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A high-repetition-rate, fast temperature-programmed gas chromatograph and its on-line coupling to a supercritical fluid chromatograph (SFC×GC)

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We present a fast gas chromatographic system that can be used as a second dimension in comprehensive two-dimensional (supercritical fluid × gas) chromatography (SFC×GC). The temperature of the short (1 metre long) capillary column is controlled by a resistively heated coaxial stainless-steel tube. The electrical resistance and therefore temperature of the stainless-steel tube is measured by continuous monitoring of the current/voltage ratio. Highly repeatable heating rates of up to $2100\,°C\,min^{-1}$ ($35\,°C\,s^{-1}$) are obtained, which should be high enough for the most demanding fast chromatograms. To reduce the cooling time between temperature programs the column is cooled by injecting evaporating carbon dioxide into the space between the coaxial heater and the column. This gives cooling rates of $5100\,°C\,min^{-1}$ ($85\,°C\,s^{-1}$) which allows quick succession of temperature programs. More repeatable heating profiles with stable GC retention times together with faster cooling are significant improvements on previous SFC×GC systems. Cycle times of four gas chromatograms per minute could readily be achieved, which allows efficient coupling to high-resolution stop-flow SFC in the first dimension. We demonstrate the fast chromatograph by separating fatty acid methyl esters, yielding information which would be useful in the food and biodiesel industries.

Keywords: high speed temperature programmed GC, sub-ambient GC, fast process GC

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I. INTRODUCTION

Speed of analysis is a most important criterion for any analytical system. Chromatography as an analytical technique is notoriously slow, compared to, say, some spectroscopic techniques. While it is of interest to (especially high-throughput) laboratories to reduce run times, at some point the faster chromatography starts outstripping the sample preparation capacity. Once the chromatographic run duration approaches the time it takes to prepare the sample, faster chromatography will not improve the sample throughput. Technology development in fast chromatography is therefore driven not by conventional injection-based chromatography, but by applications where no sample preparation is necessary and rapid results are needed.

Examples of these would be headspace analysis for detecting explosives[1], drugs[2] and fuel adulteration[3], monitoring anaesthetic agents in the breath of sedated patients[4,5], and in 'electronic noses' that can distinguish between frozen and chill-stored meat[6]. Another application for fast gas chromatography is industrial process monitoring[7].

However, in the past two decades the major application for fast gas chromatography has not been in direct sample analysis, but in the analysis of fractions of eluate from chromatographic separations. This concept is called *comprehensive two-dimensional chromatography*. For example, in comprehensive two-dimensional gas chromatography (GC×GC), fractions of a conventional gas chromatographic run are collected by a *modulator* and then admitted to a second, fast gas chromatograph[8]. GC×GC has become well established: the annual GC×GC Symposium is in its 15th year, and major reviews are published regularly[9,10].

In comprehensive 2D chromatography the second-dimension chromatography must be *fast*. The theory and practice of improving the speed of GC is well developed[11,12]. Typically, short columns and high carrier flows rates are used, which reduce retention times by reducing void times. Resolution can be maintained at even higher gas flows by using narrow-bore columns and thin films: these improve the mass transfer rate between the mobile and stationary phases, which reduces peak broadening by bringing the analyte exchange between the phases closer to equilibrium at higher-than-optimum carrier gas velocities.

Comprehensive two-dimensional chromatography depends on *orthogonality*: the second dimension (^{2}D) separation must have a different mechanism than that of the first dimension (^{1}D) separation[13,14]. The higher the orthogonality, the better the *separation space* offered by

the system. In GC×GC the different separation mechanisms that determine orthogonality are usually provided by the different stationary phases offered by column manufacturers, but it is also possible to use a different form of chromatography as a first dimension: liquid chromatography has been used as a first dimension in LC×GC[15], and in our laboratory we are developing SFC×GC instrumentation[16].

If a chromatographic ²D separation is highly orthogonal to the ¹D separation, then the ²D separation will run into the *general elution problem*[17]: the higher the orthogonality, the more diverse the compounds found in each ¹D fraction, and it becomes increasingly unlikely that one set of acceptable operating conditions (temperature, flow and stationary phase) will an give an acceptable (fast enough and with adequate resolution) ²D separation. In GC×GC as it is practised today this has become a real problem, known as *wraparound*, a well-known phenomenon[18]. Wraparound happens when a peak or peaks elute 'late' on the second dimension, so late that the next modulation period has already started before its elution and the peak only appears on the next ²D chromatogram. Careful interpretation of 2D chromatograms can identify which peaks can be attributed to wraparound, and adjusting some parameters might mitigate the problem.

If the general elution problem causes the phenomenon of wraparound in GC×GC, where the compounds found in ¹D fractions have a relatively narrow boiling point range, it will cause much greater problems in SFC×GC, since the first dimension (SFC) does not normally separate compounds in a way that correlates with vapour pressure. Indeed, SFC is particularly good in performing group-type separations[19], where compounds with a wide range of boiling points elute together. Therefore, in SFC×GC we can expect compounds with a wide range of boiling points in each ¹D (SFC) fraction, and the general elution problem makes it unlikely that an isothermal ²D (GC) run will provide an acceptable separation. This is why successful SFC×GC demands temperature programming in the GC dimension.

A. Fast column heating for GC

In GC the usual solution to the general elution problem is temperature programming, *i.e.* increasing the temperature of the column throughout the duration of the chromatographic run. Temperature programming decreases the retention times of late-eluting analytes without sacrificing the resolution of early-eluting analytes. Instrument manufacturers

have mastered the art of temperature programming, and today the vast majority of 1D gas chromatography uses temperature programming.

However, implementing temperature programming in the fast ^{2}D GC poses some challenges. Since the recommended heating rate for temperature programmed chromatography is around $10\,^\circ$C per void time[20], the short void times of fast chromatography imply that high heating rates are required. Conventional air-bath GC ovens cannot attain these high heating rates, and therefore specialized column heating is required. Resistive heating by electric current offers a simple method, as reviewed[21,22], and a recent paper[23] describes the elimination of wraparound in GC×GC of diesel samples using resistive heating to implement a simple temperature program in the ^{2}D column.

Of the three broad classes of resistive heating of capillary columns identified[21] (*i.e.* (1) direct heating of a metal column or conductive coating on the column, (2) coaxial heating by a conductive tube around the column, (3) collinear heating by a heating element parallel to the column), we have experience with direct heating and coaxial heating.

In previous work in our laboratories[16,24] a resistively heated metal column was used. The temperature of the column was controlled by following the temperature of a thermocouple glued to the column, but this method had some shortcomings, like uncertainty about the absolute temperature along the length of the column and stationary phase limitations: metal columns are often developed for high-temperature applications, and are not available with all the stationary phases offered in fused silica columns.

In this work we used a coaxial heater, in the form of a thin-walled stainless-steel tube that surrounds the capillary column. This tube is resistively heated by controlled direct current. Due to the low thermal mass the heating is rapid, and since the resistance of the tube indicates its temperature there is no need for external temperature measuring devices. The benefit of this design is that it allows the use of commercially-available fused silica columns with their wide range of internal diameters and selectivities. Columns can be exchanged without altering the temperature feedback system and therefore the rapid heating characteristics. Additionally, the co-axial space between the capillary column and the stainless steel tube can be filled with coolant to rapidly cool the column.

