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DIRECT FLUID INJECTION INTERFACE FOR CAPILLARY SUPERCRITICAL FLUID CHROMATOGRAPHY–MASS SPECTROMETRY*

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SUMMARY

A new interface for capillary column supercritical fluid chromatography–mass spectrometry (SFC–MS) is described and initial results are presented. The advantages of SFC include the ability to separate high-molecular-weight, non-volatile and thermally unstable compounds not amenable to gas chromatography. Capillary column SFC–MS has potential advantages over high-performance liquid chromatography–MS owing to the higher possible chromatographic efficiency, mobile phase volatility and the simplicity of the interface design. The direct fluid injection interface provides for transfer of the total capillary SFC effluent into a chemical ionization source. Initial results are presented to illustrate the separation and analysis of simple mixtures of aromatic hydrocarbons and styrene oligomers using *n*-pentane as the mobile phase.

INTRODUCTION

A mass spectrometer constitutes a nearly ideal detector for chromatography, as evidenced by the explosive growth in the application of gas chromatography–mass spectrometry (GC–MS) in the last decade. The success of this approach and the range of samples not amenable to GC–MS spurred the development of high-performance liquid chromatography (HPLC)–MS. However, interfacing conventional packed column HPLC to mass spectrometry has been a difficult task because of the incompatibilities in required liquid flow-rates and solvent evaporation or removal[1–3]. While significant progress has been made in the development of various LC–MS interfaces, these methods have not approached the routine application[4,5] of GC–MS instrumentation. Hence, there is a clear need for an alternative approach to HPLC for the analysis of complex mixtures of non-volatile compounds providing increased chromatographic efficiency as well as greater compatibility with mass spectrometry.

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Supercritical fluid chromatography (SFC) has developed over the past two decades as an alternative to HPLC with specific advantages in some applications[6–10]. The combination of SFC with mass spectrometry may also provide advantages over HPLC–MS. The range of compounds which may be separated with SFC is similar to that with HPLC, although the state-of-the-art in HPLC is considerably more advanced than in SFC. Both techniques allow the separation of materials which are thermally labile and of much higher molecular weight than is possible using GC[6–10]. SFC has the added capability of pressure programming, providing precise control of the solvating power of the mobile phase and an alternative to gradient elution in HPLC. Additionally, the much higher volatility of most SFC mobile phases provides a significant advantage in the design of the SFC–MS interface. These advantages were recognized by Randall and Wahrhaftig[11–13], who have previously reported on the construction of a supercritical fluid (dense gas) chromatograph–mass spectrometer interface using conventional packed columns and supersonic molecular beam techniques. This approach, however, suffered from low sensitivity, the complexity of four stages of differential pumping required by the large mobile phase flow-rates and mass spectra that were complicated by cluster formation in the beam expansion[13].

This paper describes the development of an interface for capillary column SFC–MS. The development of capillary column SFC has recently been reported[14–16]. The use of wall-coated open-tubular capillary columns provides mobile phase flow-rates compatible with chemical ionization mass spectrometry and removes the need for a liquid–gas phase transition as in HPLC–MS. Other advantages accrue from the high chromatographic efficiency projected for capillary columns owing to the low pressure drop across the column and the more uniform density of the mobile phase[14–16]. This work demonstrates the compatibility of this technique with mass spectrometry and has demonstrated sensitivities and separations comparable to or better than HPLC–MS.

EXPERIMENTAL

The emphasis of our work has been (a) the development of a working capillary SFC–MS interface, (b) determination of parameters for an optimum interface design and (c) an investigation of the range of application. Fig. 1 illustrates the SFC–MS instrument constructed in this work. The instrument incorporates a high-pressure programmable pump, a constant-temperature oven, capillary column, the direct fluid injection (DFI) interface and a tandem quadrupole mass spectrometer equipped with a dual electron impact–chemical ionization ion source.

The supercritical fluid chromatograph utilizes a Varian 8500 high-pressure syringe pump (8000 p.s.i. maximum pressure) and a constant-temperature oven and transfer line. Fused silica capillary columns, of 100- or 200-μm I.D. and lengths of 10–30 m, were used in our initial studies.

