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# First experimental realization of a thermoacoustic-based flue-gas analyzer

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ABSTRACT

Flue-gas analyzers are critical for various applications, including the optimization of combustion efficiency and air quality monitoring. While capable of accurately measuring gas concentrations, current sensors require frequent calibration, suffer short lifespans, and can be susceptible to inference from trace gases. In this report, we provide a first physical implementation of a thermoacoustic-based gas analyzer by investigating the sensitivity of a standing-wave thermoacoustic engine to variations in three different flue-gas components, $CO_2$, $O_2$, and $N_2$. Experimentally measured shifts in both the onset temperature difference and the fundamental resonance frequency with varying gas compositions confirm the feasibility of a thermoacoustic system for flue-gas analysis. The presented data paves the way for further exploration of this innovative approach, offering an efficient and cost-effective acoustic-based alternative to existing flue-gas analysis methodologies.

## 1. Introduction

The current surge in global energy demands, coupled with growing environmental concerns, necessitates a swift transition towards cleaner and more efficient energy utilization [1]. This shift demands reliable and cost-effective tools for monitoring gas emissions from various sources, including fossil-fuel power plants, industrial facilities, and waste incinerators. In this context, flue-gas analyzers play a crucial role by characterizing key gas species like carbon dioxide ($CO_2$), carbon monoxide (CO), oxygen ($O_2$), and nitrogen ($N_2$), along with trace amounts of unburned hydrocarbons (HCs), nitrogen oxides ($NO_x$), and sulfur dioxide ($SO_2$). This information facilitates vital calculations, such as air-to-fuel ratios, directly impacting combustion efficiency and adherence to emission regulations, enabling the optimization of combustion processes. Beyond combustion, gas analyzer applications extend to indoor air quality monitoring and hazard detection in healthcare and industrial settings.

Common methods for flue-gas analysis often rely on either non-dispersive infrared (NDIR) or electrochemical sensors. NDIR sensors, leveraging the principle of infrared absorption to measure specific gas concentrations, offer high sensitivity and low energy consumption. However, these sensors are susceptible to interference from trace gases and require frequent calibration [2]. Electrochemical sensors, on the other hand, function based on electrical signals generated when gases interact with an electrode, providing high resolution and good repeatability, but suffer short lifespans and high sensitivity to temperature fluctuations [3]. While these methods are established, a number of studies explored other interesting electro-acoustical gas analyzers. For instance, acoustic resonators were employed to measure concentrations of binary (He-Ne) [4] and pseudo-binary gas mixtures (Air-Helium) [5] with a remarkable accuracy of 0.1%.

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In a different realm, thermoacoustics, a field concerned with the interconversion of thermal energy and sound, offers an attractive innovative technology. Thermoacoustic engines and refrigerators, with few moving parts, are simple, inexpensive, and durable [6,7]. Moreover, recent research has shown engines designed with low onset temperature requirements, as low as 8.2 °C [8], making them suitable for waste energy harvesting [9]. Furthermore, the potential extends beyond conventional applications, as demonstrated by a recent study that successfully developed a self-powered thermoacoustic thermometer specifically designed to monitor the temperature of nuclear fuel rods, relying on the relationship between the resonant frequency and reactor temperature [10].

Building upon the aforementioned needs and available technology, Aziz et al. [11] introduced a novel approach to flue-gas analysis. They established a theoretical groundwork for a thermoacoustic-based flue-gas analyzer that leverages the primary characteristics of thermoacoustic engines, specifically the onset temperature difference and the fundamental resonance frequency of the oscillating working fluid, to distinguish between the main four flue-gas components. Such theoretical hypothesis, however, has not been practically tested. In this report, we provide a first experimental implementation of a thermoacoustic-based gas analyzer by investigating the sensitivity of a standing-wave thermoacoustic engine to variations in three different flue-gas components, $CO_2$, $O_2$, and $N_2$. In doing so, we demonstrate the actual potential of thermoacoustics as a robust platform for flue-gas analysis, offering an efficient, cost-effective, and environmentally-friendly alternative to current flue-gas analyzers.