B. Fast column cooling for GC

At the end of temperature-programmed chromatographic run, GC columns are usually cooled to the starting temperature by ambient air. This cooling is slow and inefficient because of the poor conductivity and low heat capacity of air. Fast chromatography usually implies analysis at high repetition rates, so cool-down times also need to be shortened.

There have been attempts to improve the cooling rate of air baths. Agilent™ markets a 'low thermal mass' column, which includes a collinear heating wire and a collinear sensing element bundled with a short silica column. These units cool down faster than normal air-baths, but only to ambient temperature. For short columns a cooling time of 1.3 min has been reported[25]. These columns are available with only a limited range of stationary phases. The Zip Scientific™ solution operates by forced convection. Their 'GC-Chaser' system uses a blast of (chilled) room air to the GC oven to cool it down after each GC run, allowing the use of conventional fused silica columns. In an example[26] it reduces cooling time from 16 min to 7 min. Although this can significantly decrease the cost per analysis in a high-throughput laboratory, the cooling is not fast enough for 2D chromatography. The EZ Flash™ system uses a coaxial resistive heating system, which allows the column to cool down ballistically. Reports from the literature claims cool-down periods of 30 s[27]. The Valco FTP-200 fast temperature programmer[28] (Valco Instruments Co. Inc.) uses a small, optional fan to cool down the columns.

Cryogenic coolers for GC ovens are available but are intended to cool the oven to low temperatures for the analysis of volatile compounds and not necessarily to improve cycle times. In previous SFC×GC work in our laboratories[16,24] the cryogenic function of a Varian 3300 gas chromatograph was used to cool down the column oven at the beginning of each run, using large quantities of coolant in the process. The resistively heated column cooling required 30 s to get back to the starting temperature in this cool environment. We estimate that a single SFC×GC run consumed an unacceptable 15 kg of carbon dioxide coolant.

Recognizing that the precise application of coolant will require less coolant and permit faster cooling, we developed a system that injects liquid carbon dioxide into the space between the column and the coaxial heater. The evaporating carbon dioxide rapidly absorbs heat from the column and coaxial heater, achieving a high cooling rate to sub-ambient temperatures at a minimal expense of coolant.

At the same time, the cold GC column acts as a focusing trap for the subsequent sample, and thus forms an integral part of the modulator of the SFC×GC system.

C. Application

The fast GC system described in this paper can be used in any application where fast chromatograms are needed in rapid succession, for example in process control. In our case we applied it as a fast second dimension separation, comprehensively coupled to a supercritical fluid chromatograph.

We applied our fast GC system to the evaluation of fatty acid profiles of potential biodiesel feedstock. The fast GC separation was highly orthogonal to the ^{1}D separation on SFC, showcasing this type of comprehensive two-dimensional chromatography. An easily interpretable 2D separation was obtained, with run times similar to the total run times required by official GC methods for the determination of fatty acid profiles.

II. EXPERIMENTAL

A. Introduction

For better understanding of subsequent detail, a description of the cycle of the SFC×GC is appropriate. The SFC subsystem runs in stop-flow mode. The eluate of the SFC passes through a stop valve and a static linear capillary restrictor. The end of the restrictor is inserted through the septum into the hot inlet of the GC. After the sample is injected, the SFC runs for an optional uninterrupted period, usually briefer than the void time. No data is collected during this time. Then the stop valve closes, and the cooling system activates to cool the GC column. Once the column is at the set temperature, the stop valve opens and the SFC eluate exits the restrictor into the hot splitless inlet of the GC, where it evaporates instantly. The vapour-phase material is swept from the inlet onto the column where it is trapped in the cold stationary phase. Once the desired amount of the SFC eluate has been collected, the stop valve closes and some time is allowed to elapse so that the last of the evaporated SFC eluate can be flushed into the column. Then the split vent of the GC inlet opens for a short period to vent excess carbon dioxide to the atmosphere. This normalizes the pressure in the inlet (having been raised by the high flow rate of CO_2 from the SFC)

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and allows the carbon dioxide to be replaced by the pressure-controlled hydrogen carrier gas. The closing of the split vent marks the start of the GC run, which of course means the start of the temperature program. Under control of the temperature program the analytes trapped on the head of the cold column desorb, migrate, separate, elute, and are detected. The end of the temperature program marks the end of the GC run, and the GC column is cooled to prepare for trapping the next fraction.

B. Hardware

The short-cycle fast gas chromatograph was built into a modified Varian™ 3300 gas chromatograph. The inlet was a Varian™ 1075 split/splitless inlet. The temperature control of the inlet was by the original electronics, controlled from the Varian 3300 front panel. The split vent valve was disconnected from the gas chromatograph control and connected to the control computer described below.

The detector was an unmodified Varian™ 3300 flame ionization detector (FID). The temperature of the detector was regulated by the original electronics, controlled from the front panel. The detector bias voltage was supplied by the original electronics, but a stand-alone high-speed electrometer (V.G. Micromass Ltd, Model M406-H) captured the signal, which was then conditioned by a bench-top amplifier (V.G. Micromass Ltd, Model M406) before it was sent to the computer.