Capillary columns were prepared by immobilizing the stationary phase through peroxide cross-linking of SE-52 and SE-54[17] in a manner similar to that described by Grob *et al.*[18,19]. At present the selection of mobile phases is limited by the range of columns that have been prepared for capillary SFC, restricting the use of more polar mobile phases. The injection–splitter assembly allows reproducible 0.2-μl injections[16], although the precise splitting ratio is not known. A Hewlett-Packard GC

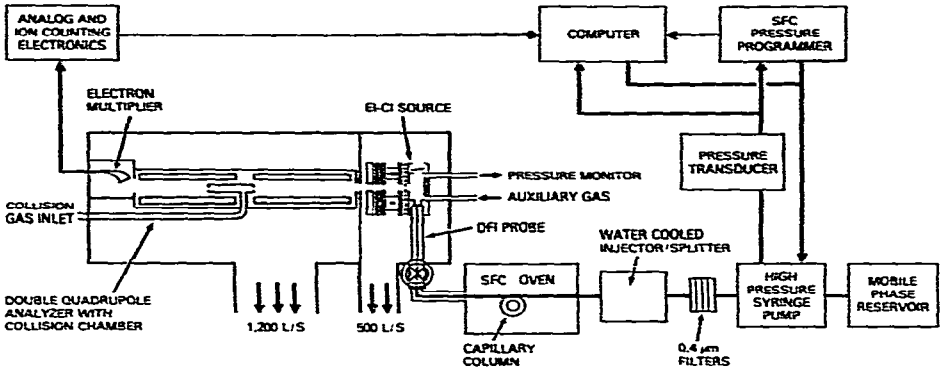

Fig. 1. Overall schematic diagram of the capillary column SFC–MS system.

temperature programmer was modified to provide pressure programming of the syringe pump[20]. In our work to date isobutane and *n*-pentane have been used as mobile phases. Most work has utilized *n*-pentane. Alternative mobile phases, such as carbon dioxide[9], offer distinct advantages for the analysis of thermally labile compounds owing to the lower critical temperatures. Column temperatures slightly above the critical temperatures (147°C for isobutane where T_c = 135°C, and 210°C for *n*-pentane where T_c = 196°C) are typically used to reduce the effects of thermal variations upon the mobile phase[10]. Pressure programs ranging from 20 to 75 atm for *n*-pentane were used in this work.

The principal design considerations for the DFI probe involved obtaining constant-temperature conditions, proper column restriction to obtain optimum flow-rates and efficient transfer of non-volatile compounds to the ionization region.

Optimum chromatographic resolution in SFC requires maintaining a constant temperature over the entire length of the column and elimination of all dead volumes between the column and the detector. The present instrument attains these criteria by extending the fused silica column through a constant temperature (±0.4°C) transfer line to within 3 cm of the DFI probe tip. The DFI probe contains separate heating elements to maintain the required temperature conditions. The fused silica capillary column is connected to the DFI probe tip by a zero dead volume connection (fabricated from a short length of 300-μm I.D. tubing) to 100-μm I.D. (300-μm O.D.) platinum–iridium tubing. A silver chloride melt is used as a sealant. The platinum–iridium tubing extends through the last 3 cm of the interface to the flow restrictor which determines the mobile phase flow-rate.

Fig. 2 illustrates two of the probe designs we have evaluated. The probe illustrated in Fig. 2A employs a laser-drilled orifice as a pressure restrictor. A 0.5–2.0-μm hole is drilled in 13-μm thick stainless steel. A small tin gasket is used to make a tight seal between the probe tip and the pressure restrictor, resulting in a dead volume estimated to be of the order of 0.01 μl. The second DFI probe design (Fig. 2B) is similar but terminates in a 0.2–0.5-mm length capillary restriction. This restriction is formed, in this instance, by crimping the tubing termination to obtain the desired flow-

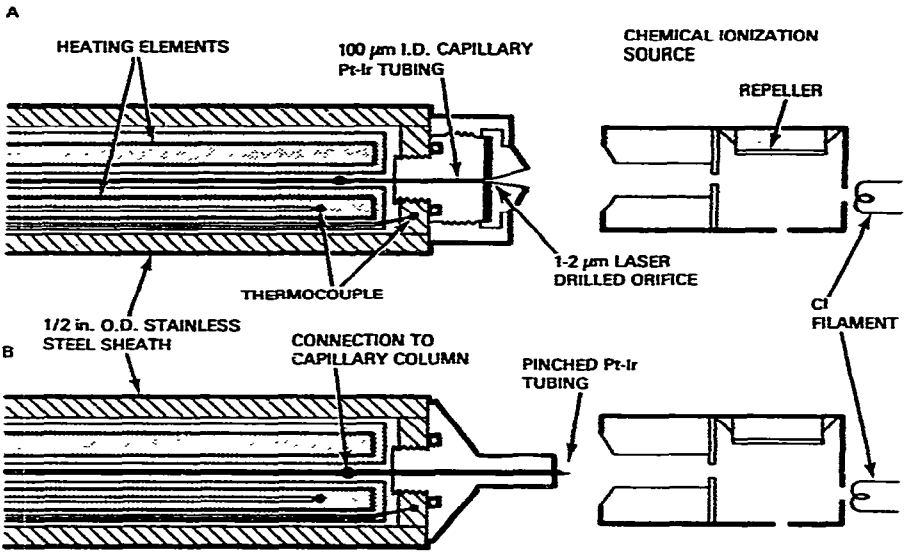

Fig. 2. Schematic diagram of two of the direct fluid injection probes designed for interfacing SFC with a conventional CI ion source: (A) a probe using a non-viscous laser-drilled orifice restrictor; (B) probe utilizing a pinched (< 1-mm) capillary restrictor.

rate. This restriction also provides an effective zero dead volume. All probe designs are operated at the SFC temperature to obtain optimum chromatographic resolution. The two probes have given similar performance in our initial studies; however, the orifice in the first design appears to plug more readily. Probe design considerations are discussed further in the next section. Additional probe designs of combined characteristics are also being evaluated.