## 2. Theoretical background

Thermoacoustics studies the intricate interplay between heat and sound, dealing with the conversion of thermal energy into acoustic energy, and vice versa. A standing-wave thermoacoustic engine consists of a tube closed at both ends (resonator) which houses a porous solid (stack) exhibiting low thermal conductivity. With an operating cycle similar to that of Brayton, heat is supplied to the engine from a high-temperature source, ideally waste heat, at one end of the stack and rejected to a low-temperature sink at the other, yielding a net amount that is equivalent to the generated acoustic power. The minimum critical temperature difference across the two ends of the stack which is necessary to initiate self-sustained acoustic oscillations within the engine is known as the onset temperature difference, $\Delta T_{\text{onset}}$, and is given by [11]:

$$\Delta T_{\text{onset}} = \frac{\pi(\gamma_{\text{mix}}-1)(L_s/L)\tan(\pi x/L)T_c}{(1+\ell_0/y_0)-\pi(\gamma_{\text{mix}}-1)(L_s/2L)\tan(\pi x/L)} \tag{1}$$

where $L$ is the resonator length, $x$ and $L_s$ are the stack position and length, respectively, while $y_0$ and $\ell_0$ define the stack half pore size and half wall thickness, respectively. $T_c$ refers to the temperature of the cold end of the stack and $\gamma_{\text{mix}}$ denotes the specific heat ratio of the working fluid at its mean temperature within the stack, i.e., at the middle of the stack assuming a uniform linear temperature gradient.

Additionally, the sound wave propagation speed within the resonator, and consequently the resonant frequency, can be identified as another characteristic property of the thermoacoustic system. Analogous to the onset temperature difference, this wave speed is primarily governed by the thermodynamic properties of the gas, as represented by the working fluid's apparent molecular weight $M_{\text{mix}}$ and specific heat ratio $\gamma_{\text{mix}}$. Specifically, the frequency of the fundamental resonance (i.e., first harmonic, $f_1$) can be expressed via the following relation:

$$f_1 = \frac{1}{2L}\sqrt{\frac{\gamma_{\text{mix}} R T_m^{\text{eff}}}{M_{\text{mix}}}} \tag{2}$$

where $R$ denotes the universal gas constant (8314 J/mol.K), and $T_m^{\text{eff}}$ refers to the effective temperature of the resonator, approximately equal to the cold duct temperature [12]. The aforementioned equations demonstrate the direct dependence of the onset temperature difference and the fundamental resonance frequency on the engine's geometry and working fluid properties. Since $\gamma_{\text{mix}}$ and $M_{\text{mix}}$ of a gas mixture encode the type and concentration of its components, their influence on the onset of acoustic oscillations can be directly correlated. This theoretical foundation lays the groundwork for the physical realization of a thermoacoustic-based flue-gas analyzer.

## 3. Experimental setup

The experimental setup, depicted in Fig. 1, is comprised of three subsystems. The core component is a standing-wave thermoacoustic engine consisting of three sections: A stainless tube constituting the hot duct, a 60 mm-long Celcor ceramic stack (86% porosity, square pores of $y_0 = 0.5$ mm and $\ell_0 = 0.1$ mm) housed within a thinned section of the stainless steel tube for minimal heat transfer across the stack, and a long polycarbonate cold duct. The stack is positioned 0.26 m from the hot end of the 1.37 m-long and 45 mm-diameter resonator. Additionally, a gas-composition analysis compartment is equipped with two wireless Vernier® gas sensors: An NDIR $CO_2$ sensor, with a 0–100 000 ppm dynamic range, and an electrochemical $O_2$ sensor. The compartment connects to the engine through an on/off valve enabling pre-experiment gas composition measurement. Finally, a data processing unit runs the experiments and captures data for analysis. The latter includes a computer running LABVIEW and MATLAB, data acquisition cards (DAQ) linked to pressure and temperature sensors, and a relay circuit controlling the heater. The pressure of the acoustic oscillations near the resonator's cold end is measured via a high-fidelity microphone (1/4 inch prepolarized BSWA MP471S IEC61672 Class 1 with a 6 Hz–40 kHz dynamic range and a 0.5 mV/Pa sensitivity attached to a BSWA MA401 ICP preamplifier) linked to a BSWA MC3242 DAQ, while the hot and cold temperatures of the stack are measured by two type K thermocouples pressed against its ends and linked to an NI USB6341 DAQ.

