quantified using multiple humidity sensors located in the vicinity of the laser measurement volume. The water mole fraction ψ is defined as the molar ratio of water vapor to the

total gas mixture. A schematic of the optical LIGS measurement setup around the flow channel is shown in Figure 1. The optical interference pattern is generated by two short-pulsed excitation

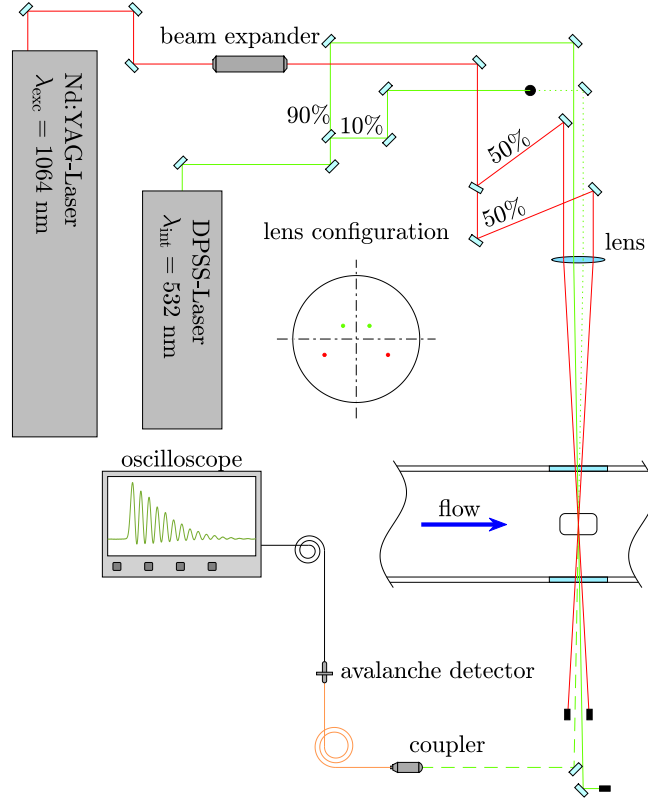


Figure 1. Optical setup of the LIGS measurement system.

laser beams emitted by a Nd:YAG laser operating at an excitation wavelength of $\lambda_{exc} = 1064 \text{ nm}$ and a pulse frequency of 20 Hz. To interrogate the induced density modulation, a continuous-wave diode-pumped solid-state (DPSS) laser with a wavelength of $\lambda_{int} = 532 \text{ nm}$ is employed. To tailor the region of highest excitation intensity, a beam expander is incorporated into the excitation beam path. The side walls of the flow channel are manufactured from quartz glass to ensure optical access with a uniform refractive index. All laser beams are crossed and focused into the measurement volume using an anti-reflection-coated lens. Within this volume, the interrogation beam is scattered by the spatially periodic perturbations generated by the excitation process.

The scattered signal is subsequently spectrally and spatially filtered using a fiber coupler with an integrated multimode fiber. Detection of the signal beam is accomplished with an avalanche photodiode, and the resulting voltage signal is recorded at a sampling rate of 20 GS/s using a digital oscilloscope.

Signal Processing

As described above, LIGS signals originate from the scattering of the interrogation beam by the laser-induced grating, resulting in an oscillatory signal whose frequency is determined by the temporal modulation of the density grating. As a result, the measured LIGS signal is composed of a superposition of electrostrictive and thermal contributions.

The extraction of macroscopic fluid properties, such as the local speed of sound, through curve fitting and Fourier analysis requires LIGS signals with a high signal-to-noise ratio in both the temporal and frequency domains. To ensure sufficient signal quality, all recorded signals are filtered in the time and frequency domains. Signals with insufficient amplitude or detector saturation are excluded from further analysis.

