Modular Miniaturized GC-MOS Platform: Design, Characterization, and Proof-of-Concept Validation

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This work presents a compact, portable prototype that combines gas chromatographic (GC) separation with a metal oxide semiconductor (MOS) gas sensor as detector for rapid analysis of both organic and inorganic volatile compounds. The system features temperature-programmable separation, piezoelectric flow control, and a modular architecture that enables rapid adaptation across applications, notably food quality monitoring and breath analysis. The miniaturized platform improves SWaP (Size, Weight and Power) parameters while maintaining the capability for complex mixture analysis. An analytical standard mixture of aldehydes could be well-separated within a 2-minute analysis time. Field-deployable applications demand portability and analytical versatility, while still enabling a large dynamic range from low ppb up to several ppm. In this work, this was achieved through hardware improvements in thermal management and flow stability.

Keywords: miniaturized GC, MOS-based sensor detector, system design, aldehydes.

I. Introduction

Portable gas chromatography systems are increasingly in demand for on-site analysis of volatile organic compounds (VOC) and inorganic compounds in food quality control, environmental monitoring, and medical diagnostics. Although laboratory-grade GC systems provide excellent analytical performance and are the gold standard, their size, power requirements, need for trained staff, and costs limit field deployment. Recent advances in miniaturization have enabled compact GC platforms; however, challenges remain in achieving truly portable systems with sufficient versatility to address multiple application domains.

This work presents a miniaturized GC platform with a MOS gas sensor as detector designed for versatile analysis of volatiles across food and medical applications. The system addresses key requirements for field deployment, including compact dimensions, rapid temperature programming for complex mixture separation, stable flow control, and a modular architecture enabling rapid reconfiguration. In addition, commercially available MOS sensors with integrated microheaters enable dynamic temperature modulation and the integration of multiple sensing materials in multi-pixel designs, allowing multi-condition sensing within a single miniaturized detector [1].

To evaluate the system characteristics and demonstrate the proof-of-concept, a group of target analytes relevant for both applications was selected – aldehydes. Oil oxidation leads to the decomposition of mainly polyunsaturated fatty acids into hydroperoxides, which can be assessed via aldehydes and other carbonyl compounds [2]. In exhaled breath analysis for colorectal [3] and gastric [4] cancer diagnostics, changes in aldehyde concentrations may indicate metabolic dysregulation.

II. System Architecture

A. Design Overview

The miniaturized GC-MOS platform comprises eight functional parts, cf. Fig. 1:

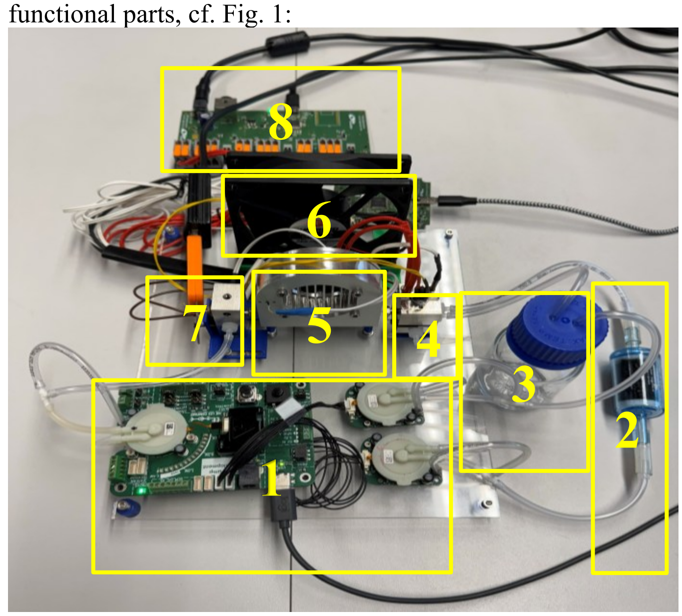

Fig. 1. Photo of the mini GC-MOS with the eight functional parts highlighted.