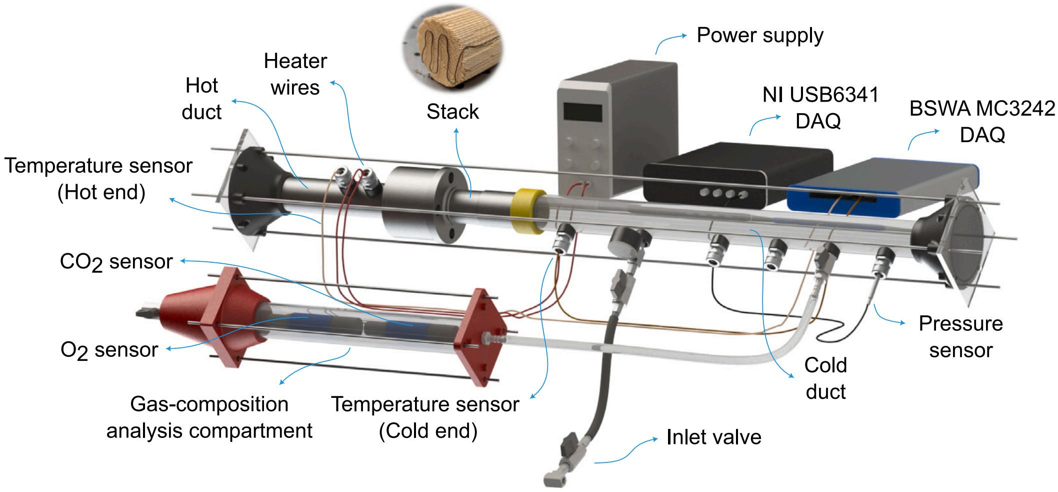


**Fig. 1.** A detailed schematic diagram of a thermoacoustic-based flue-gas analyzer, along with the experimental setup used to characterize its performance. All major components are labeled and detailed in Section 3.

Each experiment begins with an air-filled system to which controlled amounts of $CO_2$, $O_2$, and $N_2$ are introduced from pressurized gas cylinders. With the gas-composition analysis compartment valve open, a fan housed within the compartment ensures uniform gas mixing throughout the whole system, allowing the gas sensors to accurately measure the final mixture composition. Following this, all valves are closed, and if necessary, an external fan cools the system from previous runs to minimize initial temperature differences across the stack ends. Next, the heater, which is fixed to the hot end of the stack, is triggered initiating a linear heating profile controlled by a LABVIEW scheme that utilizes the relay circuit, ensuring consistent temperature rise and onset temperature difference detection across experiments. Throughout the heating process, the temperatures of the stack sides and the pressure near the resonator's cold end are recorded. Prior to the onset of sustained acoustic oscillations, initial pressure fluctuations indicate an early disturbance, followed by a gradual increase marking the onset moment, as illustrated in Fig. 2b. At this point, the temperature difference between the hot and cold ends is recorded as the onset temperature difference specific to the investigated gas mixture. Finally, the heat input is fixed, allowing the pressure to stabilize for the subsequent FFT analysis and extraction of the fundamental resonance frequency (see Fig. 2c).

## 4. Results and discussion

To begin assessing the feasibility of deploying thermoacoustics in flue-gas analysis applications, we focus on $CO_2$ detection. Initially, air present in the engine is manipulated to create a base mixture of $N_2$ and $O_2$ with a 4.7 : 1 ratio. The $CO_2$ content is then systematically increased while measuring the corresponding onset temperature difference and fundamental resonance frequency. This approach of following an iso-$CO_2$ line as captured in Fig. 2e, ensures that the observed changes in these parameters are predominantly due to the variations in $CO_2$ concentration, thus minimizing the influence of other gas species. As illustrated in Fig. 2d, the onset temperature difference exhibits a notable decrease of 1.7 °C per 1% increase in $CO_2$. Similarly, the fundamental resonance frequency displays a comparable decrease of 0.5 Hz (consider the generally higher sensitivity of pressure sensors compared to that of temperature ones). This observed sensitivity suggests promising potential for thermoacoustic flue-gas analysis.

