CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 440

Fuel slip monitoring in high-humidity flue gases from co-firing of ammonia with methane

Controls, Automation, Measurement, Monitoring & Predictive Maintenance

Liuhao Ma, Wuhan University of Technology

Hao Wang, Wuhan University of Technology
Wei Wang, Wuhan University of Technology
Yu Wang, Wuhan University of Technology

ABSTRACT

Ammonia (NH3) has been recently recognized as promising carbon-free future fuel towards decarbonizing both the power and industrial heating sectors. The past five years have seen rapid development and demonstration in co-firing of ammonia with methane for applications in engines, gas turbines, thermal power plants and industrial furnaces. However, fuel slip is of high concern because of the low reactivity and high toxicity of NH3 and strong greenhouse effect of CH4, motivating the development of sensitive sensor for real-time monitoring of fuel emissions in combustion flue gases. In this work, a near-infrared absorption spectroscopic sensor was developed for trace NH3 and CH4 measurements in high-temperature flue gas environments with water vapor (H2O) concentration as high as 50% (mole fraction), which is particularly suitable for monitoring fuel slip in ammonia-methane combustion system. The sensor used a distributed feedback (DFB) laser to target the NH3 absorption line near 6612.73 cm-1 and CH4 near 6046.95 cm-1. Proof-of-concept tests were conducted in a high-temperature multi-pass cell with a controlled temperature of 500 K and pressure of 1 atm. A custom-designed variable humidity generator was used to provide reference NH3/CH4/N2 mixture with controlled H2O concentration (10%-40%) to simulate combustion flue gases. Direct absorption spectroscopy (DAS) and wavelength modulation spectroscopy (WMS) were both used to ensure a relatively large dynamic range. H2O-induced broadening effects on the measured absorption profile were quantified. The developed sensor was firstly validated against NH3/CH4/N2 mixtures with different H2O concentrations with a lower detection limit of 0.1 ppm achieved. Real-time measurement of fuel slip in the flue gases from CH4/NH3/air flames were performed as a demonstration of the sensor for time-resolved fuel monitoring with sufficient accuracy, sensitivity, and time response.

1. Introduction

Laser spectroscopic techniques offer significant advantages, such as high sensitivity, selectivity, rapid response, and excellent quantification capabilities, and have been widely applied in environmental monitoring, hazardous chemical identification, combustion diagnostics, and pollutant emission analysis [1–4]. With the “carbon peak and carbon neutrality” strategy now incorporated into the overall framework of ecological civilization, the energy sector faces unprecedented challenges, making the deep decarbonization of conventional energy systems a critical task across various industries. Recent fundamental research and engineering practice have demonstrated that blending methane with ammonia to form a dual-fuel mixture can reduce CO_2 emissions during combustion while compensating for the poor flammability and flame stability of pure ammonia fuels. However, incomplete mixing of the dual fuel with air may result in suboptimal combustion dynamics and local flame extinction, thereby exacerbating the issue of trace-level fuel leakage. Moreover, excessive ammonia injection in denitrification systems further aggravates ammonia slip. Large-scale emissions of ammonia (NH_3) can cause soil alkalization and water eutrophication, and as an alkaline gas, NH_3 readily reacts with atmospheric nitrogen oxides to form aerosols that are directly associated with $PM_{2.5}$ pollution [5]. Additionally, methane (CH_4), a typical greenhouse gas, exerts a significant impact on global climate change. Therefore, strict regulation of trace fuel leakage during dual-fuel combustion is imperative to ensure compliance with environmental standards, and precise detection of such leakage is critical for evaluating combustion efficiency.

In response to the need for high-sensitivity detection of trace methane and ammonia at elevated temperatures, several mature and reliable spectroscopic gas detection techniques have been developed, including non-dispersive infrared/ultraviolet (NDIR/NDUV) methods, Fourier transform infrared (FTIR) spectroscopy, and laser absorption spectroscopy (LAS). The NDIR technique [6] deduces target gas concentrations by analyzing the broadband infrared absorption spectra of gas molecules. This method is relatively cost-effective and can be applied to various gases exhibiting infrared absorption features. However, the presence of water vapor interference significantly degrades measurement accuracy when detecting trace ammonia. FTIR spectroscopy [7], combined with heated high-temperature gas cells, enables rapid analysis of trace gases. Although FTIR offers improved performance compared to NDIR, water vapor spectral interference remains a challenge, and the bulky, high-cost instrumentation limits its applicability. Non-dispersive ultraviolet (NDUV) techniques [8] address water interference by shifting measurements into the ultraviolet spectral region, where water vapor absorption is negligible; however, under harsh conditions, fluctuations in UV light intensity can compromise measurement accuracy. It is also noteworthy that moisture removal by condensation—a common practice in commercial gas analyzers—is not feasible for ammonia measurements due to its high solubility in water. Furthermore, most of these sensor technologies require frequent calibration, a process that can be cumbersome for continuous flue gas monitoring. In addition to spectral cross-interference from water vapor, high water vapor concentrations can induce significant broadening of methane and ammonia absorption lines, thereby reducing measurement accuracy and reliability [9].