The DFI probes have been designed to couple with the direct probe inlet of a "simultaneous" chemical ionization–electron impact (CI–EI) Extranuclear Labora-

TABLE I

FLOW-RATES AND MASS SPECTROMETER CHAMBER PRESSURES

Typical operating conditions.

Property	*Column diameter (mm)*	
	0.1	*0.2*
Linear velocity (cm/sec)	3.0	2.2
Flow-rate (as liquid) (μl/min)*	20	60
SFC pressure (atm)	28	28
Chemical ionization source pressure (torr)	0.3	1.0
Ion source chamber pressure (torr)	$3 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$
Mass spectrometer chamber pressure (torr)	$0.8 \cdot 10^{-7}$	$2.5 \cdot 10^{-6}$

* Assuming the stated column diameter is available to mobile phase flow (*i.e.*, neglecting the contribution of the stationary phase wall coating).

tories (Pittsburgh, PA, U.S.A.) ion source. A second CI source inlet provides additional chemical ionization reagent gas (usually the SFC mobile phase). A Granville-Phillips servo-valve and a pressure controller are used to regulate gas flow. Thus, a constant CI source pressure is maintained during SFC pressure programming where the flow to the ion source changes by as much as a factor of 2–3. The ion source chamber is pumped with a 500 l/sec turbomolecular pump and the mass spectrometer chamber is pumped with a 4-in. diffusion pump at a nominal pumping speed of 1200 l/sec. Table I gives the flow-rates, ion source and mass spectrometer chamber pressures for reasonable flow-rates using 0.1- and 0.2-mm I.D. columns and *n*-pentane as the mobile phase[16].

The mass spectrometer is an Extranuclear Laboratories tandem quadrupole mass filter, providing collision-induced dissociation (CID) capability[21]. The mass spectrometer has a mass range of m/z 3–1400, with computer-controlled data acquisition and storage.

RESULTS AND DISCUSSION

DFI probe and interface design

The successful interfacing of a capillary column SFC to a mass spectrometer requires stable SFC conditions, minimizing or eliminating dead volumes and providing the necessary pressure restriction. The present interface design provides for the necessary constant-temperature conditions and essentially eliminates all dead volumes.

The design of the DFI probe tip restrictor is a critical factor in SFC–MS performance, as in LC–MS[22–24]. An ideal restrictor will provide the desired restriction and mobile phase flow-rate, will maintain supercritical conditions to as close to the probe tip as possible and will provide a jet of vapors directed into the chemical ionization volume. Additionally, the interface to the CI source should provide for minimization of solvent clusters and eliminate or reduce the condensation or decomposition of non-volatile or thermally labile compounds. The interface should also provide flexibility in the choice of CI reagent gases and provide a flow-rate compatible with CI. Finally, the interface should be simple, easily maintained and capable of prolonged operation without failure (*e.g.*, plugging of the restrictor).

The properties of supercritical fluids allow the capillary column DFI interface to approach these requirements more closely than with conventional packed column LC–MS coupling. Direct liquid injection LC–MS interfaces deliver approximately 1–4% of the total effluent into the mass spectrometer ion source[22–24], although more extreme splitting ratios have been reported by some workers. Indeed, more recent work with micro packed columns has demonstrated the injection of the total LC effluent[25]. The principal problems with this interface result from the low volatility of most solvents and the effects upon ion source operation with mobile phases such as water. Additionally, cooling of the probe and orifice has been found desirable in HPLC–MS operation to prevent solvent volatilization (which results in large changes in introduction rate and the loss, or condensation, of material near the orifice). Some of these difficulties may be avoided using an extended capillary restrictor as reported by Krien *et al.*[26]; however, it has not been demonstrated that this approach avoids the predicted problems due to volatilization in the capillary and deposition of non-volatile compounds.