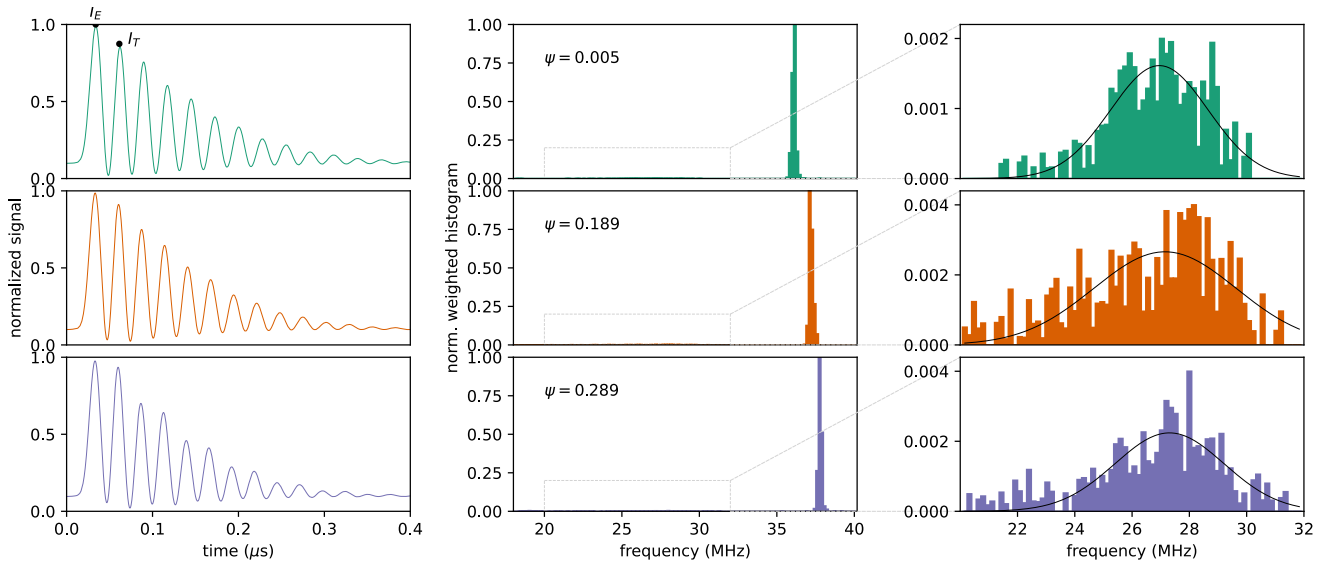


Figure 2. Normalized LIGS signals for defined water vapor conditions in time and frequency domain.

Both the electrostrictive and thermal contributions to the LIGS signal are visible in Figure 2 in the time domain on the left. Because the electrostrictive contribution oscillates at twice the frequency of the thermal component, the first intensity peak in the temporal LIGS signal is attributed to the electrostrictive component (I_E), while every second peak corresponds to the thermal component (I_T). The electrostrictive signal component dominates the thermal one, rendering it clearly discernible in the frequency domain. Conversely, the thermal contribution is only detectable under significant magnification, as illustrated in the third column of Figure 2. Because water vapor absorbs the excitation laser radiation, it acts as the primary driver for the resonant thermal grating at the measurement location. Consequently, variations in the water vapor content directly modulate the amplitude of the thermal signal component. Nevertheless, because the underlying flow is highly turbulent, the thermal signal undergoes stochastic fluctuations and is therefore approximated through a Gaussian fitting function.

Following the approach described in [1], the ratio of the thermal to electrostrictive peak amplitudes provides a measure of the resonant absorption and thus serves as an indicator of the local water vapor concentration. Accordingly, the peak amplitude ratio $R = I_T / I_E$ is expected to scale linearly with the water mole fraction ψ .

However, in order to transition from relative signal intensities to absolute concentration values, the implementation of a rigorous reference calibration measurement is indispensable. To address this methodological requirement, the development and validation of a dedicated calibration framework are currently underway, with completion and implementation expected in the near future.

Results and Discussion

Multiple LIGS measurements were performed using the previously described experimental setup under controlled, statistically stationary conditions while varying the water mole fraction in the flow. Each measurement point consists of 1000 individual LIGS signals recorded at identical boundary conditions to ensure sufficient statistical convergence.

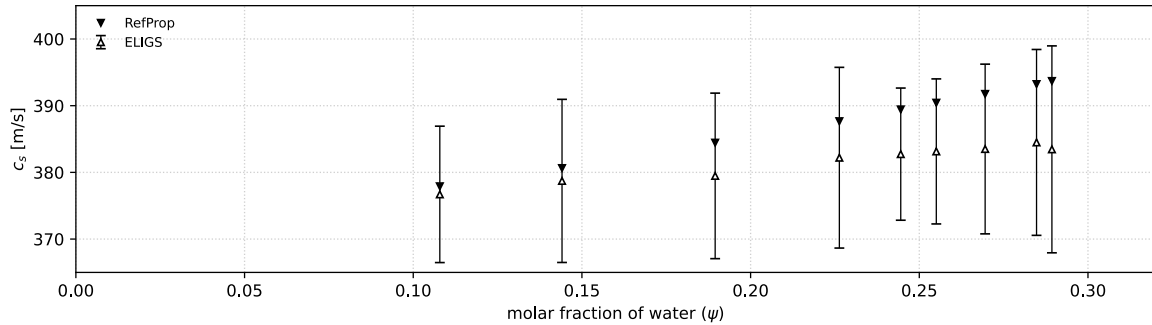


Figure 3. Speed of sound in air at elevated water mole fractions: LIGS measurements in comparison to the NIST standard reference database.