The coaxial heater was made of a 940 mm length of stainless steel (SAE 304 grade), obtained from MIFAM (Milanówek, Poland). It had an outside diameter of 1.06 mm and an inside diameter of 0.80 mm. The ends of the coaxial heater tube terminated in two identical, specially designed T-piece blocks, machined from brass (See Figure 1). These blocks fulfilled three roles: They (1) sealed the coaxial tube to contain coolant, (2) allowed electrical connection to the coaxial heater, and (3) acted as a heated transfer line between the column and the detector and inlet. Each end of the stainless-steel tube of the coaxial heater was brazed onto a block. The CO_2 coolant passed through one side, and on the opposite side a thermocouple probe inserted into a blind hole measured the temperature of the block. An electrical contact was added, to which an electrical conductor could be soft-soldered. Four holes through the width of the block allowed the fitting of four 220 V, 100 W heater cartridges (Hotset), providing each of the two blocks 400 W of heating. The
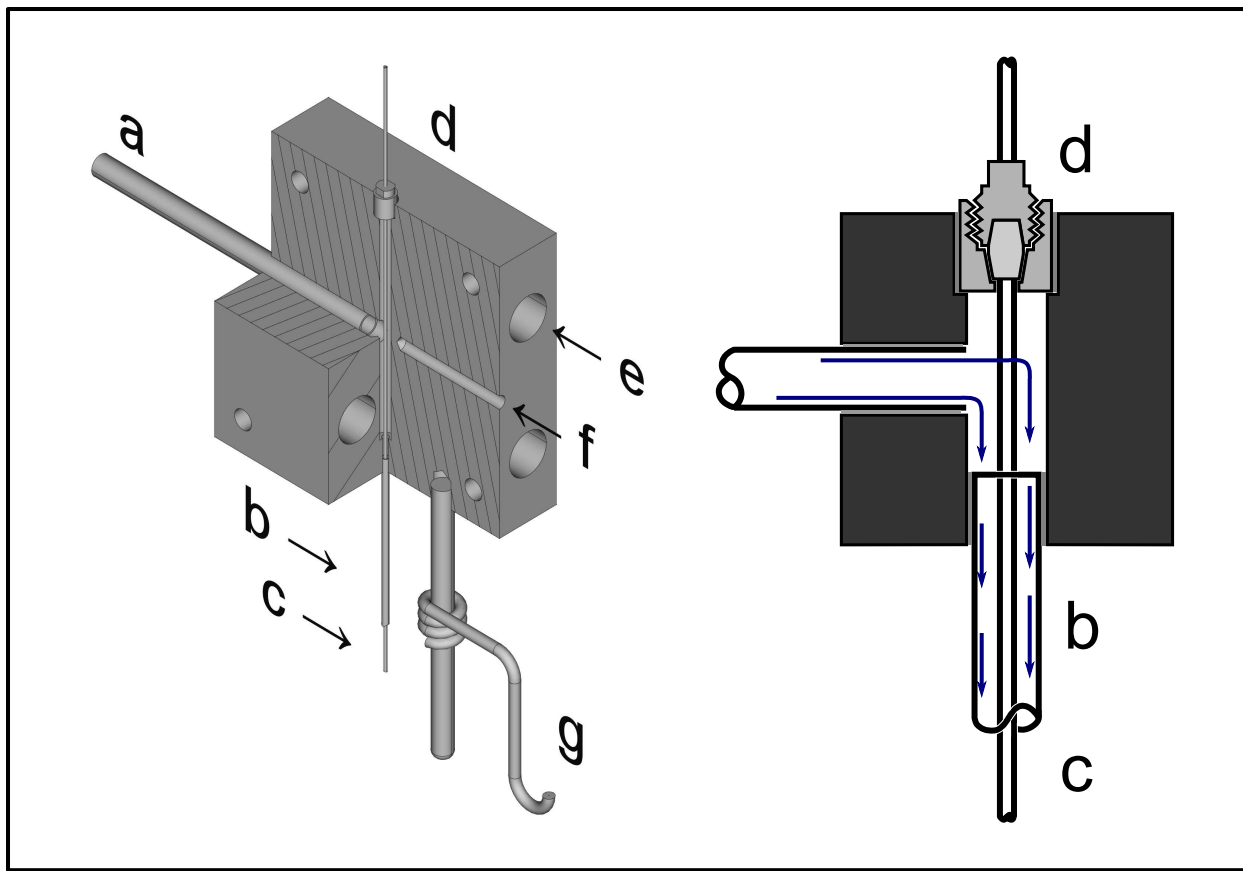
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FIG. 1. Left: A cutaway diagram of the inlet/outlet outlet T-piece blocks with all the parts to scale, showing (a) the cryogenic coolant inlet/outlet, (b) the coaxial heater, (c) the capillary column, (d) the micro-union seal, (e) the cartridge heater socket, (f) the thermocouple socket, and (g) the connector to which the power feed conductor was soft-soldered. Right: A schematic diagram showing the flow of the coolant through the T-piece block into the coaxial heater.

chromatographic capillary column entered the T-piece block via the bottom port with the coaxial heater tube and passed out through the top port, where a micro-union using a metal ferrule (Restek™ SilTite μ-Union Connectors) brazed to the block created a seal to contain the coolant. From the top port the the column crossed a small, electrically isolating air gap before entering the inlet or detector.

The T-piece blocks were mounted on 'cars' that slid up and down twin round-bar rails on brass bushes. The cars carried the weight of the inlet and outlet T-piece blocks and rigidly aligned the column with the inlet and detector of the gas chromatograph. The cars were isolated electrically from the rails by a sandwich construction that included silicone-

impregnated mica as insulating material. The whole of the inlet and outlet T-piece blocks were at the electrical potential of the coaxial heater ends.

The cryogenic carbon dioxide (Afrox, Tec (Wet)) was supplied from a cylinder equipped with a dip tube. It flowed to a coil heat exchanger mounted on top of the Varian GC from where the carbon dioxide flowed down to the cryo shut-off valve (ASCO, RedHat brand). (The heat exchanger was bathed in a cold ($-5\,°C$) propylene glycol heat transfer fluid.) This arrangement ensured a supply of liquid CO_2 at the shut-off valve, without which some gaseous CO_2 might have to vent through the coaxial heater before the liquid CO_2 coolant could reach it. Downstream of the shut-of valve a 10-turn metering valve controlled the flow of carbon dioxide into the coaxial heater. At the outlet end of the coaxial heater the carbon dioxide escaped through the T-piece block into the atmosphere.

The SFC subsystem consisted of five packed silica columns ($150\,mm \times 4.6\,mm$, $3\,\mu m$ particles) (Restek, Pinnacle DB Silica) in series, a sample valve (VICI), and a stop valve (VICI). Carbon dioxide, ($99.995\,\%$ purity, Air Products) was supplied to a Varian 8500 piston pump. The inlet pressure of the SFC columns was controlled by a software proportional controller driving the stepper motor of the piston pump. The high pressure at the column exit was maintained by a linear fused silica capillary restrictor with an internal diameter of $0.050\,mm$, $800\,mm$ long.

C.   Electronics

The electronics for controlling the fast temperature programmed gas chromatograph and the SFC front-end was developed in-house. A controlled direct current was used to heat the coaxial heater. The heating circuit consisted of the coaxial heater in series with a reference resistor and a ballast resistor. The reference and ballast resistors were constructed from stainless steel wire with a diameter of $1.0\,mm$. The reference resistor had multiple, parallel conductors, the ballast resistor had a bifilar winding, and both had air cores. These designs (see Figure 2) minimized electromagnetic interference and encouraged heat dissipation. Since the coaxial heater resistance measurement used a two-wire technique, the current-carrying circuit was made entirely of soldered joints to minimize stray resistance from developing in electrical connections.

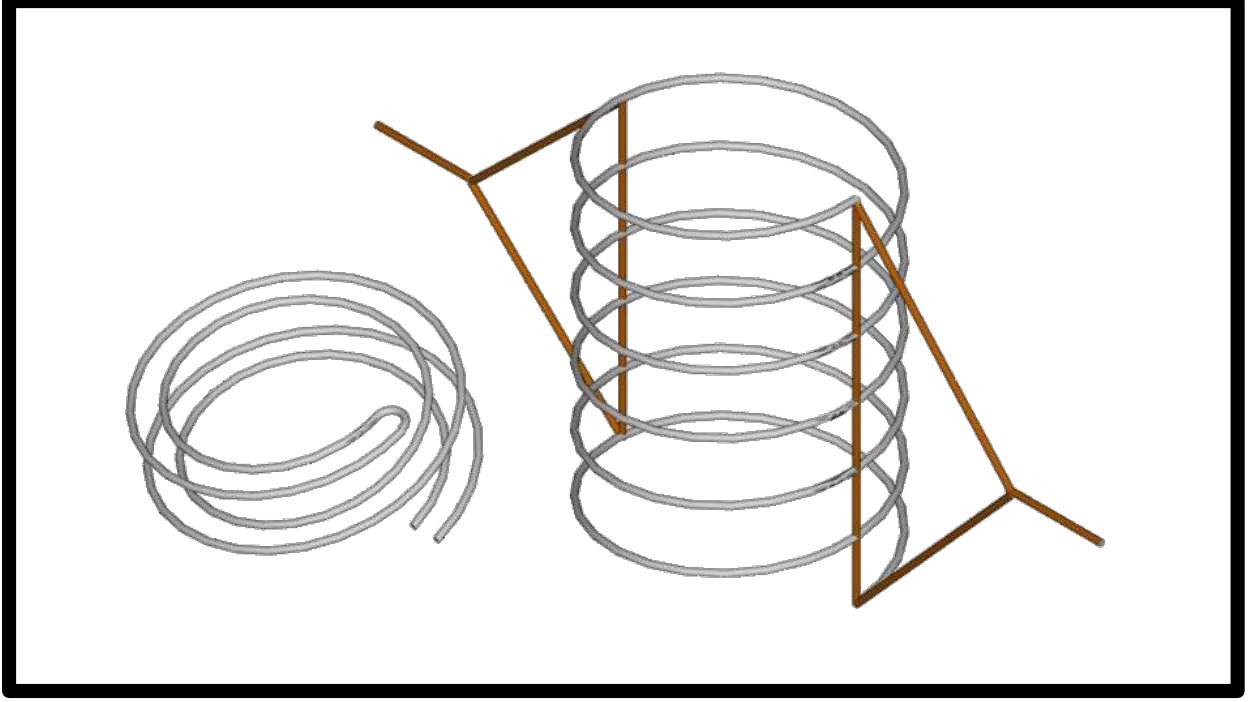The resistance of the reference resistor (R_{ref}) was about $0.005\,\Omega$, the resistance of the