The capillary SFC–MS interface avoids problems related to solvent evaporation by maintaining supercritical (dense gas) conditions up to the DFI restrictor. Proper design of the injector tip can allow a rapid expansion of the dense gas avoiding the liquid–gas phase transition in LC–MS. Additional advantages result from the much higher volatility of typical mobile phases compared with HPLC, where typical conditions result in extensive cluster formation and persistence of a jet of frozen liquid droplets extending 2–5 cm into the vacuum region[24]. In the DFI interface the *n*-pentane jet disappears after less than 0.5 cm for flow-rates as large as 100 μl/min. More typical flow-rates show no visible jet. A result of the mobile phase volatility is that the mass spectra show no evidence of ion clusters. Similar results were obtained for isobutane and can be expected for other mobile phases. Preliminary results with carbon dioxide as a CI reagent indicate that these more advantageous mobile phases are compatible with both positive and negative ion CI, suggesting significant advantages upon development of more adequate bonded stationary phases.

It is clear that the most important single component in the DFI interface is the restrictor. The restrictor is chosen to provide the desired flow-rate. Owing to the complex nature of the flow under supercritical conditions, the final design of acceptable restrictors is necessarily approached empirically. We have examined both short viscous (*i.e.*, capillary) and more nearly non-viscous (laser-drilled orifice) restrictors.

The use of extended viscous restrictors above the critical temperature is clearly undesirable, as the gradual pressure drop will lower the mobile phase density gradually and lead to solute deposition within the capillary tube. The use of an extended viscous restrictor in conjunction with cooling to below the critical temperature causes two phase changes and presents additional problems. As the dense gas condenses a liquid results in which some components may not be soluble. This is followed by an additional loss of non-volatile materials as the solvent evaporates at the probe tip[24].

The use of very short (< 1 mm) viscous and more nearly non-viscous restrictors results in a small jet of submicron droplets that disappears within < 0.5 cm of the restrictor for typical flow-rates (< 100 μl/min). The use of small laser-drilled orifices in 13-μm thick stainless steel provides a reasonably non-viscous restriction. The ideal orifice diameter size is *ca.* 0.5 μm for 0.1-mm I.D. columns and *ca.* 1.0 μm for 0.2-mm I.D. columns. The major difficulties involve selection of the orifice (as the production of uniform orifices in this size range is difficult) and possible plugging of the orifice. This is particularly a problem for the smaller orifice sizes (< 1.0 μm). Care must also be taken to minimize the restrictor surface area subjected to the high pressure, as these thin diaphragms are easily deformed, resulting in an increased orifice size and causing an additional dead volume.

These problems are substantially reduced by using very short viscous restrictors. This design avoids the phase changes associated with long capillary restrictors and allows a larger orifice. Crude restrictors of this type have been made by carefully pinching the termination of 0.1-mm I.D. platinum–iridium tubing to provide the desired flow and jet characteristics. These restrictors have been demonstrated to function for several days before plugging and mass spectra confirm efficient transfer to the CI source of non-volatile compounds, similar to non-viscous restrictors. Research into the development of reproducible and easily replaced restrictors is continuing.

DFI interface operation

The capillary SFC–MS interface is a reliable and simple device. The interface has been designed to use a direct insertion interlock for easy removal and maintenance of the DFI probe.

Typical operating procedures that have proved successful involve first starting the SFC flow prior to probe introduction with the oven and transfer line at proper temperature (210°C for *n*-pentane) and with the probe at ambient temperatures. After insertion into the vacuum the SFC pressure is increased to 20–30 atm. The flow-rate is evaluated using the ion source chamber pressure as a guide. The DFI probe temperature is then increased to 210°C. The entire start-up period requires less than 10 min.

The CI source pressure due to SFC flow ranges from 0.1 to 2 torr depending on the column diameter and the desired flow-rate. A single SFC separation may involve pressure programming over a range of 20–60 atm and result in a corresponding change in ion source pressure. As optimum ion source tuning is dependent on pressure, the CI ion source pressure was held constant using an auxiliary gas inlet and servo-valve to provide optimum and constant chemical ionization conditions regardless of column pressure. This is particularly important for 0.1-mm I.D. columns where flow-rates are small and additional gas is necessary to optimize sensitivity. The effect of CI pressure is illustrated in Fig. 3 for multiple injections of pyrene on a short 1-m column. Mass spectra were obtained for thirteen 0.2-μl injections of a 1:1000 solution in *n*-pentane, corresponding to 200 ng per injection before the splitter. Fig. 3 gives the reconstructed ion chromatogram for the $(M + 1)^+$ ion (m/z 203). Ion source pressures of 0.4 torr were obtained for the first injection and the pressure was increased in