A reference measurement using dry air at a known temperature and pressure was conducted to calibrate the fringe spacing Λ , which is required for the determination of the speed of sound. Through this procedure, the fringe spacing for the aforementioned experimental setup was found to be $\Lambda = 2.066 \cdot 10^{-5}$ m.

To verify the validity of the measurement approach in the presence of water vapor under turbulent flow conditions, the local speed of sound was extracted from the electrostrictive signal component using Equation (2). It was then compared with reference values for the speed of sound obtained from the RefProp program using boundary conditions determined by additional sensors in the duct.

The results of this comparison are shown in Figure 3. For low water mole fractions, the measured speed of sound agrees very well with the database. With increasing water content, the measurements show an underestimation of the speed of sound, though this deviation remains within the statistical uncertainty bounds of the evaluated signals.

The fundamental ability to extract the speed of sound from the acquired signals demonstrates that the turbulent flow field does not disrupt the laser-induced grating. However, given that LIGS inherently provides highly accurate speed of sound measurements, the pronounced deviations observed in the current setup strongly indicate the presence of underlying systematic bias. One primary source of this discrepancy is likely the uncertainty associated with the injected water vapor mass flow, leading to an imprecise local mixture composition. Furthermore, while the single-point calibration framework is essential for determining the initial fringe spacing, it introduces a critical sensitivity to the accuracy of this specific reference state. Any uncertainty at this calibration point directly propagates through the evaluation, potentially inducing a systematic bias affecting the entire measurement.

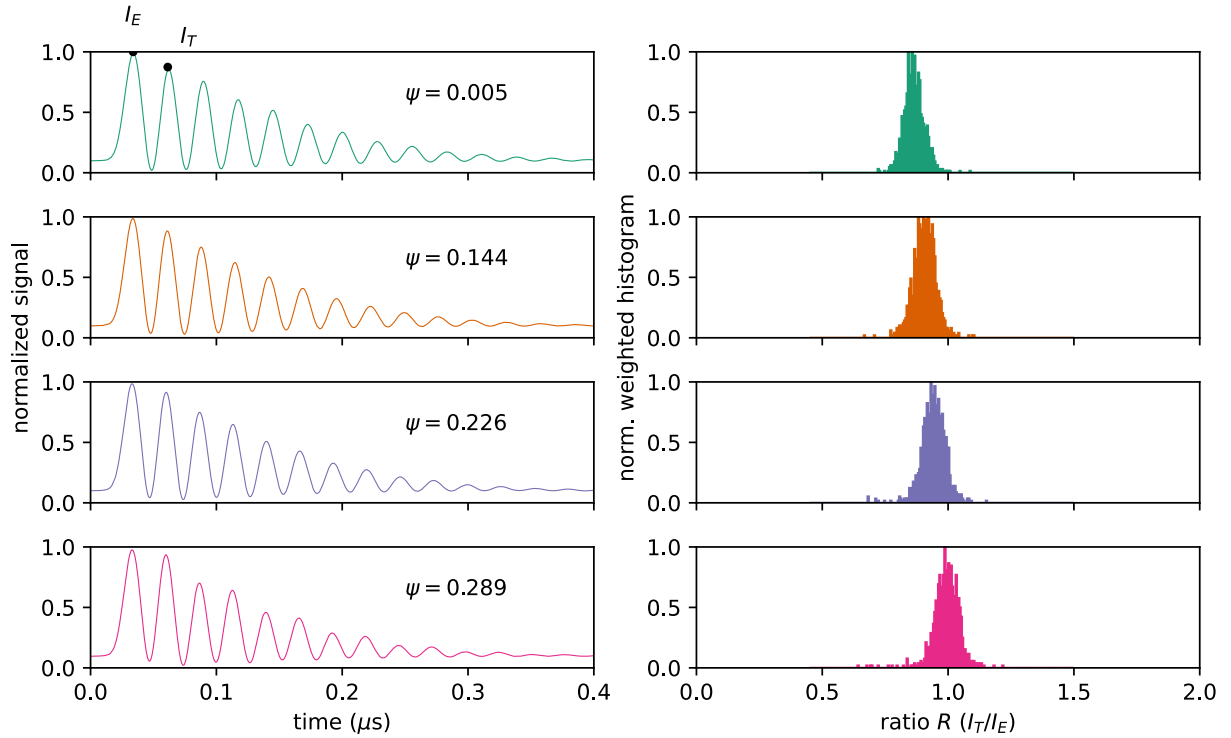


Figure 4. Intensity ratios of thermal and electrostrictive signals. Histograms of multiple measurement results statistically show distribution of the ratio R .