FIG. 2. An illustration of the designs of the ballast (left) and reference (right) resistors. The outside diameters of the coils are about $25\,\mathrm{mm}$ and $50\,\mathrm{mm}$ respectively. The designs emphasize heat dissipation by air convection and mitigation of electromagnetic interference by using parallel conductors.

coaxial heater (R_{col}) was about $0.3\,\Omega$, and the resistance of the ballast resistor was about $0.01\,\Omega$, so that most of the heat in the circuit was dissipated by the coaxial heater. The potential differences across the coaxial heater (V_{col}) and the reference resistor (V_{ref}) were measured (See Figure 3). If the resistances of the coaxial heater and the reference resistor were both constant, the ratio V_{col}/V_{ref} would be constant, independent of the current. But metals have positive coefficients of resistivity so the resistance of the coaxial heater will increase with temperature. If the assumption is made that the temperature of the reference resistor does not change, then the ratio V_{col}/V_{ref} will be proportional to R_{col}. If the resistance R_{col} is assumed to be a monotonically rising function of the temperature $(R_{col} = f(T))$, then the inverse function will provide the temperature $(T = f^{-1}(R_{col}))$. In practice the voltage V_{ref} is too small to be digitized directly and needs to be amplified to V_b, but it can be shown that R_{col} is a function of $\left(\frac{dV}{V_b}\right)$, where dV is the difference between the supply voltage and V_b. dV and V_b are of magnitudes that can be conveniently digitized.
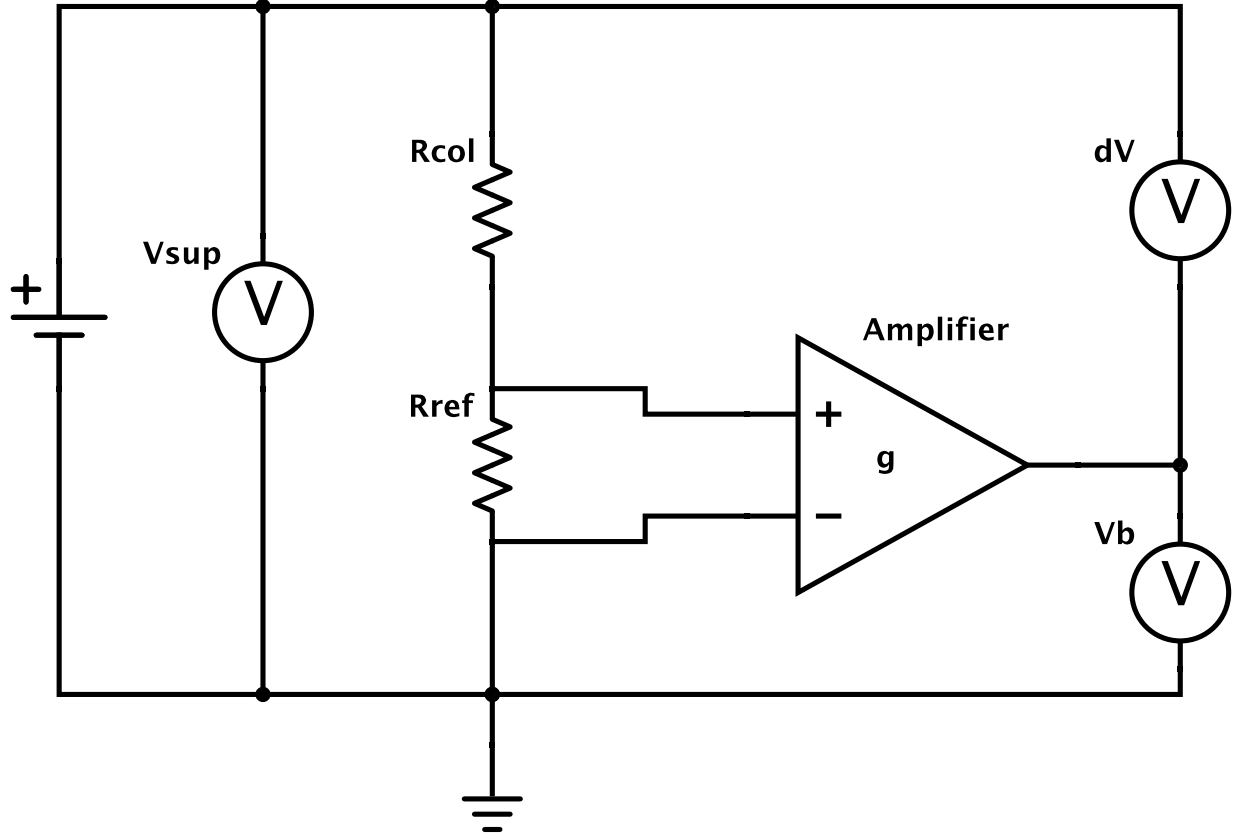
FIG. 3. A simplified circuit diagram of the resistance measuring circuit.

A bank of six PNP 2N2955 bipolar transistors mounted in parallel on an aluminium plate air-cooled by two 4-inch fans controlled a current of up to 20 A at 20 V through the coaxial heater. A two-stage control system controlled the current. The first stage of the control system was a PID controller implemented in LabVIEW 7.1™ (National Instruments). The process variable was the temperature of the coaxial heater, as calculated from its electrical resistance, and the set value was determined by the desired chromatographic temperature program. The manipulated variable was the voltage of the digital-to-analog converter (DAC) of the data acquisition board. The final stage was an electronic system, where the voltage applied to the coaxial heater was the process variable, and the set value was a voltage provided by the DAC. The manipulated variable was the base current of the power transistors. In summary, the software set a voltage, which set the power of the coaxial heater. This two-stage design allows for switching of the control of the coaxial heater from computer control to manual control by a potentiometer on the instrument front panel. Being able to

control the power of the coaxial heater manually is extremely useful during development and fault-finding.

