

COMPREHENSIVE TWO-DIMENSIONAL GAS CHROMATOGRAPHY USING A MEMS THERMAL MODULATOR

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ABSTRACT

This paper presents the first comprehensive two-dimensional gas chromatographic (GC×GC) separations of volatile organic compound (VOC) mixtures employing a microfabricated mid-point thermal modulator (μ TM). The first-dimension column was coated with a non-polar polydimethylsiloxane (PDMS) film and the second-dimension column was coated with the polar polyethylene glycol (PEG) film. μ TM heating and cooling rates of 2400 °C/s and -168 °C/s, respectively, were achieved. The effects of system flow rate and the maximum and minimum μ TM temperatures on the resolution and signal enhancement are explored with small sets of 5-7 VOCs for a fixed modulation period of 6 s. A structured 2-D chromatogram is produced and a 15-VOC GC×GC separation is achieved in 185 sec. This low-power, consumable-free μ TM provides performance rivaling many commercial macroscale thermal modulators.

INTRODUCTION

In gas chromatography (GC), a mixture of volatile organic compounds (VOC) is separated by reversible, differential partitioning of the mixture components as they are passed through a narrow capillary column, the inner wall of which is coated with a thin polymer film called a stationary phase. A detector placed at the end of the column provides time-resolved signals (peaks) whose magnitudes are proportional to the masses of the eluting analyte vapors. GC systems with a single column (1-D) are the most common. The first Si-micromachined GC system (μ GC) was reported over 30 years ago [1], and a number of groups have reported on refined μ GC systems more recently [2-6]. Primary applications include field measurements of explosives and warfare agents, environmental VOCs, and breath biomarkers, where target VOCs must be separated from numerous background VOCs in order to achieve reliable measurements. Because of the inherent limitations on column length in such microsystems, the resolution achievable and complexity of mixtures that can be effectively separated is constrained.

One approach to increasing resolution (and sensitivity) entails the use of so-called comprehensive two-dimensional GC (GC×GC) in which two columns having stationary phases with different retention properties are coupled in series through a junction-point modulator.

Analytes are first separated or partially separated on the 1st dimension (¹D) column. The modulator then focuses and re-injects piece-wise the ¹D peak segments onto the 2nd dimension column (²D) where they are further separated, typically at very high speed. Using a non-polar ¹D stationary phase permits separation dictated by analyte volatility. Using a polar ²D stationary phase permits separation dictated primarily by analyte polarity [7]. GC×GC systems can achieve much higher peak capacities than 1-D systems under ideal conditions.

Two types of modulators can be used: pneumatic and thermal. Researchers at Sandia National Laboratories have reported preliminary results of a miniaturized GC system employing pneumatic modulation [8]. We recently reported on a low-power, low-resource, microfabricated thermal modulator (μ TM) designed to be integrated, ultimately, in a μ GC× μ GC system (Fig. 1). The two-stage μ TM cryogenically traps analytes eluting from ¹D and thermally injects them into ²D. Each stage is rapidly and repeatedly heated and cooled between minimum and maximum temperatures (T_{\min} and T_{\max} , respectively; $\Delta T = \sim 230$ °C). By use of integrated μ TM heaters and a solid-state thermoelectric cooler (TEC), this system eliminates the need for cryogenic fluids and operates at ~ 20 W, which is two orders of magnitude less power than bench-scale GC×GC thermal modulators [9].

We chose a two-stage configuration because it minimizes sample breakthrough (*i.e.*, undesirable passage of a portion of the analyte peak through the modulator without focusing). In a two-stage modulator, each peak segment from ¹D is trapped/focused in the cooled first stage and then injected to the (cooled) second stage by application of a 0.1-sec heating pulse. The first stage is then rapidly cooled again to accept the next peak segment. In the second stage, which is thermally isolated from the first stage, the transferred peak segment is further focused and then re-injected into ²D by a similarly sharp heating pulse. The second stage is not heated until the primary stage has cooled to a temperature sufficient for trapping incoming components. This alternating heating and cooling of each stage results in more efficient performance. An important feature of GC×GC is that the elution order in ¹D is retained during the modulation process and all of the sample is passed through the modulator (*i.e.*, there is no loss of sample mass in the process).