The ratio R of the thermal peak amplitude to the electrostrictive peak amplitude was determined for each individual LIGS signal at different water content levels. Figure 4 shows representative averaged signals and the corresponding ratios for four selected water mole fractions. The influence of water vapor on the signal composition is clearly evident, which is consistent with the assumptions

reported by De Domenico et al. [1]. To further support this observation, the averaged amplitude ratios R obtained from all measurements were plotted in Figure 5 as a function of the imposed water mole fraction, measured by humidity sensors. A proportional dependence of R on the water mole fraction ψ is observed.

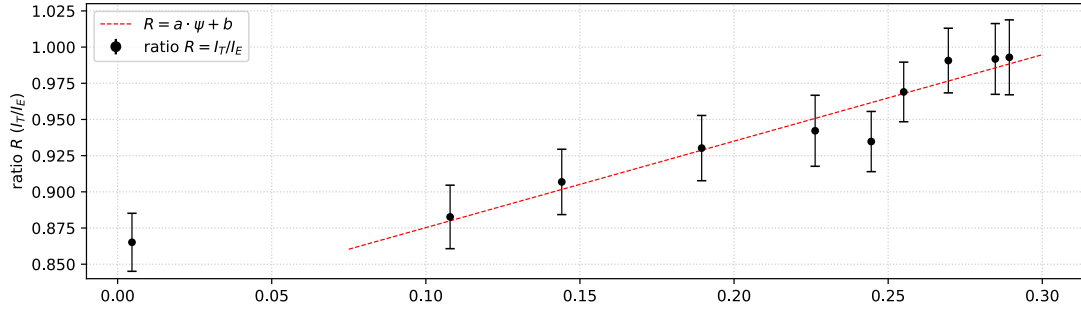


Figure 5. Calibration results. A linear trend between the measured ratio R dependent on water mole fraction ψ in the flow channel is observed.

The electrostrictive component of the Laser-Induced Grating Spectroscopy (LIGS) signal is directly proportional to the pump laser energy. In contrast, the thermal component scales linearly with the product of the pump energy and the local water mole fraction ψ . Consequently, the signal amplitude ratio R exhibits a linear dependency on the moisture content, which can be modeled as

$$R = a \cdot \psi + b \quad (3)$$

A linear regression utilizing a weighted least-squares (WLS) algorithm was applied to the experimental data acquired from the turbulent flow channel. The first data point is excluded because it corresponds to the calibration point in dry air. The regression yields the calibration coefficients $a = 0.597$ and $b = 0.816$. Since these parameters naturally depend on the local temperature and pressure, they apply exclusively to the specific thermodynamic state examined here. Once properly calibrated, Equation (3) can be inverted to determine the water mole fraction directly from the measured signal ratio R .

It must be noted, however, that the present low-pressure and low-temperature conditions result in significantly lower thermal signal intensities at low water vapor concentrations compared to typical combustion environments and thereby impose high requirements on the measurement equipment and add to the complexity of data analysis. This reduction in signal-to-noise ratio inherently increases the relative uncertainty of the amplitude ratio, leading to a larger experimental scatter in R . The observed deviations from a strictly linear correlation can be attributed to transient effects induced by the flow conditioning hardware, as well as to localized thermodynamic fluctuations within the duct. Additionally, the inherent turbulence within the duct flow prevents a uniform distribution across the channel geometry. This non-uniformity results in spatial discrepancies between the localized sensor positions and the actual LIGS measurement volume.

The humidity sensors, in particular, are prone to errors, and when combined with inaccuracies in the evaporator, the sensors in the duct are not precise enough to allow for reliable calibration. These phenomena will be the subject of future investigations.

Despite these limitations, estimating the water mole fraction via a linear fit would yield a mean absolute deviation of 0.0132 at the nominal operating condition, corresponding to a mean relative error of 5.78%.