AD595 monolithic thermocouple amplifiers (Analog Devices) with integral cold junction compensation were used to condition the signal of the K-type thermocouples that were used for temperature monitoring and calibration. Solid state relays (Opto 22, Model 240D3) were used to switch the inlet and outlet T-piece block cartridge heaters (described above) on and off. Pulse width modulation, implemented in software, was used to control the amount of heat produced by the cartridge heaters, and hence the temperature of the T-piece blocks. A PCI-6014 multifunction data acquisition board (National Instruments™) was used to interface the electronics with the computer.

D. Coaxial heater temperature calibration

The temperature of the coaxial heater was calibrated by constructing a thermocouple probe from 0.025 mm diameter thermocouple alloy wire (T1 and T2 alloys, Goodfellow) threaded inside a 1000 mm length of 0.25 mm i.d. fused silica capillary. This thermocouple probe was then threaded inside the coaxial heater (just like the capillary column during GC operation) to record the temperature of the heater. The recorded temperature could then be used to calibrate the coaxial heater resistance.

E. Heating uniformity

To determine whether the coaxial heater was heating the column with acceptable uniformity, we used two methods. Firstly, we acquired thermographic videos of the coaxial heater, using a FLIR T660 infrared camera. Secondly, for experiments in determining temperature gradients, a thermocouple probe was constructed as described above, except that the probe contained two thermocouples, 330 mm apart, equidistant from the ends.

F. Software

1. Instrument Control

The software for controlling the instrument and collecting data was written in LabVIEW. Two main loops were used. One controlled the various aspects of the instrument, in particular the temperature control, and ran with a period of 200 ms. The second main loop collected the data and ran as often as the hardware allowed.

The coaxial heater temperature was controlled by proportional-integral-derivative (PID) controllers implemented in LabVIEW. In practice it was found that only proportional and integral control was needed. We used a privately published[29] step-by-step implementation of the Cohen-Coon loop tuning method. Subsidiary PID controllers controlled the T-piece block temperatures and the CO_2 pump pressure.

2. Data structure

In GC×GC, 2D data is recorded as a continuous detector output stream, as if it were a 1D GC chromatogram, and later converted into a 2D chromatogram, using knowledge of the modulation period. For two reasons we could not use this approach. Firstly, in our instrument the first (SFC) dimension runs in a stop-flow mode making continuous data recording inappropriate. Secondly, the duration of the cooling cycle can vary slightly, which could introduce unacceptable variation in ^{2}D retention times. We therefore started detector output recording at the start of each GC fast temperature program, using the GC start time as the elution time of the first (SFC) dimension.

3. Data visualization

For data visualization we used the technical computing system Mathematica 11.3™ (Wolfram). The collected data was first converted to a list of three-element lists, with ^{1}D retention time, ^{2}D retention time, and detector signal as the elements of the inner lists. The Mathematica functions `List3DPlot[]` and `ContourPlot[]` was then used to plot 3D chromatograms or contour plots respectively.
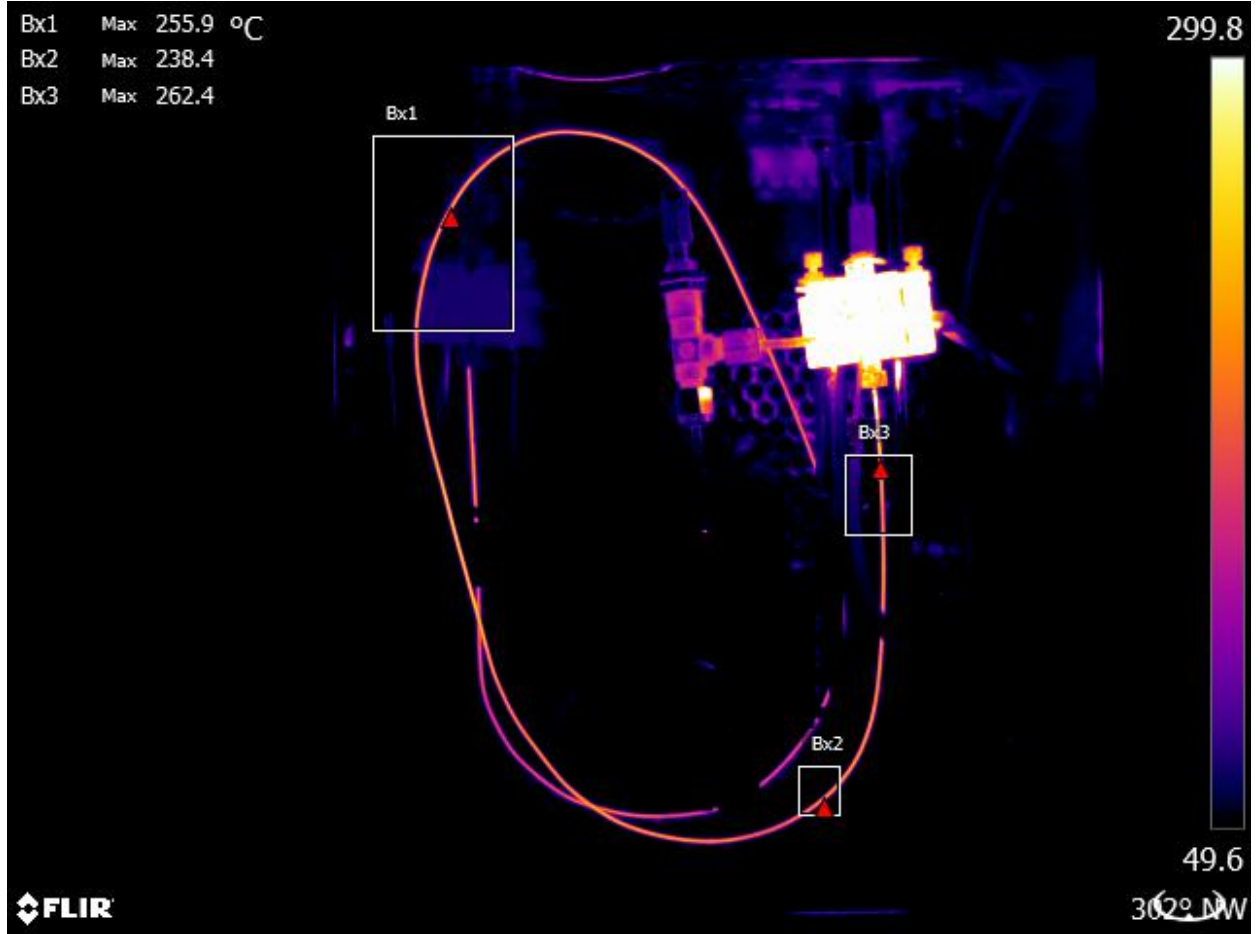
FIG. 4. A frame from the thermographic video of the coaxial heater. There are no evident run-away hot spots.

III. RESULTS AND DISCUSSION

A. Heating uniformity

As a first step in developing the coaxial heater, we tried to answer the question about its temperature uniformity. Because the temperature coefficient of resistivity of metals is positive, in the absence of equalizing heat flow along the length of conductor the resistive heating process in a long, thin tube is inherently unstable. To monitor the temperature profile along its length we acquired a thermographic video of the coaxial heater (See Supplementary Online Material). The video shows that the coaxial heater heats and cools smoothly with no run-away hot spots. A still image from the video is show in Figure 4.