1. Piezoelectric pump system for carrier gas and purge flows (disc pump, Lee Company, USA). Since this mini GC MOS is intended to be portable, ambient air is the carrier gas.
2. Charcoal filter for the carrier gas (DIA-BN-CG, Infiltec GmbH, Germany).
3. Borosilicate glass container sample unit
4. PID temperature-controlled injector with a solenoid valve for carrier gas/sample control; here there is an internal chamber for preconcentration with independent temperature control for the adsorption/desorption processes. The preconcentrator is the metal organic framework (MOF) Uio-66-BDC.

5. PID temperature-programmable circular oven for the separation column (FS-5-MS-Supreme, CS - Chromatographie Service GmbH, Germany).
6. Fan for fast cooling of the column oven.
7. PID temperature-controlled detection block with a MOS sensor chamber with standardized mounting for sensor interchangeability (UST GGS 1530, Umweltsensortechnik, Geschwenda, Germany). The dead volume is lower than 100 µL.
8. Control electronics for the control of valve, heaters, thermistors, preconcentrator, and MOS sensor.

B. *Thermal Management*

Three independent PID controllers regulate the injector, oven, and detector zones. The column oven employs a circular heater topology providing uniform temperature distribution and rapid thermal programming.

It achieves temperature ramps from 40 to 80 °C in 3 min and active cooling to 40 °C in 2 min using a coupled fan and operation at RT. PID tuning ensures thermal stability with standard deviation of ±0.2 °C at setpoint, which is critical for retention time reproducibility.

Temperature programming enables the analysis of complex mixtures with components spanning wide volatility ranges, addressing a key limitation of portable systems restricted to isothermal operation.

The system is designed for portable operation but requires external power supply due to the energy demand of the heater zones. Battery operation is a target for future development. Duty-cycling of thermal zones during idle periods [5] is a promising strategy for further energy reduction and will be considered in future system optimization.

C. *Flow Control*

Carrier gas delivery is provided by piezoelectric pumps. Key advantages include:

- Compact form (3 cm × 4 cm ×1.5 cm)
- Low power consumption (<1000 mW)
- Measured separation column flow range of 0-14 mL/min
- Operating noise below 10 dB.

Pump calibration was performed using an ASF1400 (Sensirion, Switzerland) flowmeter. Flow stability testing at 3 mL/min over 60 min showed no systematic drift.

D. *Integrated Control Software*

A custom Python-based interface provides real-time system control via USB serial communication. The software features two primary control panels:

Temperature Control: PID parameter tuning, programmable ramp profiles, live temperature monitoring for three heater zones (injector block, column oven and detector block), and power consumption tracking (voltage, current, wattage)
Flow Control: Pump parameter settings, calibrated flow readout, and pressure feedback.

III. Modular Architecture And Adaptability

A. *Column and Sensor Interchangeability*

The platform accommodates multiple column configurations without hardware redesign. MOS sensor mounting uses standardized TO-39 socket geometry, enabling rapid sensor exchange. Commercially available MOS sensors with different sensing layers (e.g. SnO_2, WO_3 etc.) can be interchanged depending on the target analyte classes, with the operating temperature controlled independently via detector block heater.

B. *Preconcentrator*

The preconcentrator is integrated upstream of the injector. Tests were performed using a MOF deposited as a thin film (< 100 µm) on a 1.5 mm x 1.5 mm heated substrate, operated under the following conditions:

- Adsorption at 40 °C during the sampling phase (≈ 150 s)
- Thermal desorption by resistive heating to 220 °C for 10–30 s
- Injection performed during the initial phase of desorption

IV. Preliminary Validation

A. *Aldehyde Reference Mixture Analysis*

To demonstrate platform applicability across food and medical domains, an aldehyde reference mixture was used as a common target analyte set. Aldehydes are relevant to food oxidation monitoring and are also of interest in exhaled breath analysis. The experiments evaluated the GC-MOS capability to resolve and detect aldehydes under portable temperature programmed operation.