In principle, combining the measured water mole fraction with the local speed of sound at a known static pressure allows for the implicit reconstruction of the fluid temperature. Consequently, this diagnostic approach theoretically enables the simultaneous, non-intrusive measurement of both species concentration and temperature. However, because an absolute a priori calibration was not performed for the present campaign, the accumulated uncertainties and deviations from the nominal boundary conditions preclude a reliable temperature retrieval at this stage. With access to a comprehensive calibration database, it becomes feasible to simultaneously determine the temperature and water mole fraction by iteratively solving the interdependent equations for the speed of sound and signal composition. Nevertheless, extracting the temperature analytically from the speed of sound demonstrates a high sensitivity to the velocity measurement itself. Consequently, a rigorous calibration, is imperative. Although this calibration substantially reduces the systematic bias, standard uncertainty propagation must still be thoroughly evaluated.

Despite these limitations, the results demonstrate that LIGS is capable of providing spatially resolved, pointwise measurements of the water mole fraction in a turbulent flow. While the measurement uncertainty remains relatively high under the investigated conditions, the fundamental feasibility of the method is clearly confirmed.

Conclusion

In this study, Laser-Induced Grating Spectroscopy (LIGS) was applied in a turbulent flow channel to investigate water vapor concentration under controlled boundary conditions. To the authors' knowledge, this work represents the first application of LIGS in a turbulent channel flow, which involves considerable experimental challenges due to the reduced gas density and correspondingly low thermal signal intensity. Despite these limitations, stable and reproducible LIGS signals were obtained, enabling a systematic evaluation of the feasibility of the method under such conditions.

The electrostrictive component of the LIGS signal was successfully used to extract the local speed of sound, showing good agreement to the NIST standard reference database over a wide range of water mole fractions. Deviations observed at higher water vapor contents remained within the statistical uncertainty and are attributed to fluctuations in the upstream evaporation process and flow conditioning hardware.

By analyzing the relative contributions of the thermal and electrostrictive signal components, a clear dependency of the peak amplitude ratio on the water mole fraction was demonstrated. This confirms that LIGS can be employed for pointwise, non-intrusive measurements of water vapor concentration in turbulent flows. Although the low-pressure and low-temperature conditions investigated here lead to comparatively large relative uncertainties, the observed linear trend and reproducibility confirm the fundamental suitability of the method. While extracting the temperature is methodologically feasible, it is currently prevented by the absence of precise calibration data.

The demonstrated capability to non-intrusively measure water vapor concentration in a turbulent flow provides a valuable diagnostic tool for future studies of fluid injection and mixing mechanisms, such as boundary layer interactions or specific transpiration cooling applications.

Outlook

As detailed previously, the data recorded within the turbulent flow channel are inherently subject to statistical fluctuations arising from the nature of turbulent fluid dynamics. To mitigate these effects and transition the present methodology from a foundational feasibility study to a robust tool for absolute quantification, a supplementary measurement campaign within a stationary, precisely defined environment is required.

Consequently, a specialized pressure chamber is currently under development. This setup will establish a rigorous calibration framework under strictly regulated boundary conditions, specifically controlling temperature, pressure, and humidity. This supplementary experimental database will further enable a direct calibration of the fringe spacing Λ , which is indispensable for the accurate determination of the speed of sound. It should however be emphasized that this calibration is intrinsically tied to the specific optical arrangement. Therefore, any modifications to the experimental setup will necessitate a renewed calibration procedure.

Furthermore, achieving such precisely defined baseline conditions will unlock the potential to additionally extract the temperature value for a known pressure. To completely circumvent the reliance on supplementary sensors for the simultaneous retrieval of temperature and water mole fraction, an iterative solver for a system of coupled equations will be employed.

Ultimately, the successful validation of this quantitative framework will pave the way for the technique's practical application in advanced aerodynamic scenarios, prominently including boundary layer investigations and turbulent two-phase flows. The complex, highly dynamic mixing processes between two phases present an ideal use case for this non-intrusive diagnostic tool, driving ongoing efforts to mature the LIGS methodology for robust operational deployment.

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Nomenclature

a	regresseion parameter	[-]
b	regresseion parameter	[-]
I_T	thermal intensity peak	[-]
I_E	electrostrictive intensity peak	[-]
R	peak amplitude ratio	[-]
f	frequency	[1/s]
c_s	speed of sound	[m/s]
Θ	Bragg angle	[-]
ψ	water mole fraction	[-]
Λ	fringe spacing	[m]
λ_{exc}	excitation wavelength	[m]
λ_{int}	interrogation wavelength	[m]

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