Previously, we have presented preliminary performance evaluations using a single upstream separation column [10]. Here, we report on a new μ TM configuration/assembly and demonstrate its use in a complete GC \times GC system. The influence of various

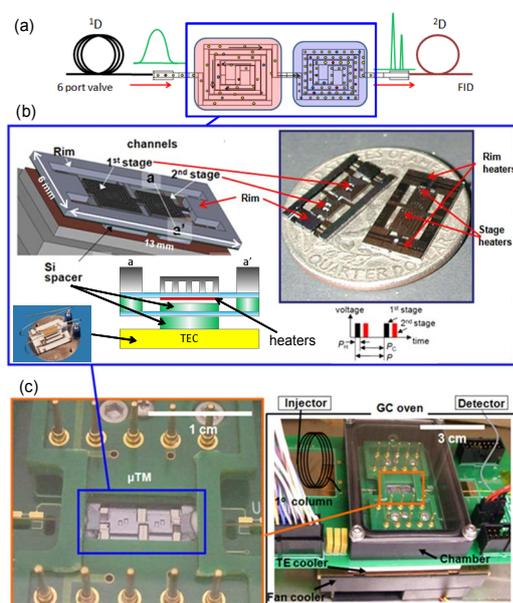


Figure 1 Schematic of (a) operation of μ TM (b) fabricated μ TM and schematic of assembly (c) assembled μ TM

operating parameters (flow rate, temperature modulation range) on the resolution, peak capacity, and separation efficiency was explored. Then we show a ‘structured chromatogram’ of a mixture containing compounds from several functional group classes, and demonstrate a complex VOC mixture separation using our system.

METHODS

Our two-stage μ TM couples spiral micro-channels (Fig. 1b) 4.2-cm and 2.8-cm long through a serial interconnection channel (IC) 0.5-mm long. The channels and IC are monolithic and have a cross-section of 250 (w) \times 140 (h) μ m and a wall thickness of 40- μ m. Devices were fabricated from Si by DRIE and anodically bonded to a Pyrex wafer. Heaters and sensors were patterned from evaporated Ti/Pt by a lift-off process. To reduce the thermal mass of the μ TM, the patterned wafer was back etched using a combination of DRIE and EDP [10].

After fabrication, the μ TM chip was coated with polydimethylsiloxane (PDMS) using static coating method [11], mounted on a custom printed circuit board, and wire-bonded for electrical connection. Two microfabricated Si spacers (7.5 \times 4.5 and 7.5 \times 3.5 mm, respectively) designed to create a 19- μ m air gap were attached to the Pyrex beneath each stage. In addition, two 3 \times 3 mm, 450- μ m thick Si blocks were placed on top of the Si spacers to improve the localized thermal contact between the Si spacers and the cooling unit. A thin layer of thermally conductive paste (Silicon Heat Sink 340, Dow Corning, Midland, MI) was placed on both sides of the Si blocks. This assembly was inverted, manually mounted and aligned near the top surface of a four-stage

thermoelectric cooler (TEC, SP2394, Marlow Industries, Dallas, TX). A small axial fan facilitated heat transfer. The mounted μ TM was covered with a shroud that was purged with dry air to prevent ice formation on the μ TM and TEC surfaces.

The fully assembled μ TM testing platform was placed inside the oven of a bench-scale GC (HP6890, Agilent, Santa Clara, CA). The TE cooler was operated continuously by applying a constant voltage while the modulations were achieved by applying 100-ms voltage pulses to the stage heaters. Sequencing was controlled by a Visual C# program through two solid-state relays (D1D12, Crydom, Moorpark, CA). A DAQ card (NI USB-6212, National Instruments, Austin, TX) was used to measure the temperature sensors. A constant voltage was applied independently to each rim to keep them near room temperature.

A 6-m long, 0.25-mm i.d., capillary column coated with 0.25- μ m PDMS (1 D), was coupled to the inlet of the 1st stage of the μ TM. Similarly, the 2 D, a 0.5-m long, 0.1-mm i.d., capillary column coated with 0.1- μ m PEG, was coupled to the outlet of the 2nd stage. The 2 D was wrapped with insulated Cu wire (100- μ m o.d., EIS, Inc., Atlanta, GA), and then with a heat-resistant thin polyimide tape (7648A713, McMaster Carr, Santa Fe Springs, Ca), and was kept at 90 $^{\circ}$ C.