Over the past several decades, laser absorption spectroscopy (LAS) has attracted extensive attention in the field of trace gas detection due to its high sensitivity, rapid response, robustness, accuracy, compactness, and selectivity [10]. Frequency division multiplexing (FDM) technology enables the simultaneous coupling of multiple lasers at distinct wavelengths, permitting individual modulation and demodulation of each laser signal

while preserving temporal resolution. When combined with LAS, this approach facilitates rapid and precise quantification of multi-component gas concentrations. High-temperature trace methane and ammonia detection systems based on LAS have been successfully demonstrated in various experimental and industrial applications. Notably, Ma et al. [9] were the first to design a sensor capable of measuring trace NH_3 concentrations in high-temperature, high-humidity environments, systematically investigating the influence of water vapor concentration near 1512 nm on NH_3 absorption and achieving accurate detection of ammonia slip under humid conditions. Duan et al. [11] developed a calibration-free wavelength modulation spectroscopy-based sensor for simultaneous NO and NH_3 detection, attaining low detection limits for both species. Guo et al. [12] utilized time division multiplexing to couple multiple lasers, enabling concurrent detection of NH_3, NO, and temperature, and later introduced a machine learning approach to denoise the absorption signals and improve the signal-to-noise ratio [13]. Li et al. [14] used a single laser covering NH_3 absorption at 6612.73 cm^{-1} and H_2O absorption at 6612.03 cm^{-1} and 6609.85 cm^{-1} to simultaneously measure ammonia, temperature, and water vapor concentration. Guo et al. [15] also developed a portable integrated NH_3 sensor, with quantitative analysis indicating that ammonia adsorption is significantly suppressed at temperatures of 415 K or higher, thereby enhancing sensing accuracy at elevated temperatures. These studies demonstrate that while wavelength modulation spectroscopy has been widely applied in high-temperature or multi-species and multi-parameter sensing, research on multi-species detection under high-temperature and high-humidity conditions remains relatively scarce.

In the present study, we combine frequency division multiplexing with normalized wavelength modulation spectroscopy to couple two lasers with central wavelengths of 1512 nm and 1654 nm, thereby developing a synchronous measurement system for NH_3 and CH_4 under high-temperature, high-humidity conditions. This system is specifically designed for the quantitative detection of trace NH_3 and CH_4 in humid flue gas environments. A multi-line fitting method is employed to accurately determine water vapor concentration. By designing a mixed gas system that simulates trace-level methane and ammonia under high water vapor backgrounds, we obtained harmonic signals for NH_3/CH_4 in the concentration range of 1ppm to 100ppm within water vapor concentrations ranging from 10% to 50%, thereby quantifying the influence of water vapor on the harmonic signals. Furthermore, the reliability of the system was verified by comparing the FDM-based measurement results with those obtained from single-channel measurements. The detection system exhibits excellent linearity for trace dual-fuel concentrations between 1ppm and 100ppm, with detection limits of 82ppb for CH_4 at an integration time of 92 s and 88ppb for NH_3 at an integration time of 40 s.

2. Experimental system

2.1 Optimal selection of absorption lines

For achieving high-sensitivity detection of the target gases, the careful selection of appropriate absorption lines is of paramount importance. In the context of trace dual-fuel leakage during methane-doped ammonia combustion, it is essential first to avoid spectral interference from the primary combustion products (namely, water vapor (H_2O) and carbon dioxide (CO_2)) as well as from pollutants (such as carbon monoxide (CO) and nitric oxide (NO)). Secondly, sufficiently strong absorption lines must be selected to enable high-sensitivity detection. Although the fundamental absorption bands in the mid-infrared offer robust absorption features, the associated interband cascade lasers, quantum cascade lasers, and their respective controllers and photodetectors are prohibitively expensive, limiting their scalability for online industrial flue gas monitoring. In contrast, advancements in optical communication

technology have led to the maturity of near-infrared lasers and detectors. When combined with fiber-delivered light and compact multipass gas absorption cells, these systems can achieve high-sensitivity detection at a significantly lower cost.

Figure 1(a) illustrates the spectral line intensity distributions of NH_3 and CH_4, along with those of H_2O, CO, CO_2, and NO, within the 1–3 μm wavelength range at 473.15 K. It is evident that NH_3 and CH_4 exhibit excellent spectral isolation from the other gas components within the 1.5–1.7 μm range. Based on spectral analysis, the absorption lines for NH_3 and CH_4 at 6612.73 cm^{-1} and 6046.95 cm^{-1}, respectively, were selected because the spectral features of these target species in the vicinity of these wavenumbers are minimally affected by interference from CO, CO_2, and NO. Figure 1(b) and 1(c) demonstrate that as the H_2O concentration increases from 10% to 50%, the spectral analysis of NH_3 becomes increasingly challenging due to water vapor interference, thereby complicating the measurement of NH_3 concentration. In contrast, the CH_4 absorption features near 1.65 μm are less susceptible to the influence of H_2O. It is noteworthy that our previous spectral simulation studies revealed that even the widely used mid-infrared NH_3 absorption lines cannot fully mitigate the effects of high water vapor interference [15]. Although the absorption characteristics of NH_3 are affected by water vapor, employing a 1512 nm laser to simultaneously scan the absorption lines of H_2O and NH_3 enables the assessment of interference by quantifying the H_2O concentration, thus facilitating sensor performance optimization. Consequently, the absorption lines at 6046.95 cm^{-1} and 6612.73 cm^{-1} were ultimately chosen for the detection of CH_4 and NH_3, respectively.

