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Article

Developments in Ultra-Fast Temperature Programming with Silicon Micromachined Gas Chromatography: Performance and Limitations†

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Various commercially available ultra-fast temperature programming approaches were integrated to silicon micromachined GC (micro-GC) for performance improvement assessment. The combined technique of micro-GC and ultra-fast temperature programming up to a rate of 6°C/second yielded an extended analysis range to undecane (nC_{11}), improved signal detectability by at least a factor of three for the solutes studied with respectable one day reproducibility of less than 1% relative standard deviation in retention time (n = 20). Through careful control of various variables affecting retention time, performance improvements can be extended further. The various effects temperature programming has on the stability of thermal conductivity detector as well as criteria that need to be met for the successful implementation of ultra-fast temperature programming in micro-GC are presented.

Introduction

Gas chromatography (GC) is one of the most popular techniques in analytical chemistry. GC is a key enabler to many industrial sectors, from defense to petrochemical and chemical. In the oil and gas business, as well as many other industrial areas, GC gains popularity because of its low cost of ownership, reliable with sufficient sensitivity, easy to operate, ideal for use with fast moving, low boiling point, and small molecules often encountered in petrochemical and chemical industries. GC affords the measurement of solutes that are crucial to the businesses such as oxygen, nitrogen, carbon dioxide, and volatile sulfur containing compounds like hydrogen sulfide, carbonyl sulfide, and alkyl mercaptans for instance.

Despite the well-articulated needs, challenges remain in several areas for the successful implementation of said technique such as solute separation especially when single dimensional gas chromatography is employed along with a universal detector as in the case of thermal conductivity detection. It has been estimated that the probability of separation of every component in a complex matrix such as natural gas with single dimension GC, despite the availability of efficient columns, is in the range of 19 to 37% in a random mix as described by Giddings (1, 2, 3). Further challenges involve the transportation of the analytical equipment, and equipment set-up that might require days to reach operational status, sampling technique, and the need for skilled analytical practitioners. Recent developments in micro-electrical mechanical systems (MEMS) and advances in silicon machining technologies have reduced chromatograph size without significantly degrading the basic performance a contemporary bench-top gas chromatograph has to offer.

Due to the popularity of the analytical technique involved, miniaturization of gas chromatographic components such as injector, column, and detector have been a subject of intense interest. These efforts eventually led to the reduction of the overall size of the GC, and the transformation from bench-top to hand-held gas chromatograph.

The quest for a smaller size gas chromatograph has been a common goal for both academicians (4–9), and many GC manufacturers in an attempt to deliver solutions to various spaces ranging from emergency response to space discovery (10–12). One of the main drivers for such goal is there will be substantial capability improvement if this effort is realized. For example, lower power consumption by a factor of approximately five hundred times or more, higher chromatographic performance with small bandwidth of injection and narrow diameter columns to deliver improved theoretical plates per unit length, columns with high degree of selectivity including wall-coated and porous layer open tubular columns as well as a reduced sample size (mass) if a more sensitive detector compared to TCD is used (9). The incorporation of ultra-fast temperature programming to non-micromachined GC was shown to be successful (13–15). In contrast, the use of temperature programming with silicon machined microGC is still relatively new and is an active area of research in chromatography.

Effort in developing commercial micro-GC has spanned over a few decades. In the seventies, one of the most significant efforts in miniaturization was the concept of "GC-on-a-Chip" as taught by Terry et al. in his dissertation at Standford University (4).

In the eighties, Microsensor Technology Inc., (MTI) commercialized a "Mini-GC" that incorporated micro machined injector, and micro machined detector coupled to conventional micro packed or capillary column. Meanwhile in Europe, Chompack B.V. also offered products with similar performance known as the CP-2001, CP-2002 and CP-2003 series micro-GCs.

The nineties have been an excellent decade for the advancement of micro machined gas chromatography in that in 1994, Kolesar et al. (16) reported a lab prototype GC for the

measurement of environmentally interest molecules such as ammonia and nitrogen dioxide. In 1998, another major breakthrough involved the development of the first MEMS subsystem for chemical warfare agent (CWA) by Frye-Mason, et al. of Sandia (17). In the same year, Agilent Technologies acquired MTI Scientific. Subsequently, an improved version of micro-GC, was introduced as Agilent 3000 with many desired features like integrated sampling system, fixed volume injector, heated transfer line as well as an injector to prevent solute condensation and column back-flushing capability was commercialized (11).