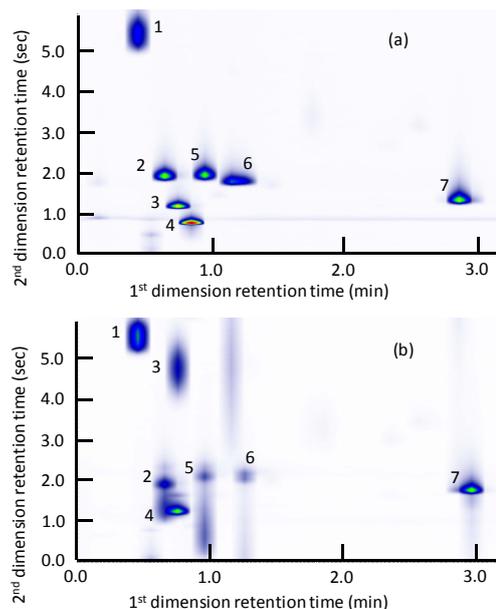


Figure 2: 2D chromatogram showing effects of the modulator T_{min} and T_{max} . (a) $T_{min} = -20$ $^{\circ}$ C; $T_{max} = 210$ $^{\circ}$ C, (b) $T_{min} = 20$ $^{\circ}$ C; $T_{max} = 250$ $^{\circ}$ C. VOCs (boiling point): 1. benzene (80.1 $^{\circ}$ C), 2. hexanal (121 $^{\circ}$ C), 3. isoamyl alcohol (131 $^{\circ}$ C), 4. n-octane (125 $^{\circ}$ C), 5. 2-methyl-2-hexanol (141 $^{\circ}$ C), 6. 2-heptanone (151 $^{\circ}$ C), 7. n-decane (174 $^{\circ}$ C).

VOC test mixtures were prepared in 10-L Tedlar bags (SKC Inc., Eighty-Four, PA) and diluted with N₂. To perform the separations, 112 μ L of the sample was injected into the 1 D using a gas sample loop connected to a pneumatically actuated 6-port valve. The volumetric flow rate through the system was varied by changing the inlet pressure of the GC. The GC oven was kept at 33 $^{\circ}$ C. The

data sampling rate and temperature of the flame ionization detector (FID) were 200 Hz and 250 °C, respectively. GC Image (Rev 2.2, Zoex, Houston, TX) was used for data processing.

EXPERIMENTAL RESULTS

Effect of the μ TM temperature range

In a GC \times GC chromatogram, the horizontal axis shows the retention times on the first column, and the vertical axis shows retention times on the second columns. The 'spots' are the contours of the modulated peaks of a certain compound on the retention time plane. The effect on resolution/separation of changing T_{\min} and T_{\max} was examined for a subset of 7 VOCs. Figure 2 shows the variation in GC \times GC separation obtained using increasing values of T_{\min} and T_{\max} , while maintaining a similar range of 230 °C. At $T_{\min} = -20$ °C, benzene suffers from breakthrough and breaks into two peaks. This phenomenon occurs due to thermal crosstalk between the two modulator stages. Increasing T_{\min} to 20 °C and T_{\max} to 250 °C, results in breakthrough (multiple spots) of benzene, octane and other compounds. There was no significant effect when T_{\max} was varied between 210 and 250 °C.

Values of $T_{\min} = -20$ °C and $T_{\max} = 210$ °C gave the best overall separation of these compounds. The data also show that it is necessary to ramp the operating temperature regime (T_{\min} and T_{\max}) of the μ TM, to obtain good resolution of high boiling compounds on the GC \times GC chromatogram.

Effects of flow rate on GC \times GC separations

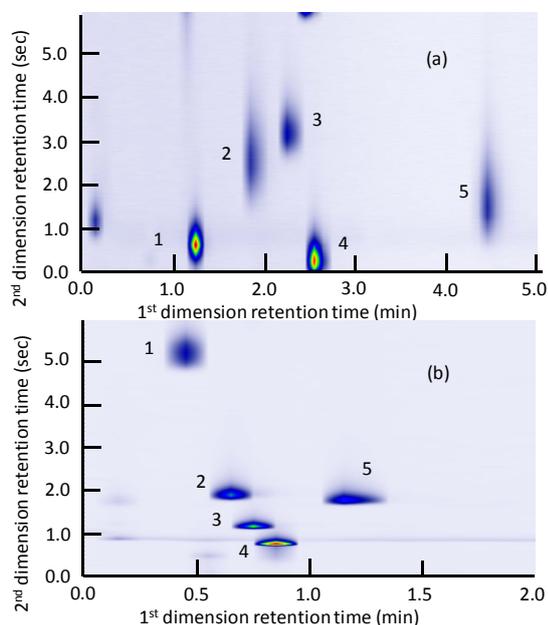


Figure 3: 2D Chromatogram showing separation of multiple VOCs with varying flow rate (Q) (a) $Q=0.1$ mL/min (b) $Q=0.9$ mL/min VOC: 1. benzene, 2. isoamyl alcohol, 3. hexanal, 4. n-octane, 5. 2-heptanone

Figure 3 demonstrates the effect of flow rate on the GC \times GC separation. For this test, a mixture of 5 VOCs was used. Two volumetric flow rates were tested: 0.1 and 0.9

mL/min. Optimal 2-D separation was obtained with a flow rate of ~ 0.9 mL/min. Higher flow rates result in shorter 1 D and 2 D retention times, thus giving rise to poor separation between compounds on the GC \times GC plot. At 0.1 mL/min, the 1 D and 2 D retention times increased significantly. This resulted in severe wraparound and long peak tails along the y-axis (note: wraparound arises when the 2 D retention time of a compound is greater than the time period between successive first-stage heating events). The 2 D retention times, as shown in the GC \times GC plot are, no longer representative of the actual 2 D retention times.