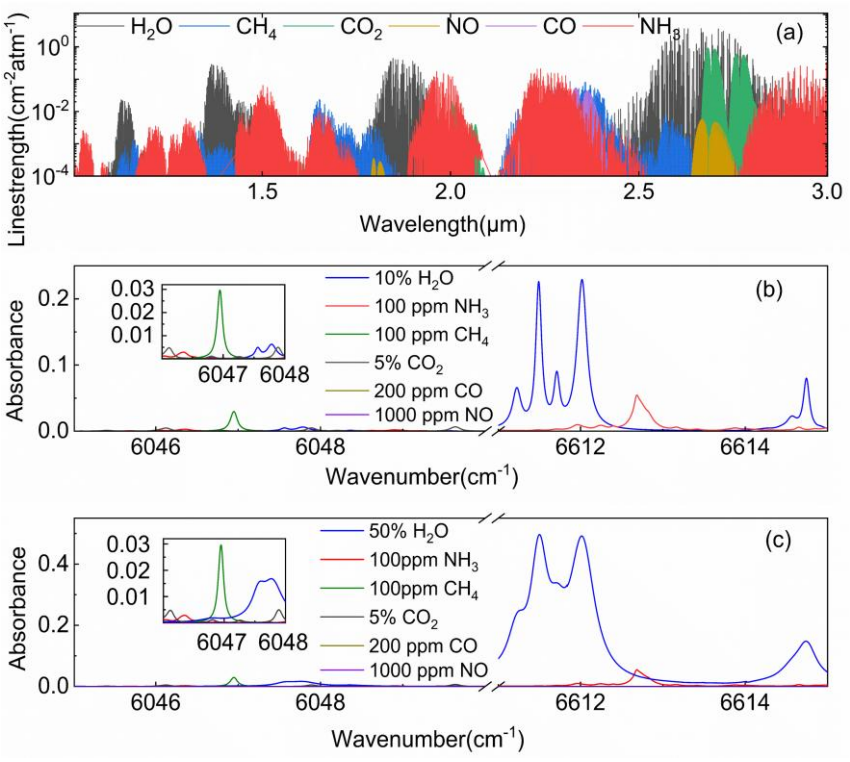

Figure 1. (a) Line intensities of NH_3, CH_4, CO_2, NO, CO and H_2O in 1-3μm; (b-c) Simulated absorbance of 10% H_2O and 50% H_2O, 100 ppm NH_3 and 100 ppm CH_4 at 473 K based on Hitran2020 database

2.2 Optical setup

Figure 2 illustrates the experimental system for high-humidity trace dual-fuel measurements, which comprises two primary subsystems: a high-humidity trace mixed-gas configuration module (left dashed box) and a laser absorption

spectroscopy measurement module (right dashed box). Experiments were conducted at atmospheric pressure, and precise target gas concentrations were achieved by finely adjusting the mass flow controllers (D07, Qixing Huachuang) to regulate the flow rates of trace CH_4/N_2 standard gas, trace NH_3/N_2 standard gas, and N_2. Nitrogen was supplied in two separate streams: one served as the carrier gas to the nebulizer (TR-50-K2, Meinhard) for atomizing distilled water delivered via an injection pump (LSP01-3A, Longer), while the other acted as a diluent to establish a high-humidity background (with H_2O concentrations ranging from 10% to 50%) for mixing the target gases at trace levels (1ppm–100ppm). To prevent condensation of the nebulized water vapor—which could dissolve ammonia—a high-temperature heating tape was wrapped around the gas delivery lines, and both the high-temperature gas cell and the heating tape were maintained at 473 K to ensure complete vaporization of the distilled water. Under these conditions, water and ammonia remain in the gaseous state, and the mixture of trace ammonia, water vapor, and nitrogen does not form ammonium hydroxide, thereby eliminating potential interference in the detection of trace NH_3.

To achieve synchronous measurements of H_2O, trace CH_4, and NH_3 under high-humidity conditions, two lasers with central wavelengths of 1512 nm and 1654 nm (EP1512-DM-B06-FA and EP1654-DM-B06-FA, Eblana) were employed. These lasers cover the spectral features of H_2O at 6612.03 cm^{-1}, NH_3 at 6612.73 cm^{-1}, and CH_4 at 6046.95 cm^{-1}, respectively. The temperature and injection current of the lasers were precisely controlled using low-noise commercial laser controllers (LDTC5020 and M01). A LabVIEW-based program was utilized to generate the required modulation signals for both direct absorption spectroscopy (DAS) and wavelength modulation spectroscopy (WMS); this program superimposed sine-wave modulation onto a triangular scanning signal. In the experiments, both lasers were modulated with a 10 Hz triangular scan, while sine-wave modulation signals at 15 kHz and 11 kHz were applied to the 1512 nm and 1654 nm lasers, respectively, to facilitate subsequent signal demodulation. The two laser beams were combined via a fiber beam combiner (HJFT-FBT, Hangjia Optoelectronics) and directed into a high-temperature, multipass White-type gas cell. Within the gas cell, multiple reflections yielded an effective absorption path length of 1800 cm. Upon exiting the cell, the laser beam was focused by a convex lens onto the active area of an indium gallium arsenide photodetector (PDA20CS2, Thorlabs), and the resulting signal was transmitted via a BNC cable to a data acquisition card (USB6363, NI). Additionally, to mitigate NH_3 adsorption on the cell walls, the interior of the high-temperature gas cell was coated with polytetrafluoroethylene, and measurements were conducted under continuous flow conditions. The core hardware of the experimental system—including the 16-bit data acquisition card, high-precision laser controllers, and low-noise photodetectors—is of high quality, effectively preventing data degradation due to hardware limitations.