In 2000, Muller et al. launched SLS Microtechnology, offering a commercially available prototype MEMS gas chromatograph for OEM purpose (10). In 2001, Varian Inc., after acquiring Chrompack commercialized an improved version of the CP-2002 series micro-GC, known as Varian CP-4900 with many desirable features described later in this paper (12).

Current product offerings of micro-GC do have some constraints. One of the limitations is the injector, which is only capable of handling samples in gaseous state. Another is the thermal conductivity detector (TCD). The TCD is a universal detector. As such, the matrix component will generally be detected and this can in turn mask components of interest that elute close to the matrix. Further, the TCD lacks the sensitivity required for sub ppm level analysis.

Yet another constraint of micro-GC equipment is the effect of isothermal operation of the instrument. This limits the application and boiling point ranges that can be handled by the analytical system. Irrespective of the column types and flow rates used, if the solutes elute from the column, the peak widths of the late eluting peaks tend to get broadened to such an extent that the sensitivities of said components are reduced. This effect is more pronounced on PLOT columns as these columns generally have lower plate numbers compared to WCOT columns. Also, as a consequence of the isothermal operation, the cycle time tends to be long due to the fact that highly retained components need to elute from the column before a new analysis can be initiated.

Recent technical collaborations between Varian Inc., the Dow Chemical Company (Dow), and at a later stage, the joining of Valco, have led to developments to enhance overall chromatographic performance of portable gas chromatographs in terms of sensitivity and selectivity. In order to address the lack of selectivity and sensitivity of the micro machined thermal conductivity detector (μTCD) commonly used in portable GC, a μDMD (Micro Differential Mobility Detector) has been successfully incorporated and commercialized in 2004 (18, 19). With two detectors on board and in series, the field of applicability of the analytical system improved. Speed of analysis can be gained by the incorporation of the μDMD with the extra selectivity gained. A sole μTCD detector, however, was employed in all the experiments described herein.

This paper demonstrates extending solute range and sensitivity improvement especially for highly retained solutes can be accomplished with the incorporation of ultra-fast temperature programming to μGC. The addition of fast temperature programming capability will further lead to faster analysis time, thereby improve analytical throughput.

Further, this paper focuses on the various effects temperature programming has on the stability of the TCD signal.

Experimental

All experimental work has been performed with Varian CP-4900 micro GC equipment (Varian, now Agilent Technologies, Middelburg, The Netherlands). As this instrument is only capable of performing isothermal analysis, temperature programming control was done externally using controller hardware from either RVM scientific (Agilent technologies) or Valco Instrument Co. Inc. (VICI, Houston, TX). For general use a Eurotherm (Invensis, UK) type 3500 temperature controller was used. All these controllers were placed externally to the micro-GC instrument.

The chromatographic columns were originally Varian standard columns equipped with propriety fast programming technology of RVM scientific or Valco Instrument Corporation. Unless otherwise stated, all fused silica capillary columns dimensions were with inner diameter of 0.25 mm and length of 5 meters; all coated with non-polar, polydimethylsiloxane stationary phase. MEMS type columns were obtained via SLS Micro Technology GmbH. (SLS, Hamburg, Germany).

The different columns were installed in the micro-GC as can be seen from the different pictures shown in Figure 1. A separate reference column which is an uncoated piece of narrow bore fused silica with a flow restriction equivalent to the analytical column is installed in the reference channel of the detector. The reference column length was determined by matching the flow rates between the reference and the analytical columns.

The RVM Low Thermal Mass (LTM) fast column temperature programming technology has been described in literature (20, 21). The VICI concept, although similar to the LTM technology, has some important physical differences. For this study, the length on the different capillary columns was between 5 and 7 meters. Both RVM and VICI column assemblies are air-cooled with an electrical fan.