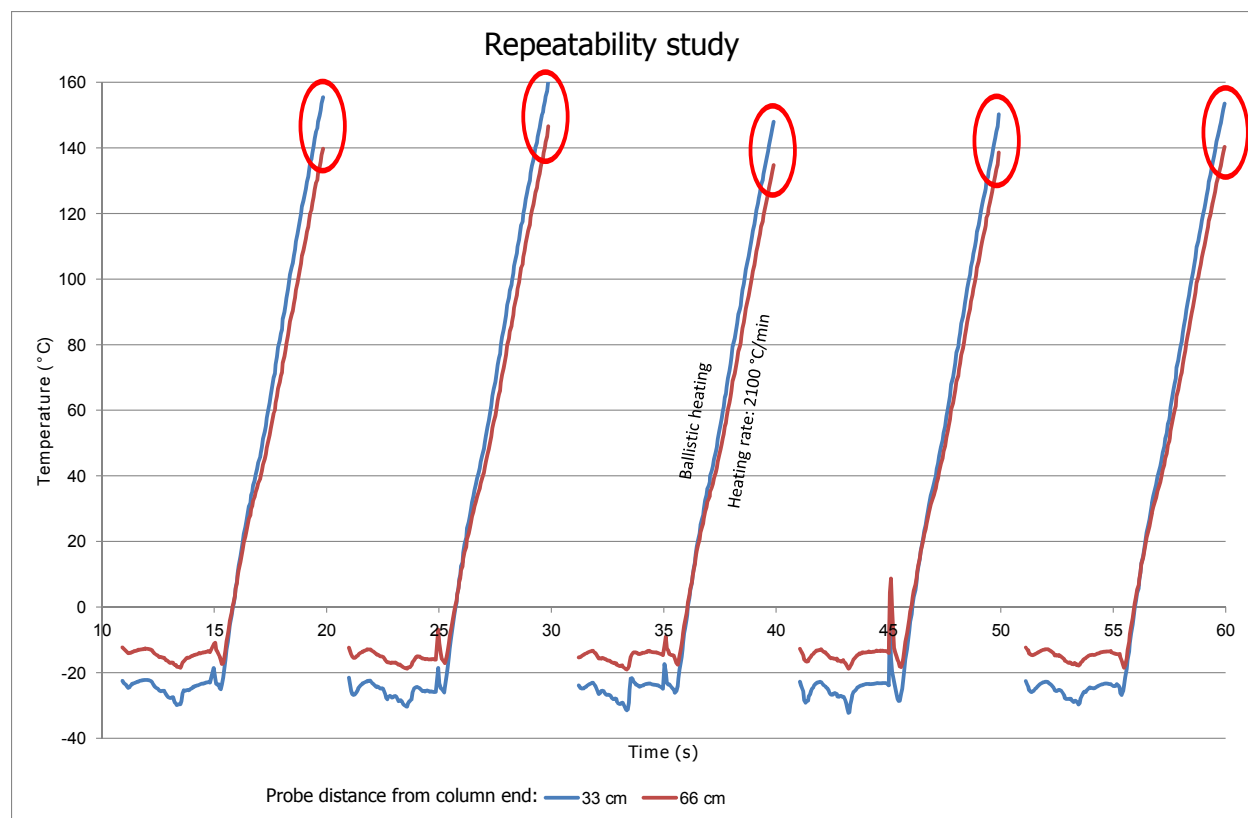To quantify the non-uniformity of the coaxial heater, a dual thermocouple probe was

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FIG. 5. The temperature difference between two points in the coaxial heater. The temperature difference established during cooling is reversed during heating, which shows that gradients exist, but they are small and repeatable.

inserted into the coaxial heater. The two thermocouples in the probe were 330 mm apart and positioned in the central third of the coaxial heater. The coaxial heater was submitted to a repeated program of cooling and ballistic heating. The recorded data (see Figure 5) shows that the two thermocouples reported different temperatures and that the difference changed during the heating, implying that the coaxial heater did not cool or heat perfectly uniformly. But the temperature differences between the two points were small (approximately 10 °C at most), stable, and repeatable and should not prevent good chromatography. In fact, a small longitudinal gradient, with the lower temperature nearer the detector, will produce sharper peaks[30]. These data also show that ballistic heating is not repeatable enough for gas chromatography, as can be seen in the variation in temperatures at the end of the heating runs.

B. Temperature calibration

While it is conceptually possible to have a fast temperature program by using the voltage/current ratio alone as a temperature indicator and controlled variable, it would be hard to design chromatographic methods or translate methods without a knowledge of the real temperature. Therefore, we went to some effort to calibrate the coaxial heater.

To calibrate a thermometer, the thermometer under test and its calibration environment must be in equilibrium. This requirement is hard to meet in our calibration, because a single point (the junction of the thermocouple) needs to be in equilibrium with the length of the coaxial heater during the full fast heating cycle. This equilibrium would be very difficult to maintain, especially because the uniformity of heating cannot be guaranteed, and is additionally influenced by the presence of the hot T-piece blocks — for a totally uniform heating of the coaxial heater the T-piece blocks would have to be at the same temperature as the coaxial heater. Acknowledging these limitations, we performed a calibration procedure assuming that the thermocouple junction was in equilibrium with the coaxial heater, which was assumed to be of uniform temperature over its length. Because these assumptions are simplifications, or for other overlooked reasons, the calibration curve (see Figure 6) is oddly curved, and we arbitrarily fitted a B-spline to the data points. This procedure can be automated[31]. Points from this B-spline curve were then extracted to create a calibration curve, from which an estimate of the temperature can be calculated by linear interpolation[32].

C. Heating rate

To achieve good resolution in temperature-programmed chromatography, a good rule of thumb for the heating rate is $10\,°C$ per void time[20]. With hydrogen as carrier gas in a $0.25\,mm$ i.d. column the efficiency-optimized linear velocity is $40\,cm\,s^{-1}$. Then the void time of a $1\,m$ column is $2.5\,s$, so the recommended heating rate is $10\,°C$ per $2.5\,s$, which is $4\,°C\,s^{-1}$, or $240\,°C\,min^{-1}$. Since in fast chromatography excess peak resolution is traded for shorter run times, higher-than-optimum flow rates will be used, so higher heating rates will be required. For narrower columns the flow will be even higher so that heating rates of more than $1000\,°C\,min^{-1}$ will be required.