Interestingly, equivalent changes to the air composition with respect to $O_2$ or $N_2$ concentrations have a lower impact on both parameters, as demonstrated by the flatness of the contour lines in Fig. 2e. This suggests a stronger influence of $CO_2$ compared to $O_2$ and $N_2$, presumably due to their dominant presence in air (the starting gas) compared to the trace amount of $CO_2$ added before each experiment. However, we anticipate a pronounced effect when analyzing gases at low concentrations, which can be particularly relevant in combustion applications where $O_2$ and/or CO levels are low, yet crucial in determining combustion efficiency. While CO is a vital indicator in combustion analysis, we did not explore its impact due to safety concerns. This initial exploration underscores the potential of thermoacoustics for flue-gas analysis, particularly for detecting trace components within dominant gas mixtures.

Additionally, further experiments are conducted to investigate the impact of various gas compositions spanning a wide range of concentrations of the three flue-gas components. Fig. 2e presents a ternary diagram, with each axis representing the concentration of one gas component as a percentage. Two sets of contours, derived from the onset temperature difference and the fundamental resonance frequency measurements at specific gas compositions (highlighted in the figure), are constructed on the diagram. Most importantly, minor changes in the gas composition result in observable shifts in both parameters, further highlighting the potential of utilizing thermoacoustics for sensitive gas detection.