Method:

A reference mixture of linear aldehydes (C3–C7) was prepared by dissolving the compounds in rapeseed oil at ppm level concentrations. The spiked oil was transferred into a 100 mL borosilicate glass container for headspace generation.

Measurements were performed using the GC system without make-up flow. Headspace sampling was conducted at 40 °C. The sampling phase was followed by a stop-flow phase and subsequent injection into the gas chromatographic system.

Each measurement cycle had a total duration of 180 s, consisting of a sampling phase, thermal desorption and injection. Six consecutive measurement cycles were recorded, where the first measurements could serve as reference measurements. The MOS sensor was operated at a constant temperature of 400 °C during detection.

This study is devoted to the investigation of compound separation and detector sensitivity toward the target analytes, while the analytical characterization of the system, including calibration and the determination of the limit of detection (LOD) and limit of quantification (LOQ), is currently in progress.

Results:
The repeated runs showed stable retention times but variable peak amplitudes, particularly for propanal and butanal. This behavior is consistent with headspace depletion during continuous gas-phase sampling, together with incomplete re-equilibration between runs. The potential effects of detector partial saturation and preconcentrator variability will be evaluated after further optimization of the sample preparation method.

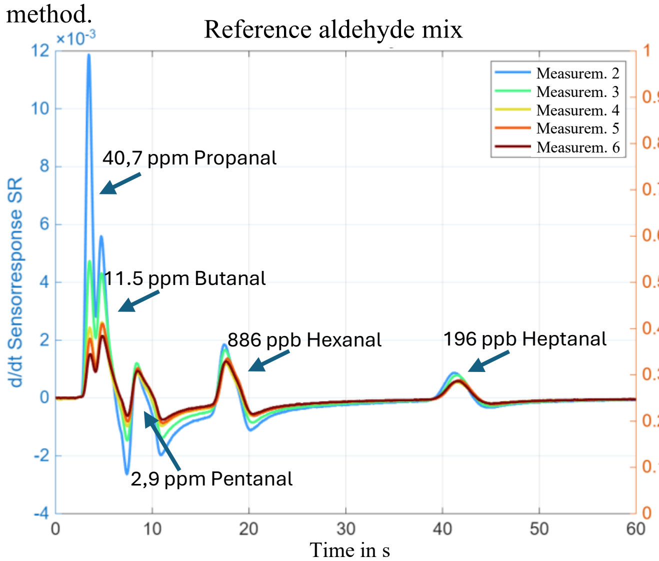

Fig. 2. Chromatogram of the aldehyde reference mixture in rapeseed oil.

V. Application Readiness

The platform is being developed in two parallel projects focused on food and breath analysis. The target analytes comprise a broad range of compounds, including hydrocarbons, oxygenated compounds (e.g., aldehydes, alcohols, and carboxylic acids), and sulfur-containing compounds.

In food analysis, these substances are relevant as markers of oxidation and spoilage, whereas in breath analysis they serve as volatile biomarkers of physiological and pathological processes. With the current configuration, detection limits in the ppb range are achievable.

VI. Conclusions

This work presents a miniaturized GC-MOS platform achieving portable dimensions through the integrated design of thermal management, flow control, and electronics. Key features include temperature programming capability (40-80 °C in 3 min and cooling 80-40 °C in 2 min), stable flow delivery, and modular architecture enabling rapid adaptation across applications.

Preliminary validation with an aldehyde reference mixture demonstrates reproducible chromatographic separation and detection of aldehydes relevant to both food quality assessment and medical breath analysis. Hardware improvements in the current system configuration are expected to further enhance performance through faster analysis, improved peak shapes, and quantitative reproducibility.

The combination of portability, analytical performance, and modularity positions the platform for field-deployable applications in food quality monitoring and breath screening, with ongoing validation experiments establishing application-specific performance benchmarks.

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