The VICI column heating technology, under development since 2005, uses a single nickel wire or nickel clad layer to function as both column heating element and temperature sensor (22). The nickel clad column has an electroplated nickel coating on the fused silica column; a thin layer of polyimide over the nickel acts as an electrical isolation. The nickel wire column assembly is a fused silica column and nickel wire wrapped together with a thin thread of fiberglass. Both types are coiled and bundled together into a 5.72 cm (2.25 inch) diameter and wrapped with aluminum foil. The single nickel wire or nickel clad layer act as both heater as well as temperature sensor, so the temperature controller will heat and sense the column temperature without a time delay due to heat transfer. The working principle of the controller is based on the large temperature coefficient of resistance for nickel (23). The complete temperature control process is as follows: The controller continuously monitors voltage and current that is applied to the column bundle (nickel and column bundled together) and calculates its resistance using Ohm's law. Using this resistance and the column temperature-resistance calibration data stored in the microprocessor, the controller calculates the current column temperature. If the reading temperature is lower than the set value, the controller will increase the voltage applied to the column and vice-versa. Experimental data show the column temperature is controlled

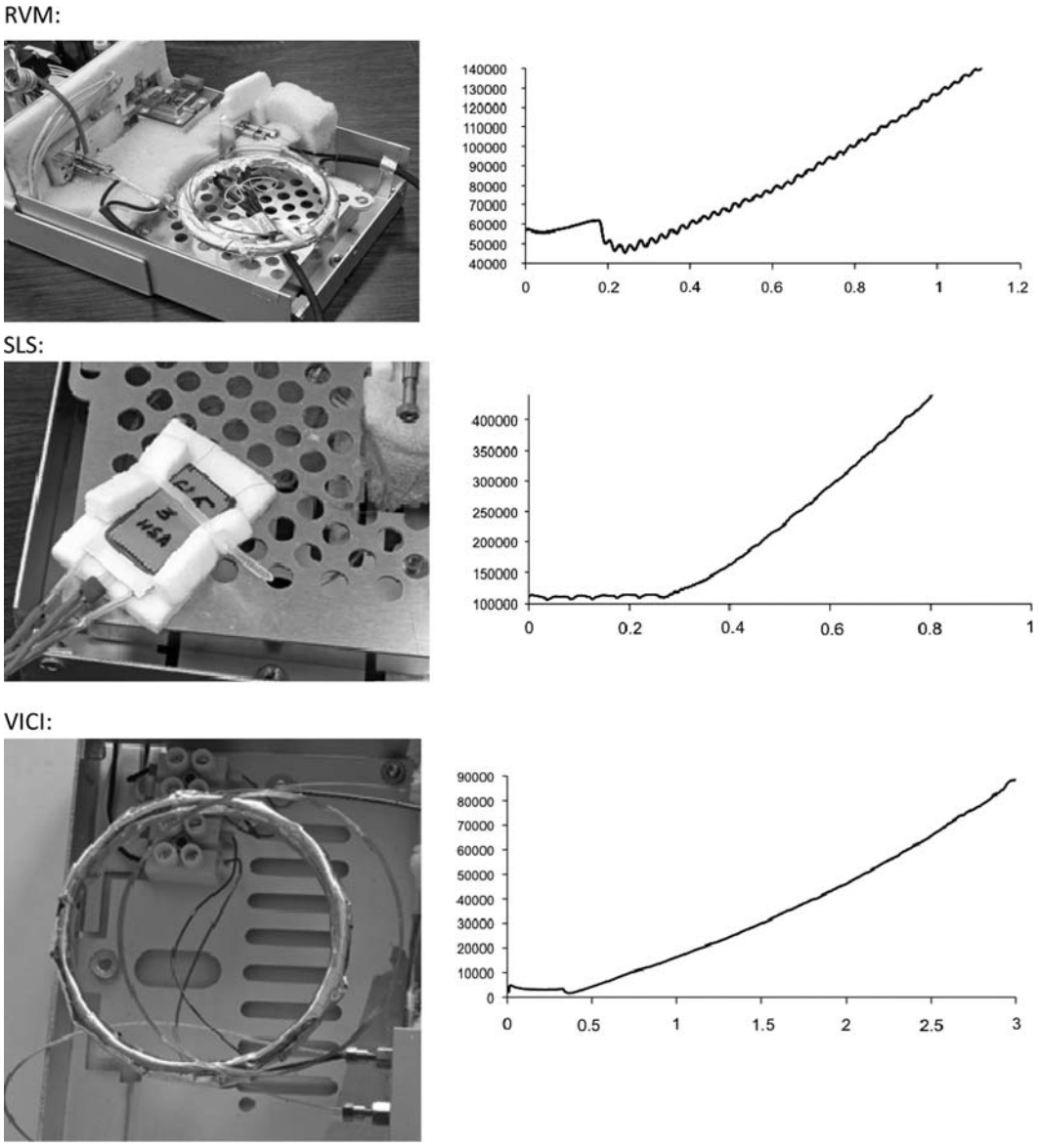


Figure 1. Pictures of different hardware for fast temperature programming concepts. *From top to bottom: RVM, SLS, VICI and their representative baseline profiles. The profiles show some control imperfections*.

with high precision as shown Figure 2. The downside of this approach is that each column needs to be calibrated with respect to its resistance-temperature relationship. The accuracy of the temperature depends on the column temperature-resistance calibration data.