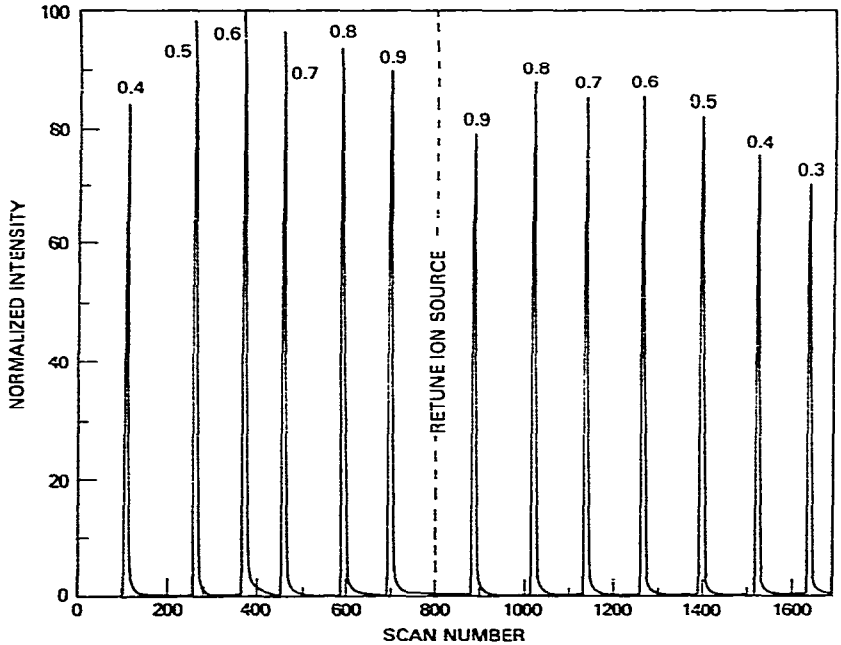

Fig. 3. Ion current for m/z 203 for a series of identical pyrene injections at various ion source pressures (in torr). The ion source was tuned at 0.4 torr and left unchanged for five subsequent injections at higher pressures and then retuned at 0.9 torr for the subsequent injections.

0.1-torr increments using the auxiliary gas inlet for the next five injections without retuning the ion source and ion optics voltages. The ion source was then retuned and pressures were decreased in 0.1-torr increments. These results demonstrate that the effects of pressure changes are relatively minor and that optimum sensitivity is obtained for approximately 0.6–0.8 torr pressure in our ion source. If constant CI source pressure is maintained using the auxiliary inlet, then the mass spectrometer response (peak area) is independent of flow-rate (SFC pressure) and the variation in response results from the injector operation (approximately ±5%).

The chemical ionization source provides both excellent sensitivity and flexibility owing to the potential for the addition of different CI reagent gases. For 100-μm I.D. columns at optimum column flow-rates the added gas can amount to as much as 90% of the CI reagent gas. This allows the capability of mixed CI reagent gases and eases limitations due to the ionization method. The two CI reagents used to date, isobutane and *n*-pentane, provide "mild" ionization conditions owing to the dominant proton transfer process. Many compounds analyzed in this manner yield spectra with a dominant $(M + 1)^+$ ion and little additional fragmentation, although for *n*-pentane $(M + 43)^+$, $(M + 55)^+$ and $(M + 71)^+$ peaks, often with distinctive