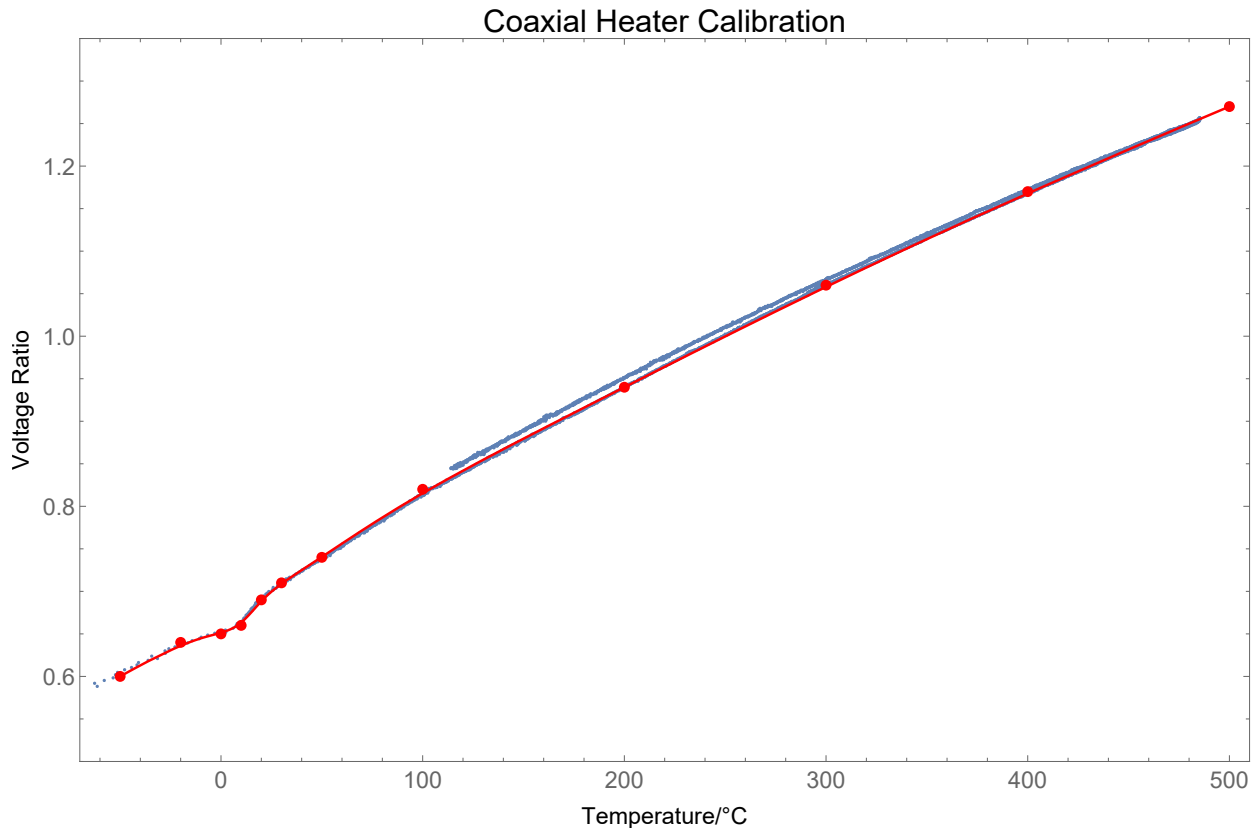The attainable heating rate is a function of power to the heater and of the temperature

FIG. 6. A calibration curve of the coaxial heater. The blue points represent the experimental data, and the red line is a B-spline fitted manually to the data. The red markers are points extracted from the B-spline. The temperature is obtained by linear interpolation between markers.

required. (In the instrument presented here the power was limited by the voltage output range of the DAC of the data acquisition board, and not by the power of the heater.) We were able to maintain controlled heating rates of $2500\,°\mathrm{C\,min^{-1}}$ up to $400\,°\mathrm{C}$, or up to $4000\,°\mathrm{C\,min^{-1}}$ up to $350\,°\mathrm{C}$ (See Figure 7). The heating rates attainable seem to be high enough for the most demanding fast gas chromatography.

D. Cooling rate

Using evaporating carbon dioxide as a powerful coolant, it was possible to cool down the column at a rate of $5100\,°\mathrm{C\,min^{-1}}$. The cooling rate depends on the setting of the metering valve, with the lowest coaxial heater temperatures and smallest gradients achieved at an intermediate flow of about $30\,\mathrm{g\,min^{-1}}$.
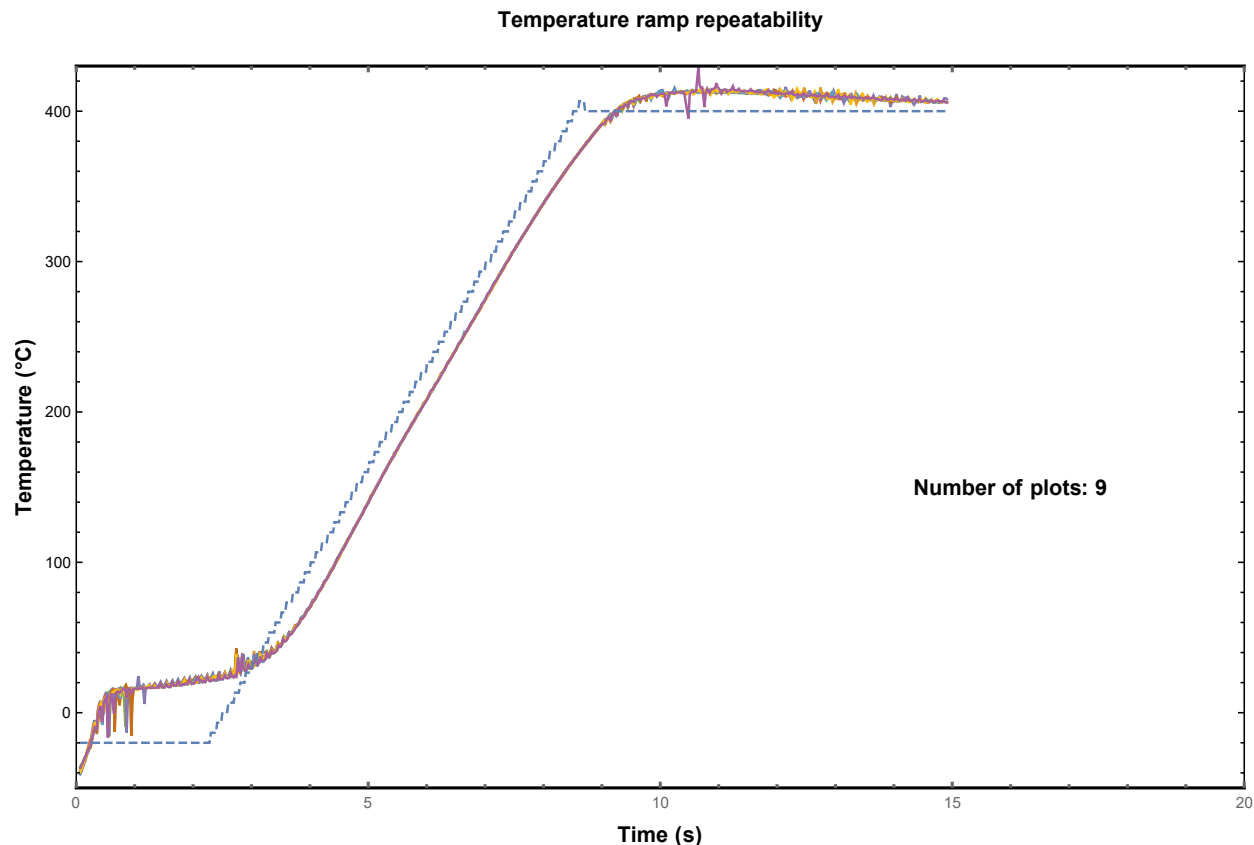
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FIG. 7. A graph of 9 identical, consecutive temperature ramps overlaid. The heating rate is $4000\,°\mathrm{C}\,\mathrm{min}^{-1}$. The temperature follows the setpoint faithfully up to $350\,°\mathrm{C}$

E. Repeatability

Comprehensive two-dimensional chromatography depends heavily on repeatable ^{2}D separations. To test for chromatographic repeatability, we added small amounts of hydrocarbons to the ^{1}D mobile phase. They are unretained on the silica stationary phase and are therefore present in every fraction of the SFC eluate in equal amounts and should yield identical ^{2}D chromatograms. Results obtained from creating a 2D blank chromatogram with two alkanes in the mobile phase are summarized in Table I. The peak widths were about $500\,\mathrm{ms}$, so the $20\,\mathrm{ms}$ standard deviation for hexadecane means that the variation in retention time is only about $10\,\%$ of the peak width. The relative standard deviations (RSD) of retention times were similar to those obtained in GC×GC[33].