Gas standards used for testing were obtained either from local vendors or manufacturing facilities at the Dow Chemical, Fort Saskatchewan Site, Alberta, Canada.

Results and Discussion

Improving detection limits

As with bench top GC, column temperature programming in micro-GC can extend application, boiling point and polarity ranges when compared to isothermal operation. It will also create a faster analysis time. In order to improve cycle time, for many applications a more critical parameter than analysis time, fast column cool down is required. The combination of low thermal mass column assemblies and forced, fan facilitated air cooling will give cooling rates in the order of a few degrees per second.

Column temperature programming in micro-GC also helps improve signal detectability, and hence overall system detection limits when compared to isothermal operation. This is caused by a reduced peak width for the later eluting peaks with increasing ramping rate as illustrated in Figure 3. Here, a three-fold increase of the peak height for butane, the last eluting peak in the chromatogram, with noise levels being unchanged, was observed when increasing the ramp rate from 1 to 6°C per second. Improved detection limits may also result from an increased peak height due to a cold trapping effect;

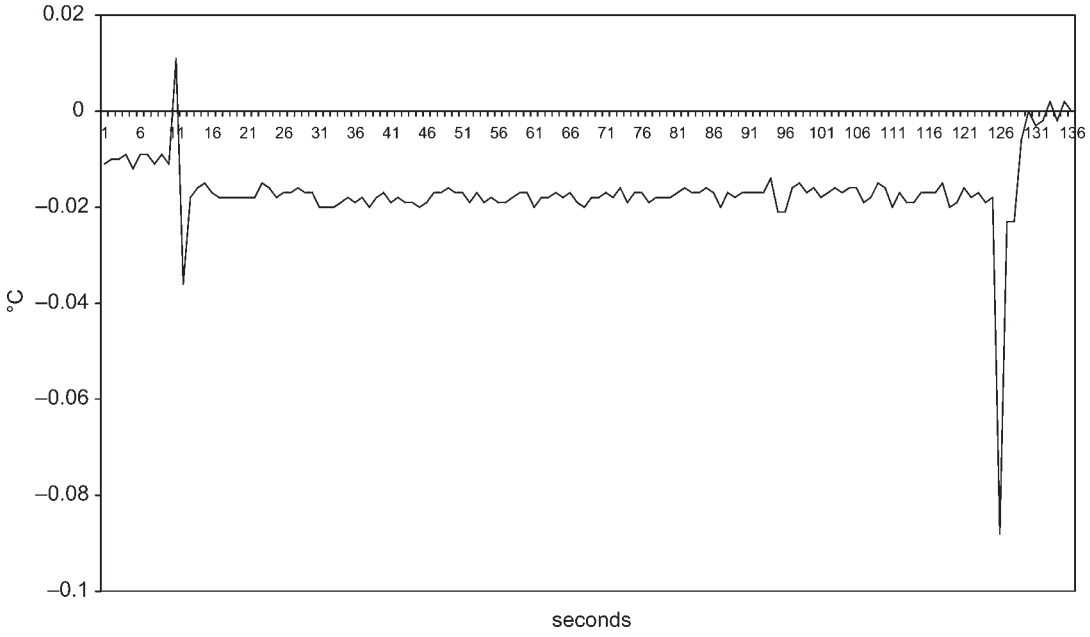


Figure 2. Difference between set and actual temperature from 35 to 150°C at 1°C/sec: Temperature control stability < 0.02°C absolute. Column: CP-sil 5, 5 meter; type VICI. Column: 35°C (10 sec) >> 50°C/min >> 150°C (10 sec).