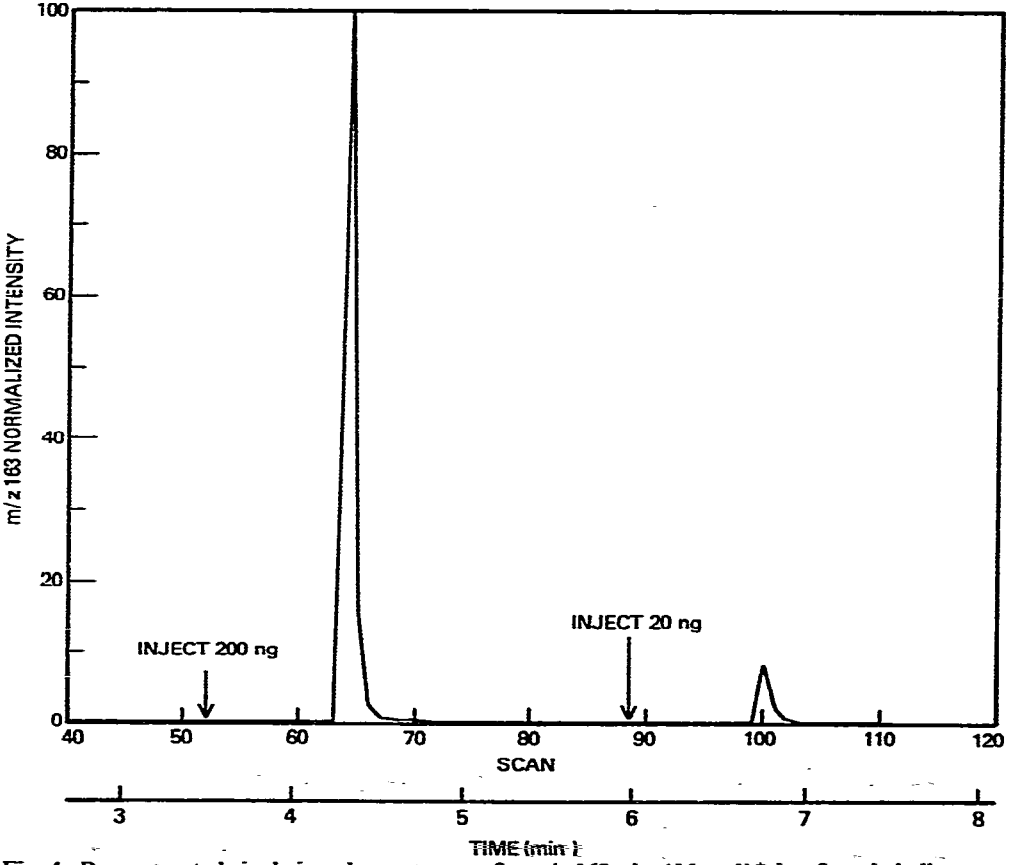

Fig. 4. Reconstructed single ion chromatogram for *m/z* 163, the $(M + 1)^+$ ion for triethylbenzene. Plot shows the response for two injections of 200 and 20 ng.

relative intensities, are also observed for some compounds. For cases where additional information is necessary for identification one can use either more energetic mixed CI reagents or the CID capability of the double quadrupole analyzer[21].

Fig. 4 illustrates the response obtained for two triethylbenzene injections of 200 and 20 ng, respectively, for a flow-rate of *ca.* 17 cm/sec (*ca.* 30 μl/min of liquid) using a 0.1-mm I.D. column. The mass spectra show a dominant $(M + 1)^+$ ion at m/z 163 to constitute the base peak and no other ions amounting to more than 10% of m/z 163. These results obtained while scanning the mass spectrometer illustrate the excellent sensitivity of the technique even with overall decreased ion currents resulting from the use of a tandem quadrupole mass filter and an uncertain injector splitting ratio. The signal-to-noise ratio for the $(M + 1)^+$ ion is greater than 100 for 20-ng injections, suggesting detection limits in the subnanogram range while scanning and in the low picogram range for single ion monitoring even for broad peaks for compounds with long retention times. Owing to the decreased splitting ratio, at present greater sensitivity is obtained using 0.2-mm I.D. columns while improved chromatographic resolution can be obtained with 0.1-mm I.D. columns[16].

Fig. 5 illustrates the application of the capillary SFC–MS to a mixture of five polycyclic aromatic hydrocarbon compounds in methylene chloride. The separation used a 20 m × 0.2 mm I.D. column and *n*-pentane as the mobile phase. The injected mixture contained a nominal 100 ng of each component. The reconstructed total ion chromatogram shows that the mixture of naphthalene, anthracene, pyrene,

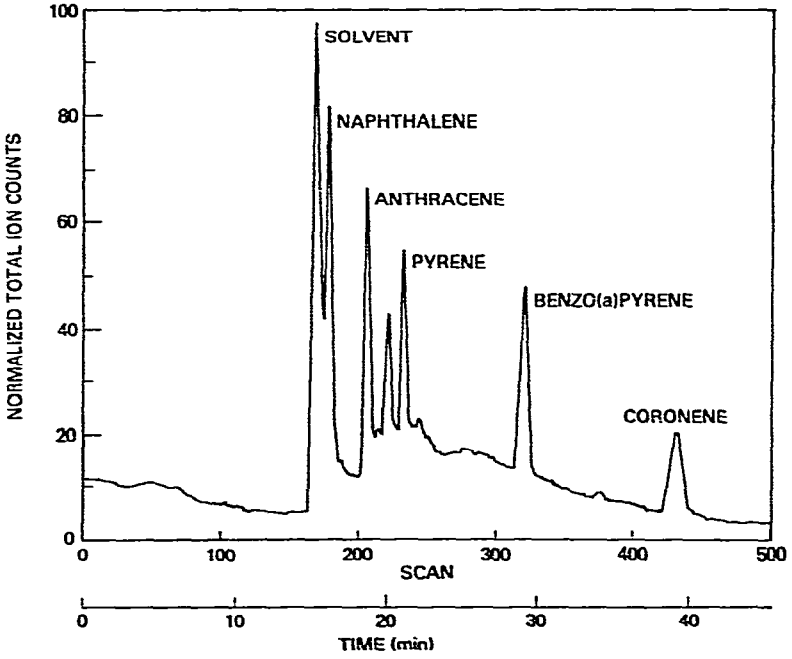

Fig. 5. Total reconstructed ion chromatograph for a SFC–MS analysis of a mixture of five polycyclic aromatic hydrocarbons and associated impurities. The separation used a 20 m × 0.2 mm I.D. column and a pressure program involving isobaric conditions at 24 atm for the first 15 min followed by a 0.8 atm/min increase to 40 atm.