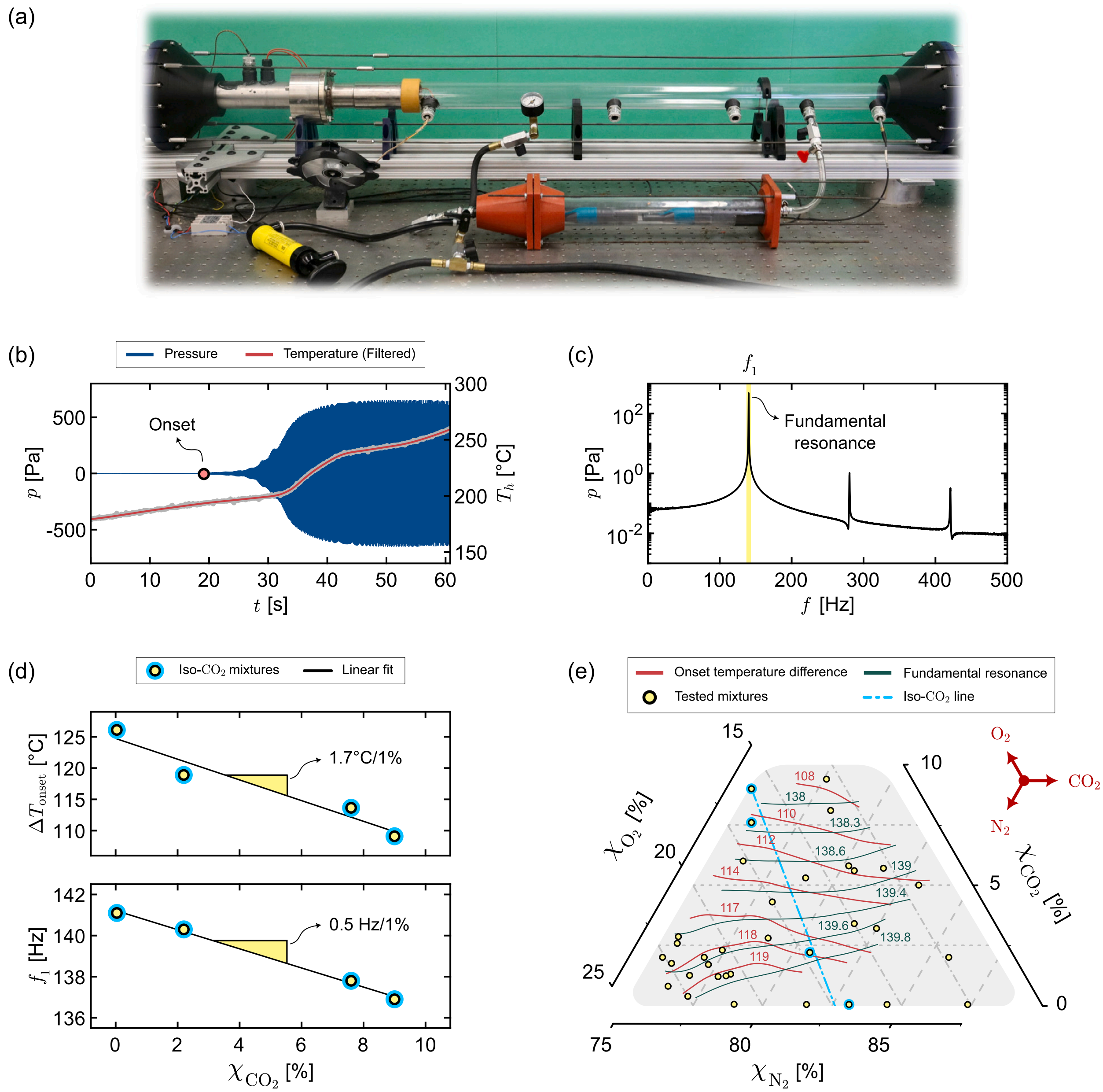


**Fig. 2.** (a) Actual photograph of the experimental setup, including the thermoacoustic engine and gas-composition compartment. (b) Time response of the pressure fluctuations near the resonator's cold end (blue) and the stack's hot side temperature (red). The onset moment, at which self-sustained pressure oscillations start, is marked. (c) Frequency spectrum of the pressure signal at steady-state, dominated by the fundamental resonance with two weaker higher harmonics. (d) Sensitivity of onset temperature difference and fundamental resonance frequency to variations in $CO_2$ concentration. Data points lie on an iso-$CO_2$ line, meaning the ratio of $O_2$ and $N_2$ is constant while $CO_2$ concentration is varied. The linear fit indicates that a 1% increase in $CO_2$ leads to a decrease of 1.7 °C and 0.5 Hz in the onset temperature difference and the fundamental resonance frequency, respectively. (e) Ternary diagram depicting the tested gas mixtures with estimated contours of both parameters, emphasizing the effect of varying gas composition on the thermoacoustic behavior of the device. The composition of a data point can be determined by following the red arrows of corresponding gases and projecting it on the axes, representing the percentage concentration $\chi_i$ of the three gases: $CO_2$, $N_2$, and $O_2$. The data points used in the sensitivity analysis are highlighted via cyan circular markers.

## 5. Concluding remarks

In summary, this study provided first experimental evidence of the feasibility of a thermoacoustic-based flue-gas analyzer. By quantifying the sensitivity of the system's onset temperature difference and fundamental resonance frequency to variations in three different flue-gas components, $CO_2$, $O_2$, and $N_2$, the parameters associated with the onset of self-sustained acoustic oscillations were shown to be a solid indicator of the gas mixture inside the thermoacoustic cavity. The experimental results showcased observable changes in these parameters following several variations in the working gas composition. Notably, minor $CO_2$ changes within dominant gas mixtures yielded shifts in both $\Delta T_{\mathrm{onset}}$ and $f_1$, demonstrating the capability for sensitive detection of low-concentration components. While further investigations are important, including exploration of other gas compositions and optimization of the engine design, this work successfully demonstrates the cornerstones of thermoacoustic-based flue-gas analysis. We anticipate further research and development, particularly focusing on the analysis of key gases, like CO, at low concentrations and the practical implementation, are crucial to fully realize the potential of this innovative technology.

## CRediT authorship contribution statement

**M. Mousa:** Writing – original draft, Investigation, Formal analysis, Data curation. **E. Fort:** Software, Investigation, Data curation. **M. Nouh:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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