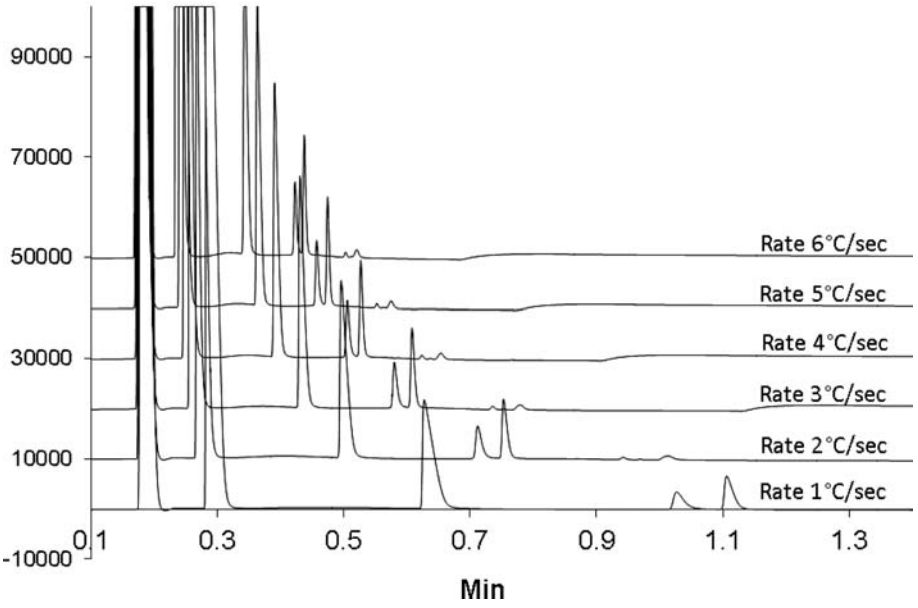


Figure 3. Impact of temperature programming rate on peak width of solutes 1°C/sec (lower trace) to 6°C/sec (upper trace). Column: PoraBOND Q, 7m x 0.25mm, $d_f = 3$ μm; type: RVM; Column: 30°C (15sec) > >varying > >220°C (10sec); Sample: Synthetic natural gas C_1-C_4 with butane as last eluting peak (Rt = 1.1 min at 1°C/sec rate trace).

allowing the injection of a large amount of sample. The CP4900 uses a programmable, time based microinjection device. Under isothermal conditions, injection times ranging from 10 to 100 milliseconds are used. Larger injection times will lead to "square" peaks, as the injection width exceeds the chromatographic distribution. In Figure 4, a 7 fold increase in peak height for the later eluting peaks was obtained when injecting 999 milliseconds instead of 100 milliseconds with temperature programming. Temperature programming allows the user to inject up to 1 second and above. Figure 4 also shows that by combining ultra-fast temperature programming with micro-GC, the solute range can be extended up to undecane (nC_{11}); this substantially increases the envelope of operation for micro-GC. Using the combined technique, respectable one day reproducibility of retention time of less than 1% relative standard deviation was attained (n = 20). By further optimizing parameters which have a direct influence on reproducibility of retention time, such as those described

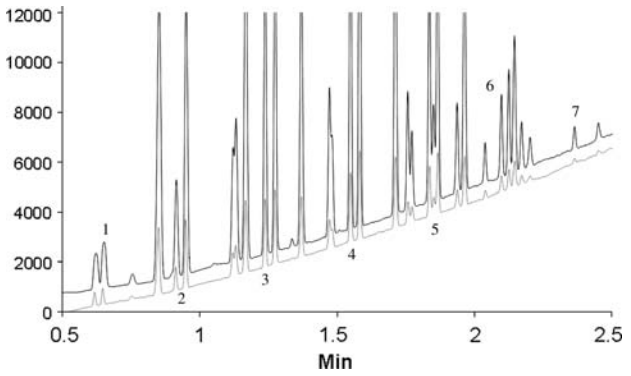


Figure 4. Impact of injection time on chromatography with on-column trapping at low starting temperature. Injection at 50 milli-second (lower trace) and at 999 milli-second (upper trace). Column: CP-Sil 5, 5m x 0.2 mm, $d_f = 1.2$ μm; type: VICI. Column: 30°C (20sec) > >1°C/sec > >220°C (10sec); Sample: Hydrocarbons spiked in helium; (1: n-pentane; 2: n-hexane; 3: n-heptane; 4: n-octane; 5: n-nonane; 6: n-decane; 7: n-undecane).

below, further improvements in both signal detectability and reproducibility of retention time can be realized.