benzo[*a*]pyrene and coronene was easily separated. The solvent peak actually results from response due to increased solubility of material on the column or a slight stripping of the column resulting from the use of methylene chloride solvent. Fig. 5 also shows evidence of several additional impurities. Fig. 6 gives reconstructed single ion chromatograms for eight $(M + 1)^+$ ions for compounds in the mixture, including three impurities having molecular weights of 208, 226 and 276. Evidence has been obtained for at least 20 additional minor impurities in this mixture. Fig. 7 gives the mass spectra obtained for anthracene, pyrene and benzo[*a*]pyrene in this

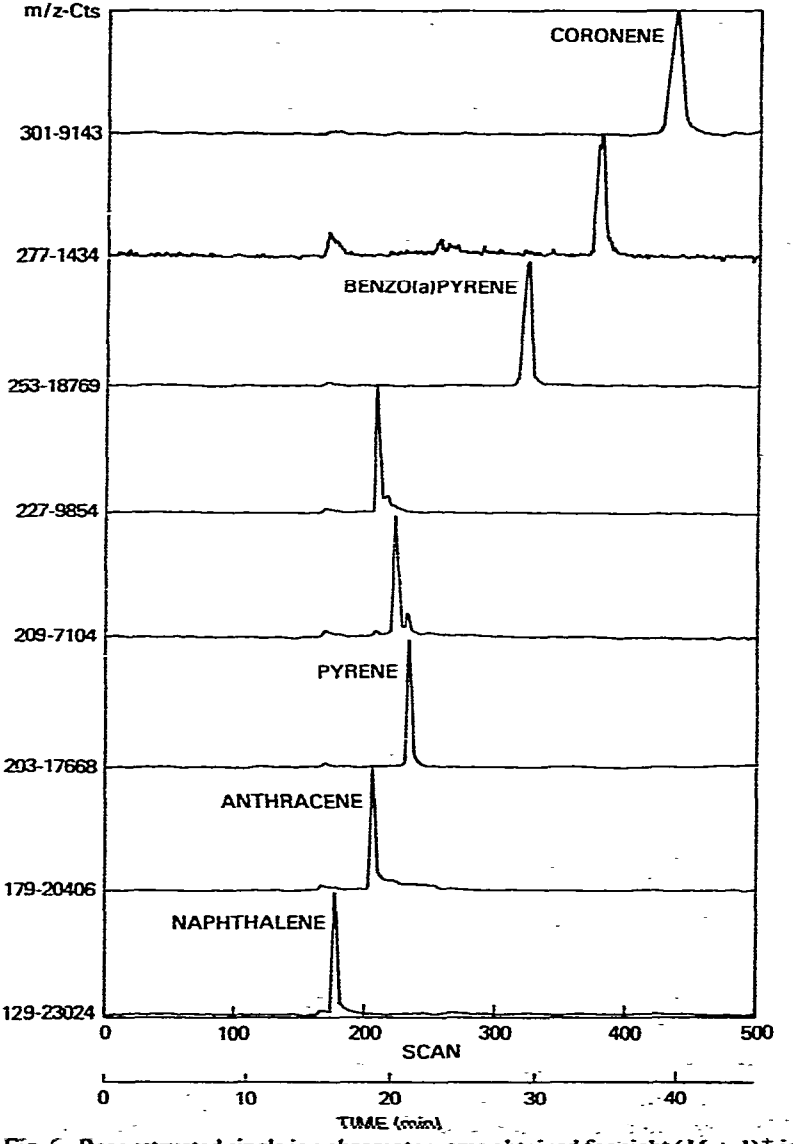

Fig. 6. Reconstructed single ion chromatograms obtained for eight $(M + 1)^+$ ions in the separation shown in Fig. 5. Also given are the $(M + 1)^+$ chromatograms for three impurities having molecular weights of 208, 226 and 276.

separation. The spectra show minor contributions of $(M + 43)^+$, $(M + 55)^+$ and $(M + 71)^+$ ions in most cases. The anthracene spectrum also shows a sizable impurity of molecular weight 226 which elutes simultaneously. These spectra demonstrate that high quality mass spectra can be obtained during capillary SFC–MS analyses.