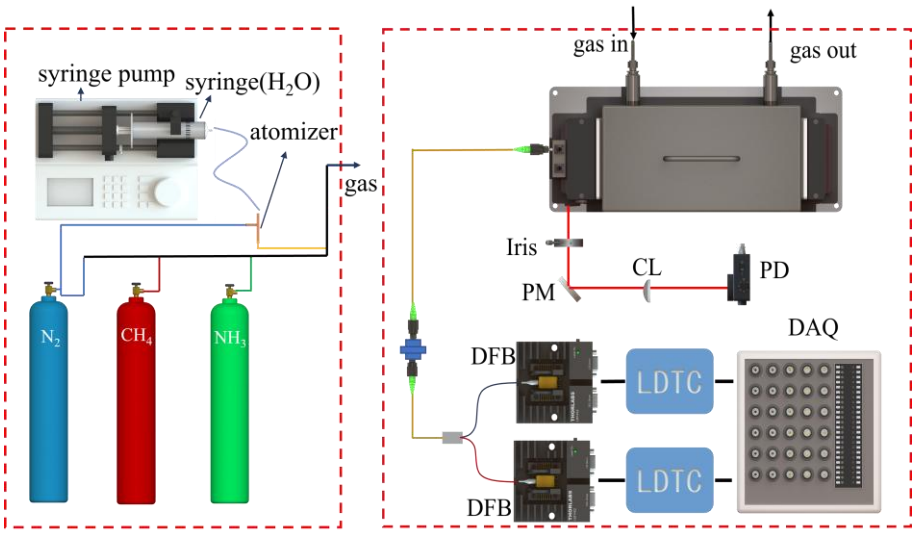

Figure 2. Experimental system for trace NH_3/CH_4 measurements under high-temperature, high-humidity conditions

3. Results and discussions

3.1 Measurement of Water Vapor Concentration in a High-Humidity Environment

In this study, the accurate configuration of a high-humidity environment is essential for sensor development, validation, and calibration. The required injection pump feed rate for generating the high-temperature, high-humidity gas mixture was determined based on mass conservation principles and the ideal gas law [15]. The configuration procedure is as follows:

First, the total gas flow rate at high temperature is established. In the experiment, the total flow rate was set to 5000 mL/min at 473 K. From the total flow rate, the volume flow rate of water vapor at the designated temperature and water concentration is calculated, and subsequently, the liquid water flow rate is determined according to Equation (1):

$$Q_{H_2O} = \frac{V_{H_2O} \times M_{H_2O} \times 273.15}{22.4 \times 1000 \times r_{H_2O} \times T_1} \quad (1)$$

Here, Q denotes the liquid water flow rate (mL/min), ρ_H_2O represents the density of liquid water (g/mL), and M_H_2O is the molecular weight of water (g/mol). Secondly, based on the total gas flow rate, the target gas concentration, and the concentrations of the CH_4/N_2 and NH_3/N_2 standard gases, the high-temperature volume flow rate of the standard gas can be calculated; then, using Equation (2), the standard gas volume flow rate at room temperature can be determined.

$$V_0 = V_1 \times \frac{T_0}{T_1} \quad (2)$$

Here, V_0 represents the gas volumetric flow rate at room temperature (mL/min), V_1 is the gas volumetric flow rate at the set temperature (mL/min), T_0 denotes the room temperature (K), and T_1 corresponds to the designated temperature (K).

To verify the accuracy of the high-humidity configuration, the water concentration was determined by measuring the integrated absorbance near 1512 nm using direct absorption spectroscopy (DAS). Figure 3(a) displays the raw absorption spectrum obtained at a 10% H_2O concentration, where the weak baseline absorption is attributed to the minimal water vapor present in ambient air at room temperature. Figure 3(b) presents the typical absorbance signals, along with the Voigt fitting results and corresponding fitting residuals, for water vapor concentrations of 10% and 50%. Figure 3(c) compares the configured water concentrations with the actual measured

values. In this comparison, the vertical error bars represent the uncertainty of the DAS measurements (approximately 4.0%), while the horizontal error bars indicate the uncertainty in the high-temperature water vapor configuration (approximately 2.2%). Across the range of five water concentrations from 10% to 50%, the measured values closely match the configured values, with a maximum error of 3.5%, which is within acceptable limits. These results confirm the reliability of the high-humidity environment configuration system.