Thermal Conductivity Detector noise

As shown earlier, temperature programming is capable of improving the detection limits of the analytical system. During this study, however, a number of events were encountered that had a negative impact on the TCD noise and therefore on the signal-to-noise ratio. Improvements obtained by temperature programming will be restricted without careful considerations of instrument design and control as well as laboratory environment. Stated below are a few examples:

Temperature control instabilities

The TCD signal is very sensitive to flow variations through the columns a result of small changes in the column temperature. Any control ripple will be reflected in the resulting TCD baseline signal. This was generally observed with an off-line control for the chip column as well as for the LTM column heating technology as shown in Figure 1. Due to the design involved, direct actual temperature feedback is not available to confirm the observed variations. With the VICI control module, the availability of the temperature feedback enables real time correlation between a baseline disturbance to an imperfection in the temperature control as illustrated in Figure 5.

Impact of carrier gas impurities and moisture

Column conditioning is a requirement before actual sample analysis takes place. Any first analysis on a new system, using a new column or after a longer idle period will show high elevated baseline profiles, often referred to as system "bleed". A couple of temperature cycles are required to drive out residual solvents and/or other volatile impurities and column bleed products.

On PLOT type columns such as porous polymers and/or alumina, in combination with TCD detection, moisture and other non-FID sensitive components will be detected as the TCD is a universal detector. Practitioners in gas chromatography had shown that water in the form of moisture

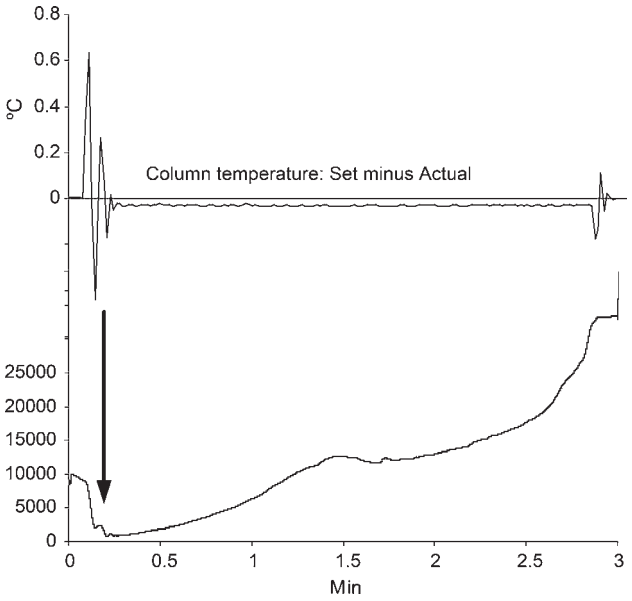


Figure 5. Observed baseline instability induced by the lack of system control stability. Column: Molsieve 5A, 5m x 0.25mm, $d_f = 30$ μm; type VICI. Column: 30°C (5sec) >> 1°C/sec >> 200°C (5sec). No sample injected.

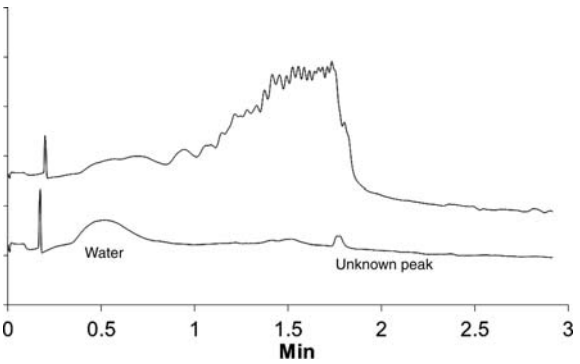


Figure 6. Overlay of baseline of new column (upper trace) and baseline after column has been conditioned (lower trace). Column: PBQ 5 m x 0.25mm, 3 μm; type VICI. Column: 30°C (5 s) >> 1°C/min >> 200°C (10 s).

in a sample can be determined by using porous polymer columns and a TCD. After an idle period, moisture and eventually other contaminants in the carrier gas and or pneumatic system can accumulate at the first part of the column as this is at a relatively low temperature. Upon temperature programming, these components will elute at their proper retention temperature as a baseline disturbance, a broad peak or plateau as illustrated in Figure 6. One way to minimize this problem is to leave the chromatographic system at an elevated temperature to minimize the trapping of moisture in the carrier gas or impurities in the chromatographic system.