Structured Chromatogram of complex VOC mixture

Similarity in functional-group separations is a hallmark of good GC \times GC, and can assist in analyzing very complex mixtures where it may be difficult to identify individual VOCs. Here it is important that compounds from different groups are separated into different bands depending on their individual polarity. Figure 4 shows that homologues within a given functional group class (i.e., alkanes, aromatics, aldehydes and alcohols) occupy definable clusters within the 2-D space. VOCs within a group have similar polarities, while their boiling points increase with increasing molecular weight. Since VOCs are separated in the 1 D column based on volatility and in the 2 D column based on polarity, the non-polar alkanes are essentially unretained in the 2 D column, in contrast to the more polar compounds. Aromatics are slightly retained in the 2 D column, aldehydes display intermediate retention, and alcohols exhibit the longest retention.

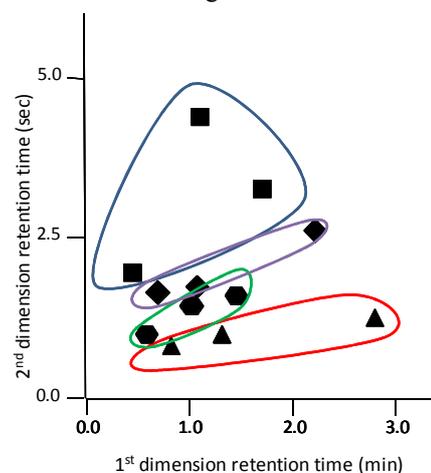


Figure 4: Structured chromatogram of multiple VOCs
▲ = alkanes, ● = aromatics, ◆ = aldehydes, ■ = alcohols

Chromatogram of Complex VOC mixture

Figure 5 shows a 15-compound mixture separation in < 3 min. To identify the individual peaks we started with subsets of homologous compounds and identified them on the GC \times GC chromatogram on the basis of their relative boiling point and polarity. Peak capacity is a measure of the separation efficiency. It is defined as the number of peaks that can fit in a chromatogram within a specified elution time. For our GC \times GC system, it is estimated to be 543 (for C_{10}). For a 1-D system utilizing similar column lengths and other similar operating parameters, peak capacity is ~ 40 .

Table 1. Test compounds and boiling points.

No.	Compound	B.P. (°C)
1	1-propanol	97-98
2	1-hexanol	155-159
3	1-heptanol	175
4	Hexanal	119-124
5	Heptanal	153
6	Benzaldehyde	178
7	n-Octane	125
8	n-Nonane	151
9	n-Decane	174
10	Hexanone	127
11	cyclopentanone	130-131
12	Heptanone	150
13	Toluene	111
14	m-xylene	139
15	cumene	152

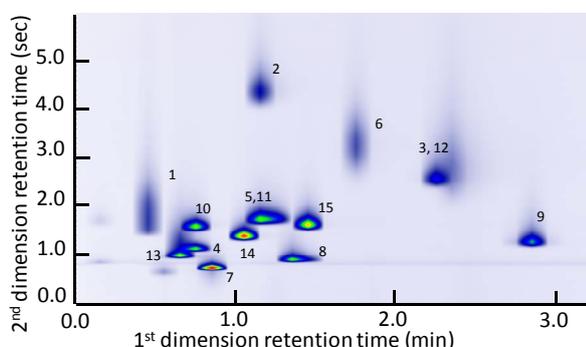


Figure 5. Chromatogram showing separation of 15 compounds in 185 seconds.

CONCLUSIONS

This is the first study to demonstrate a comprehensive GC×GC separation using a MEMS based thermal modulator. A 15-component mixture was separated in < 3 min. The performance of this GC×GC system is comparable to that of conventional bench-scale thermal modulators, but it operates at significantly reduced power and requires no consumable fluids. To further improve the μ TM performance, T_{\min} and the cooling time constant can be lowered by reducing the stage-TEC air gap. This will reduce breakthrough of low-boiling compounds. We are also working on integrating our μ TM chip with microfabricated separation columns and a micro sensor array to produce an all-MEMS μ GC× μ GC system.

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