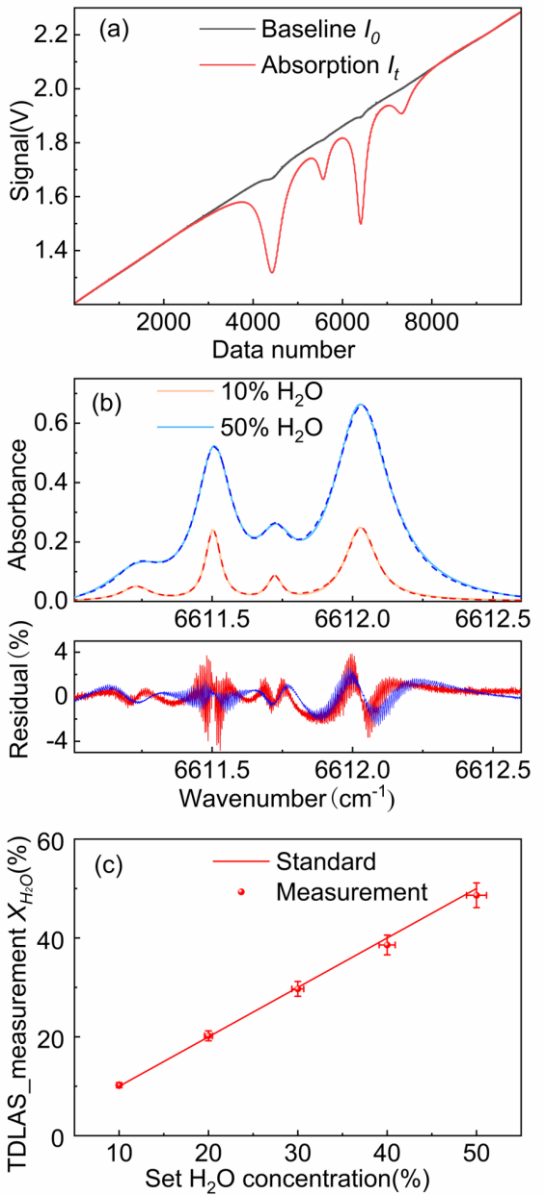

Figure 3. (a) Raw signal from direct absorption of measured H_2O concentration; (b) Voigt fit curve for 10%-50% H_2O concentration; (c) Comparison of set H_2O concentration and experimental H_2O concentration

3.2 Detection of trace NH_3/CH_4 concentration in high temperature and high humidity environments

Figures 4(a) and 4(b) present the raw WMS signals for individual measurements of 100ppmNH_3 and 100ppm CH_4 in a 30% H_2O environment. Figure 4(c) shows the raw WMS signals obtained using frequency division multiplexing to simultaneously measure CH_4 and NH_3 under the same conditions; the overall decrease in voltage is attributed to a reduction in the amplification gain of the photodetector (PD). It is observed that the raw WMS signals for the two gases exhibit a periodic variation, with the voltage amplitude rising and subsequently falling within each cycle. This behavior results from the differing high-frequency modulation frequencies applied to each gas signal prior to modulation, which leads to alternating additive and subtractive effects when the signals are superimposed. Figures 4(d) and 4(e) display the WMS-*2f/1f* signals for various concentrations of NH_3 and CH_4, demodulated based on their respective modulation frequencies during simultaneous measurements in a 30% H_2O environment. Notably, even under high-humidity conditions, the detection limits for NH_3 and CH_4 remain at 10ppm and 2ppm, respectively, underscoring the sensor's exceptional sensitivity.

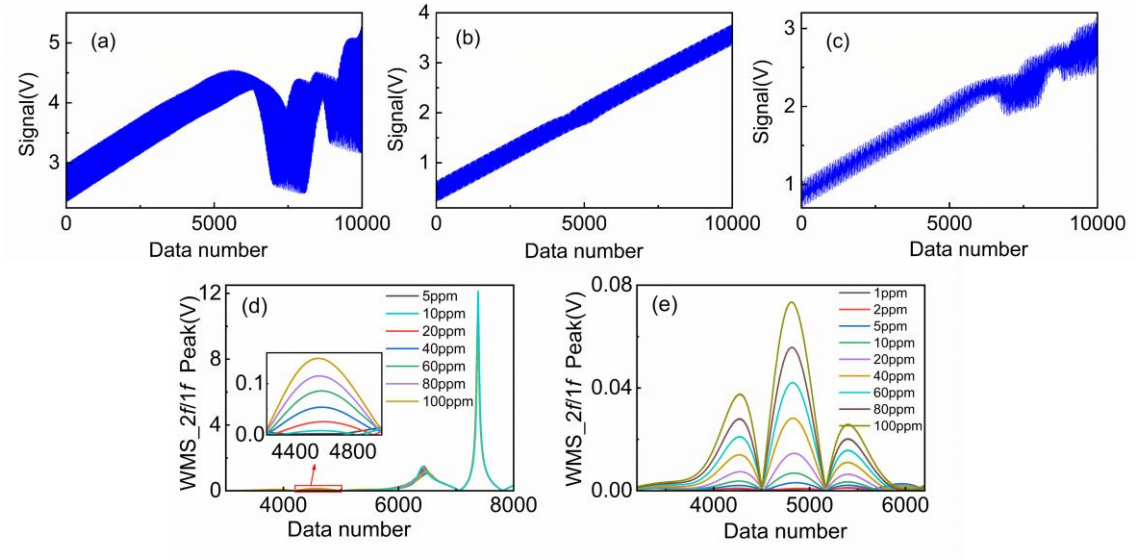

Figure 4. (a-c) Raw WMS signals of 100 ppm NH_3, 100 ppm CH_4, and co-measurements of 100 ppm NH_3, 100 ppm CH_4 measured individually and co-measurements in 30% H_2O environment; (d-e) NH_3/CH_4 WMS-*2f/1f* curves of different concentrations when measured co-measurements are made in 30% H_2O environment