Impact of air turbulence around the column

It was found that the air turbulences inside any laboratory have a big contribution to the noise level, even under normal isothermal operation. Air turbulence commonly occurs inside an analytical lab as a result of traffic activities and ventilation/

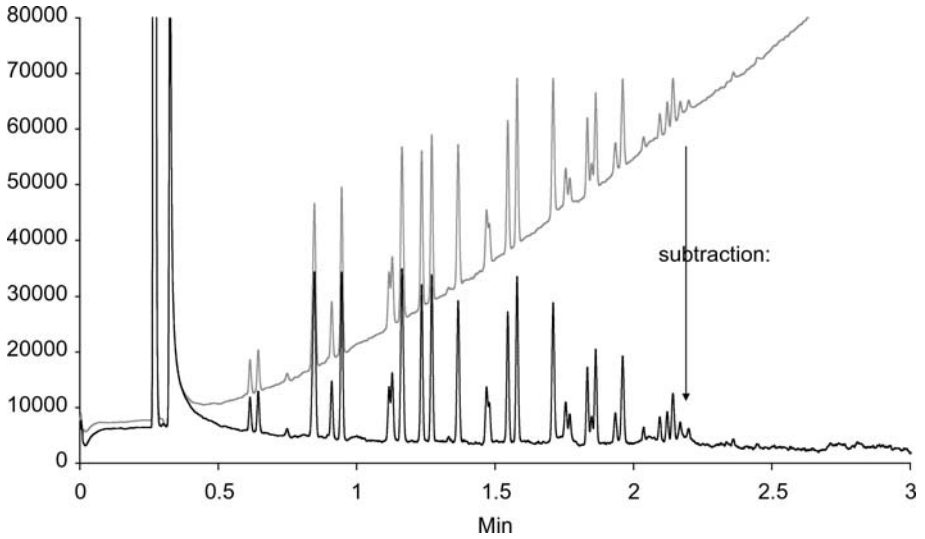


Figure 7. Baseline instability with baseline subtraction approach - Noise increases by a factor of 2. Column, CP-Sil5, 5m x 0.2 mm, $d_f = 1.2\mu$m, type: VICI; Column, 30°C (20sec) >> 1°C/sec >> 220°C (10sec); Sample, hydrocarbons spiked in helium.

circulation systems such as fume hoods. This turbulence creates slight temperature differences over the column, and thus minute flow fluctuations leading to an erratic baseline. It is necessary to reduce these air movements around the capillary column to a minimum by means of proper instrument design to reduce the analytical system's noise and thereby, increase signal-to-noise for improvement in system detection limit. In contrast, for isothermal operation, the column is well insulated in order to improve column temperature stability; and as such, the impact of lab air turbulence has not been observed.

Baseline subtraction

One way to correct baseline drift during a programmed analysis is to employ baseline subtraction as illustrated in Figure 7. Baseline subtraction is a standard feature available in contemporary chromatographic data acquisition software. The drawback of this mathematical operation; however, is the inherent increase in noise level. Subtraction doubles the variance value which will lead to two fold increases in noise level for the detector used. This results in a higher system detection limit. For higher concentration applications, baseline subtraction creates pleasant visual results. For trace analysis; however, this concept is of limited benefit and is contra-indicated in the effort to improve system overall signal detectability.

Reference column integration

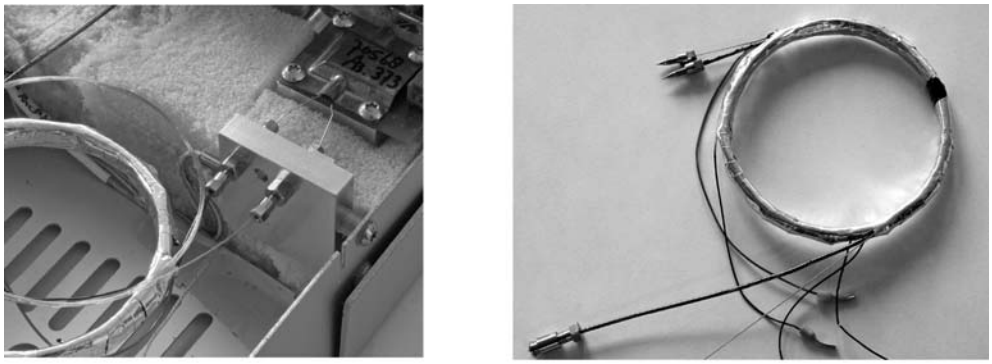
Most gas chromatographic instrumentation equipped with a TCD detector uses a reference column to counteract flow fluctuations that might take place in the analytical column as a result of flow or pressure control. The reference column feeds a separate cell which is electrically, together with the analytical cell, placed in a Wheatstone bridge. The reference column is often chosen with identical dimensions as the analytical column or with different dimensions but having an identical flow restriction as the analytical column. The latter is the case in the CP-4900 where a short piece of narrow bore capillary tubing having the identical flow restriction to the analytical capillary column is used as the reference column.