TABLE I. A summary of retention time repeatability of alkanes separated on the fast temperature programmed chromatograph.

Compound	n	t_r (s)	S.D. of t_r (s)	R.S.D. of t_r (%)
Dodecane	73	5.07	0.023	0.46
Hexadecane	73	6.58	0.052	0.78

F. Chromatography

Comprehensive two-dimensional chromatography is made possible by having different retention mechanisms in the columns of the two dimensions. When fatty acid methyl esters (FAMEs) are chromatographically separated on bare silica with neat carbon dioxide as a mobile phase, they are separated according to the number of double bonds, independent of chain length[34]. On a GC column, FAMEs are separated according to volatility or, equivalently, chain length. Therefore, when SFC and GC are comprehensively coupled, we can expect FAMEs to have a highly orthogonal separation.

We prepared FAMEs by esterifying oil samples, following an official method[35]. Of these samples, $0.2\,\mu l$ was injected into the pure carbon dioxide mobile phase at $200\,bar$ and room temperature and eluted through bare silica. We collected $10\,s$ fractions of SFC eluate on the cold GC column. The fast temperature program ramped the GC column temperature from $-20\,°C$ to $350\,°C$ in $10\,s$ ($2200\,°C\,s^{-1}$), then maintaining $350\,°C$ for $2\,s$. Then the cooling system would activate and cool the column to $-20\,°C$ or below, ready to trap the next SFC fraction. In this way a series of GC chromatograms of SFC fractions were recorded to build up a 2D chromatogram. Figure 8 shows a 2D chromatogram of a sample of FAME prepared from canola oil. This 2D chromatogram consists of 132 fast GC chromatograms collected in approximately $90\,min$.

IV. CONCLUSION

To our knowledge, the cycle time of this new temperature programmed GC is unmatched in the literature, and it allows for the improved performance of SFC×GC instruments. The fast GC will be of interest to all GC analyses of highly dynamic chemical systems, including on-line monitoring and control of fast laboratory or industrial reactions.
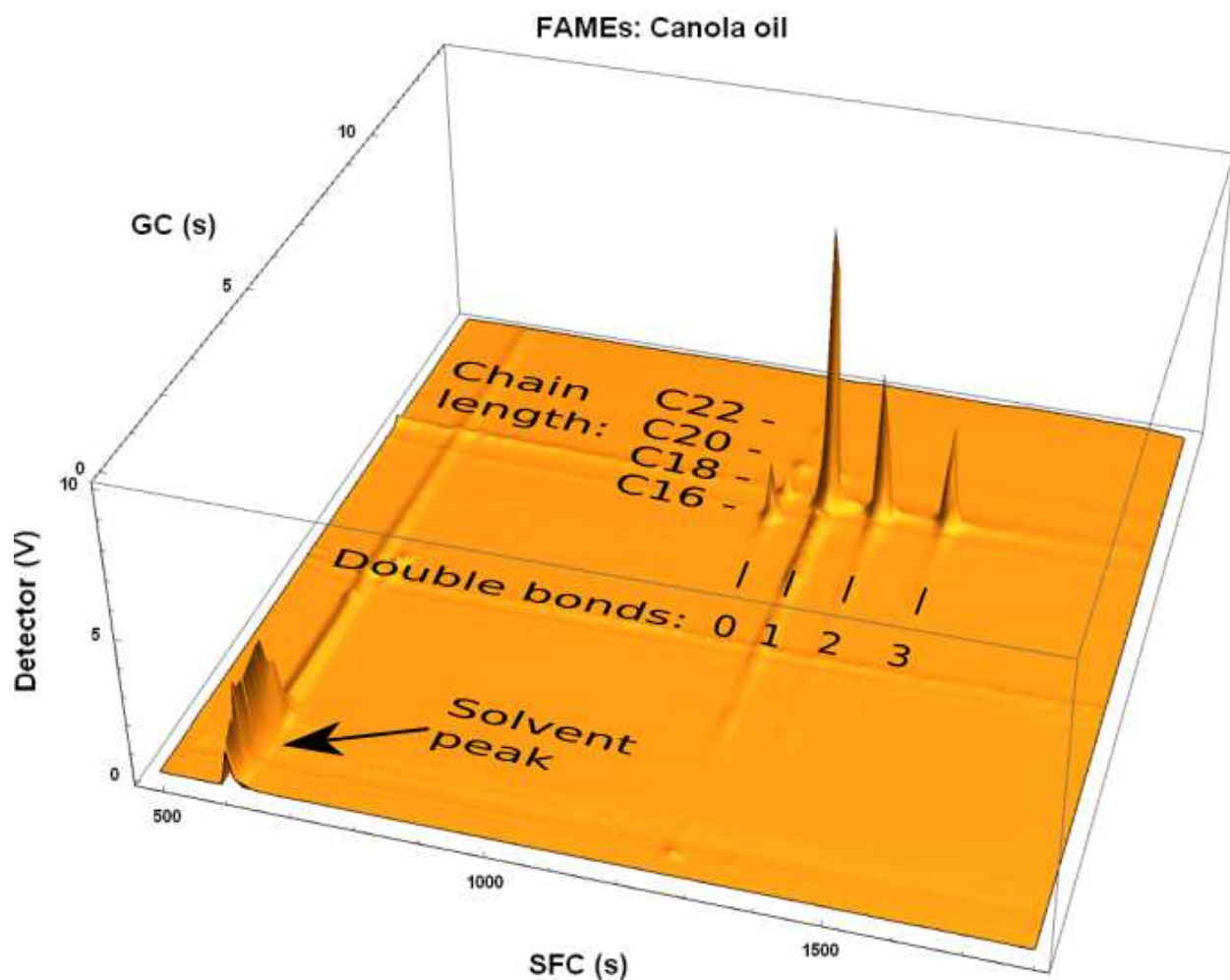
FIG. 8. A 2D chromatogram of FAMEs derived from canola oil. It is clear that the oil consists mostly of unsaturated fatty acids.

The low thermal mass of the heater and column simplifies heating and cooling of a portable fast GC, reducing electrical and carbon dioxide coolant requirements. When subambient temperatures and extreme cycle times are not essential, compressed air could also serve to cool the column.

SUPPLEMENTARY MATERIAL

In the supplementary material we provide a thermographic video of the coaxial heater heating and cooling, which demonstrates the even of heating of the coaxial heater and its rapid cooling by evaporating carbon dioxide.

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