To comprehensively evaluate the synchronous detection performance of the sensor and assess the influence of high humidity on the WMS-*2f/1f*

signals, this study compared the simultaneous measurement signals of CH_4 and NH_3 with those obtained from independent measurements under varying H_2O concentrations. Initially, independent measurements of NH_3 and CH_4 were conducted in a high-humidity environment to establish baseline data. Figures 5(a) and 5(b) display the WMS-*2f/1f* peak curves for individually measured NH_3 and CH_4 (with concentrations ranging from 1ppm to 100ppm) at H_2O concentrations between 10% and 50%. These data reflect the absorption characteristics of the individual gases under different humidity conditions and serve as reference standards. Figures 5(c) and 5(d) present the WMS-*2f/1f* peak curves for the simultaneous detection of NH_3 and CH_4 (within the same concentration range) under identical H_2O concentration conditions. By plotting the WMS-*2f/1f* peak amplitudes as a function of gas concentration and fitting the data, the resulting linearity (with R^2 values exceeding 0.997) confirms that both the independent and simultaneous measurement curves exhibit excellent linear responses, thereby demonstrating the sensor's outstanding linearity.

Analysis of the measurement signals indicates that, regardless of whether the gases are measured individually or simultaneously, the WMS-*2f/1f* peak signals for both NH_3 and CH_4 decrease as the H_2O concentration increases from 0% to 50%. Under synchronous measurement conditions, the WMS-*2f/1f* peak signal for NH_3 decreased by approximately 36%–38% at 50% H_2O relative to 0% H_2O, while that for CH_4 decreased by about 20%–25%. The more pronounced reduction in the NH_3 signal is primarily attributable to the broadening effect induced by high water vapor, which significantly enhances collisional broadening of NH_3 relative to CH_4, thereby reducing the peak absorbance. It is noteworthy that, in addition to the broadening effect, the selected NH_3 absorption feature is subject to interference from baseline elevation near 6612.01 cm^{-1} under high water vapor conditions, and similarly, the chosen CH_4 absorption feature is affected by baseline elevation near 6047.79 cm^{-1}. Although such interference would tend to increase the signal, the observed decrease in the harmonic signal clearly indicates

that the broadening effect is dominant. Moreover, since water vapor influences the two target gas molecules differently—NH_3, with its higher broadening coefficient, is more strongly affected than CH_4—the water vapor broadening effect significantly degrades the detection limit for NH_3, and this degradation intensifies with increasing H_2O concentration. Specifically, at H_2O concentrations of 10%, 30%, and 50%, the detection limits for NH_3 increased from 1ppm to 5ppm and 20ppm, respectively, exhibiting a clear upward trend. In contrast, for CH_4, the detection limit remained at 1ppm for H_2O concentrations below 30%, and even at 50% H_2O, a low detection limit of 5ppm was maintained. A comparison between the results of simultaneous and independent measurements revealed that the demodulated synchronous measurement signals obtained via frequency division multiplexing are essentially identical to the individually demodulated signals of CH_4 and NH_3, with both maintaining excellent linearity. These findings confirm that the developed trace dual-fuel sensor for simultaneous detection is capable of meeting practical measurement requirements, offering high accuracy and significant practical value for real-world applications.