Under temperature programming, the column flow decreases with increasing column temperature due to increasing carrier gas viscosity. The result on the TCD signal is a continuous, almost linear increase of the baseline signal. If no reference column is used, this signal drift is obvious and directly related to the flow variation with temperature. With a reference column in place, the signal drift is related to the difference in flow between the analytical column and the reference column. The larger the flow difference, the bigger the drift. In the case of an almost constant flow through the reference column, meaning the reference column is positioned outside the heated assembly, severe drifting of the baseline occurs. If the reference column is coiled together inside the heated assembly where the reference and the analytical columns are heated together following the exact temperature profile, the baseline drift is reduced. An almost horizontal baseline is observed if the reference column flow closely matches the flow of the analytical column. Yet, the reference may be of different column inner diameter.

As a consequence of the bundling together of the analytical and reference columns, any imperfection in the control as well as external influences are balanced resulting in a much more stable baseline signal as shown in Figure 8.

Conclusions

With the described equipment, temperature programmable micro-machined gas chromatography for practical use has been successfully demonstrated. This will lead to more flexible and capable instrumentation. The combined technique of micro-GC and ultra-fast temperature programming up to a rate of 6°C/second yielded an extended analysis range to undecane (nC_{11}), improved signal detectability by at least a factor of three for the solutes studied with respectable one day reproducibility of less than 1% relative standard deviation in retention



Reference column apart (left) and integrated (right).

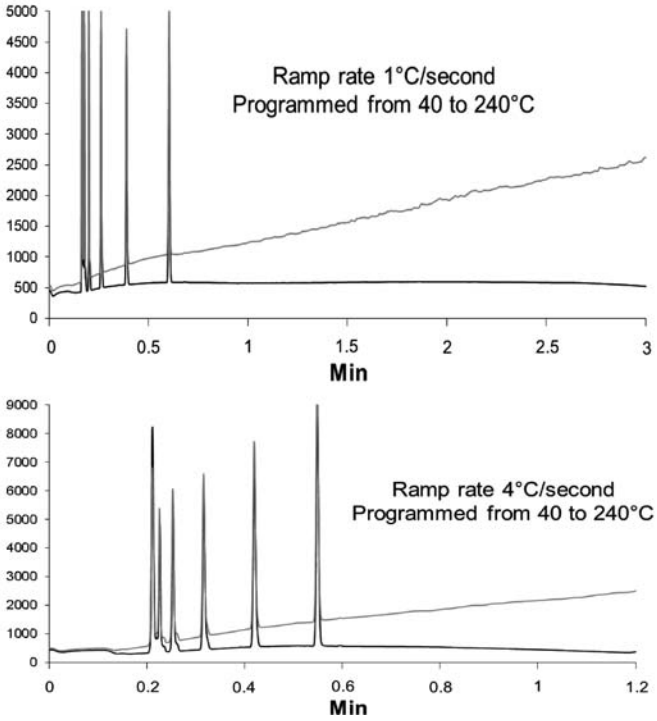


Figure 8. Overlay of system baselines generated using an integrated (lower trace) and isolated (upper trace) reference column. Column: 7 m x 0.15 mm x 1.2 μm Silica (SiO_2) phase: type VICI. Reference:100 cm x 0.075mm x .2mm.

time (n = 20). Improved analytical system throughput and sensitivity can further be attained with careful design of the instrument.

Factors affecting performance, not limited to the ones investigated in this publication such as type of controller and associated algorithms, the impact of ambient air circulation, impurities in carrier gases and chromatographic pneumatic systems, baseline subtraction technique, the selection and the incorporation of reference column inside the column bundle, should play an important role in system design and implementation.

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