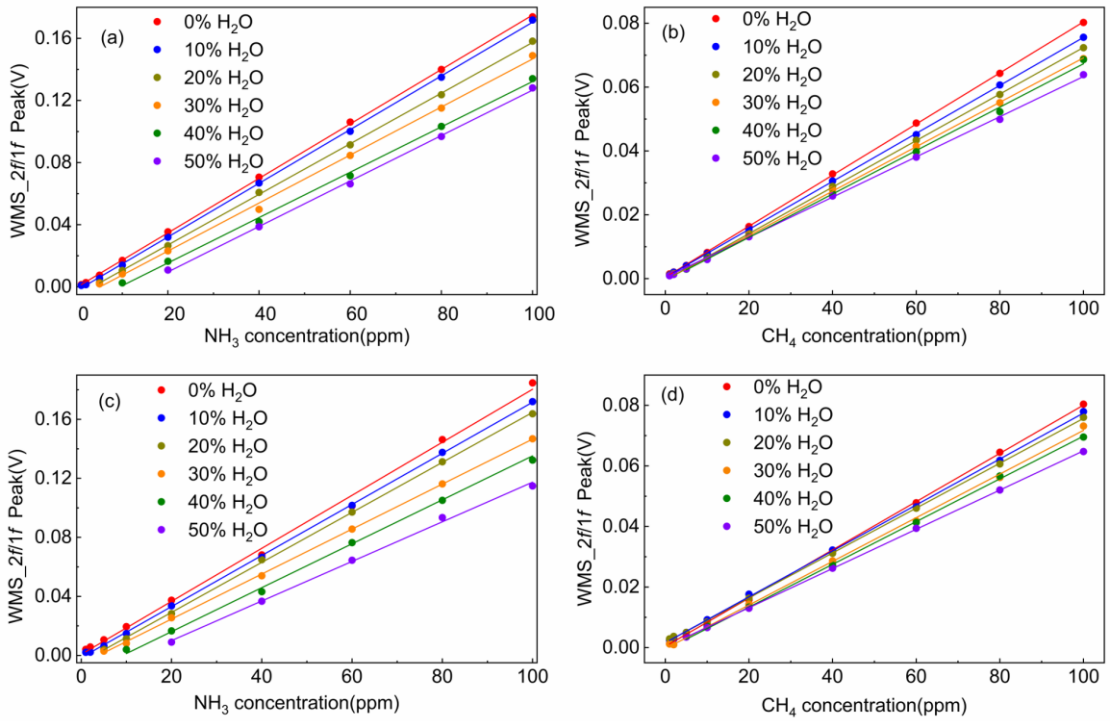

Figure 5. (a-b) NH_3/CH_4 WMS-*2f/1f* peak signals during standalone measurements; (c-d) NH_3/CH_4 WMS-*2f/1f* peak signals during frequency-division multiplexing measurements.

For WMS measurements, the Allan-Werle variance was employed to analyze the system noise level, assess the sensor's long-term stability, and determine the minimum detection limits. Figure 6 presents the Allan variance for a continuous 1800 s measurement, from which the detection limits for NH_3 and CH_4 were found to be approximately 82ppb and 88ppb, respectively, with integration times of 91 s and 40 s. On a 1 s timescale, the detection limits for NH_3 and CH_4 are 0.44ppm and 0.81ppm, respectively.

To further evaluate the performance of the trace CH_4/NH_3 simultaneous detection sensor, a series of experiments were designed. A gas mixture of H_2O, CH_4, NH_3, and N_2 was introduced into the high-temperature gas cell of the experimental system. The concentrations of CH_4 and NH_3 were continuously adjusted while monitoring the sensor's response, and the measured signals were converted into corresponding concentration values

for real-time monitoring. The experimental results indicate that the sensor rapidly responds to changes in gas concentration and maintains excellent stability during long-term continuous operation. Figure 7 provides a detailed illustration of this process, revealing the stable response characteristics of the sensor and its capability for accurate detection of trace CH_4 and NH_3. These findings demonstrate that the developed sensor achieves high measurement accuracy and operational stability, thereby fulfilling the requirements for trace CH_4 and NH_3 detection in industrial and environmental monitoring applications.

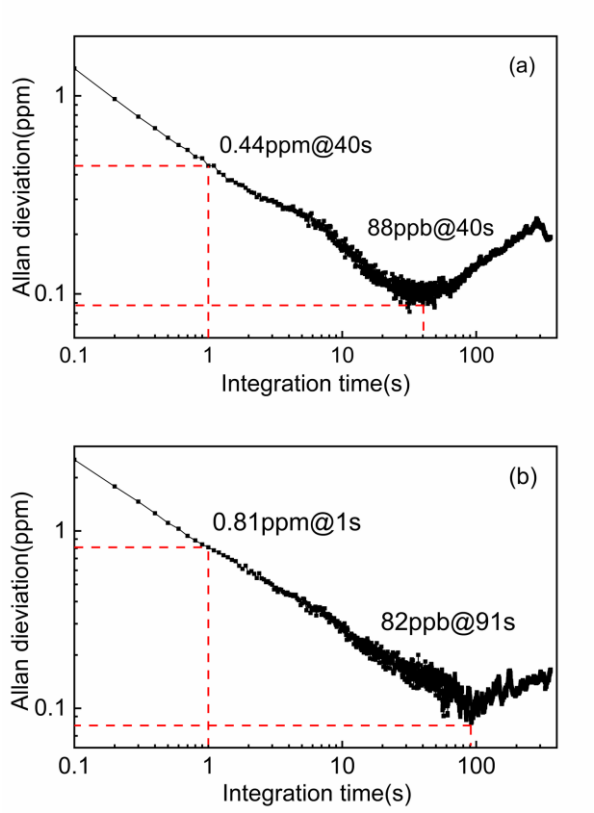

Figure 6. Allan variance of NH_3/CH_4 under continuous measurement

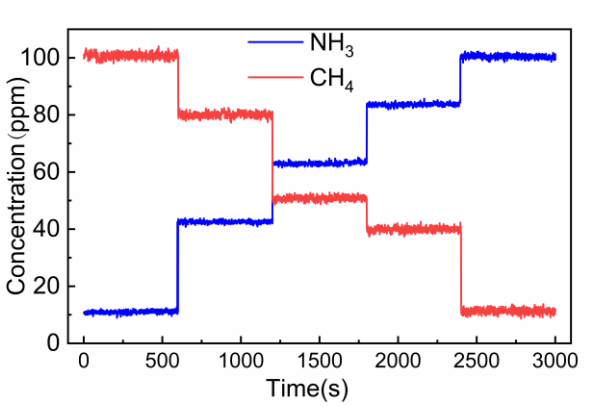

Figure 7. Continuous measurement results for trace NH_3/CH_4 mixtures.

4. Conclusions

This study presents the first sensor capable of simultaneously detecting trace levels of CH_4 and NH_3 in high-temperature, high-humidity environments. The innovative approach combines frequency division multiplexing with wavelength modulation spectroscopy by coupling 1512 nm and 1654 nm DFB lasers, thereby enabling quantitative, real-time measurements of trace CH_4 and NH_3 under challenging conditions:

(1) A high-humidity trace mixed-gas configuration system was developed to accurately generate the desired target gas and water vapor concentrations. To verify the precision of the high-humidity setup, direct absorption spectroscopy (DAS) was employed to measure H_2O concentrations in the 10%–50% range, resulting in a maximum error of 3.5%. This confirms the reliability of the water vapor concentration control.

(2) Subsequently, wavelength modulation spectroscopy (WMS) was used to detect trace concentrations of CH_4 and NH_3. The sensor's performance was first evaluated in a high-temperature multipass gas cell, where temperature, pressure, and water vapor concentration were precisely controlled. Measurements of $CH_4/NH_3/N_2$ mixtures with known concentrations and humidity levels yielded a detection limit of 88 ppb for NH_3 (with an integration time of 40 s) and 82 ppb for CH_4 (with an integration time of 91 s). Although the

2f/1f signal peaks for both trace components are significantly affected when H_2O concentration exceeds 10%, a robust linear relationship with concentration is maintained.

(3) Experimental results demonstrate that the sensor exhibits excellent sensitivity, stability, and rapid response in real-time monitoring, satisfying the requirements for detecting trace fuel leakage in industrial combustion systems. In applications such as flue gas monitoring in CH_4–NH_3 combustion systems and fuel leakage detection, the sensor provides precise measurements of trace CH_4 and NH_3, offering critical data support for the safe, efficient, and low-emission operation of industrial combustion processes. In practical applications, the gas cell is operated at atmospheric pressure, and the sampling lines are insulated to maintain a constant temperature. Future research will explore the influence of temperature and pressure variations on the measurement of trace NH_3 and CH_4, develop correction methods for such variations, and employ a calibration-free spectral model for concentration inversion to further enhance measurement reliability and accuracy in complex environments.

5. References

[1] Xia J B, Zhu F, Zhang S S, et al. Probing greenhouse gases in turbulent atmosphere by long-range open-path wavelength modulation spectroscopy[J]. Optics and Lasers in Engineering, 2019, 117: 21-28.

[2] Chao, X., Jeffries, J. B., and Hanson, R. K. 2012. Wavelength-modulation-spectroscopy for real-time, in situ NO detection in combustion gases with a 5.2μm quantum-cascade laser, *Applied Physics B*, 106(4): 987-997.

[3] Sun, P., Zhang, Z., Li, Z., et al. 2017. A study of two dimensional tomography reconstruction of temperature and gas concentration in a combustion field using TDLAS, *Applied Sciences*, 7(10): 990.

[4] Chao, X., Jeffries, J. B., and Hanson, R. K. 2012. Wavelength-modulation-spectroscopy for real-time, in situ NO detection in combustion gases with a 5.2μm quantum-cascade laser, *Applied Physics B*, 106(4): 987-997.

[5] Gu, B., Zhang, L., Van Dingenen, R., et al. 2021. Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM2.5 air pollution, *Science*, 374(6568): 758-762.

[6] Jha, R. K. 2022. Non-Dispersive Infrared Gas Sensing Technology: A Review, *IEEE Sensors Journal*, 22(1): 6-15.

[7] Kira, O., Shaviv, A., and Dubowski, Y. 2019. Direct tracing of NH_3 and N_2O emissions associated with urea fertilization approaches, using static incubation cells, *Science of the Total Environment*, 661: 75-85.

[8] Moller, C., Wunscher, H., Frank, T., et al. 2021. Ammonia Sensors – Different Measurement Principles, *Proceedings of the 2021 Smart Systems Integration (SSI)*, IEEE, Zurich, Switzerland, 1: 1-4.

[9] Ma, L., Wang, W., Zhou, C., et al. 2023. A laser absorption sensor for fuel slip monitoring in high-humidity flue gases from ammonia combustion, *Measurement Science and Technology*, 34(9): 094005.

[10] Goldenstein, C. S., Spearrin, R. M., Jeffries, J. B., et al. 2017. Infrared laser-absorption sensing for combustion gases, *Progress in Energy and Combustion Science*, 60: 132-176.

[11] Duan, K., Ji, Y., Wen, D., et al. 2023. Mid-infrared fiber-coupled laser absorption sensor for simultaneous NH3 and NO monitoring in flue gases, *Sensors and Actuators B: Chemical*, 374: 132805.

[12] Guo, S., Li, J., Wei, Y., et al. 2024. A multi-laser

hybrid absorption sensor for simultaneous measurement of NH3, NO, and temperature in denitrification flue gas, *Infrared Physics & Technology*, 136: 105034.

[13] Guo, S., Li, Z., Liu, Z., et al. 2024. Simultaneous measurement of NH3 and NO by mid-infrared tunable diode laser absorption spectroscopy based on machine-learning algorithms, *Measurement*, 234: 114858.

[14] Li, J., Zhang, C., Wei, Y., et al. 2020. In situ, portable and robust laser sensor for simultaneous measurement of ammonia, water vapor and temperature in denitrification processes of coal fired power plants, *Sensors and Actuators B: Chemical*, 305: 127533.

[15] Guo, X., Zheng, F., Li, C., et al. 2019. A portable sensor for in-situ measurement of ammonia based on near-infrared laser absorption spectroscopy, *Optics and Lasers in Engineering*, 115: 243-248