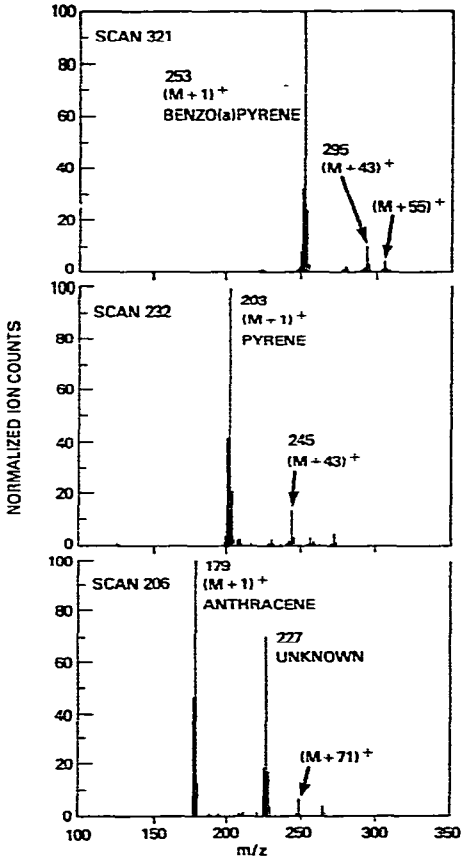

Fig. 7. Mass spectra for three of the peaks in the chromatogram given in Fig. 5. The mass spectra show the presence of $(M + 43)^+$, $(M + 55)^+$ and $(M + 71)^+$ ions for some compounds. Scan 206 contains evidence of a large impurity eluting nearly simultaneously with anthracene (see Fig. 6).

The application of the SFC–MS instrument to non-volatile high-molecular-weight compounds is illustrated in Fig. 8, which gives the total reconstructed ion chromatogram for a separation of a polystyrene sample having a nominal molecular weight of 800. The separation used a 0.2-mm I.D. column, a programmed pressure increase from 28 to 60 atm and *n*-pentane as the mobile phase. The chromatogram shows the first twelve styrene oligomers to be clearly resolved. The molecular weight of the individual oligomers is $104n + 58$; thus the twelfth oligomer has a molecular weight of 1306. The mass spectra show $(M + 1)^+$ ions and distinctive fragment ions for each oligomer, clearly proving the separation and demonstrating that the mass spectra are obtained without detectable decomposition of the individual oligomers. Additionally, the largest peak areas are obtained for the $n = 7$ and $n = 8$ oligomers as

would be expected from the known average molecular weight. These results demonstrate the efficient transfer of compounds (*i.e.*, the larger oligomers) expected to be non-volatile for the ion source temperature of 210°C. Although similar separations can be obtained using HPLC, these results demonstrate that capillary column SFC is a potentially powerful alternative technique. Similar results have been obtained for other essentially non-volatile compounds, demonstrating that such compounds can be efficiently transferred to the ion source and ionized.

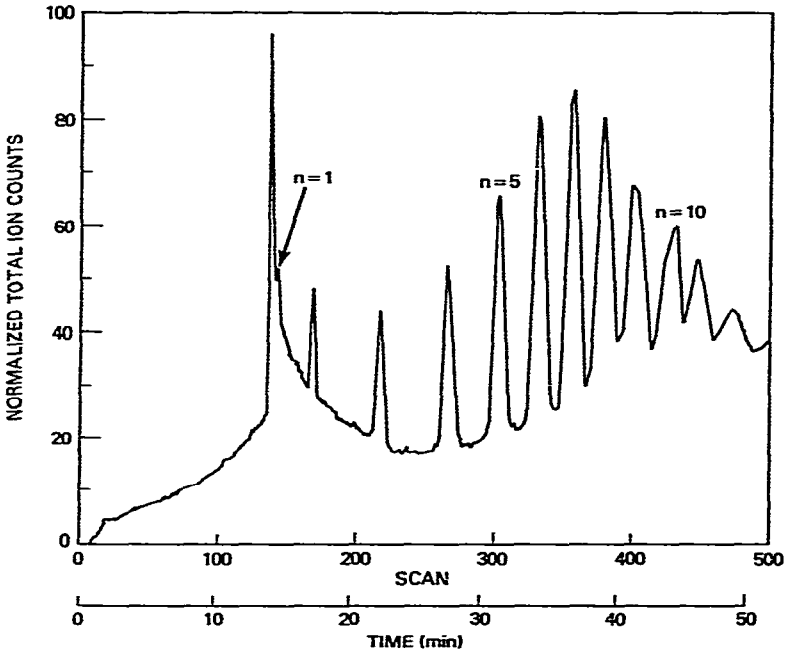

Fig. 8. Total ion chromatogram for the SFC–MS analysis of a polystyrene sample having an average molecular weight of 800. The chromatogram shows the first twelve oligomers which have molecular weights of $104n + 58$. The separation used a 20 m × 0.2 mm I.D. column and isobaric conditions for the first 15 min followed by a 1.2 atm/min increase to 60 atm.

CONCLUSIONS

Excellent sensitivities for a variety of compounds have been demonstrated with the developed capillary column SFC–MS interface. Our initial work has also demonstrated separations comparable to those obtained with HPLC. In principle, capillary SFC should be capable of significantly improved resolution compared with conventional packed column HPLC[16]. The range of samples amenable to SFC approaches that of HPLC and, if substantially increased chromatographic resolution can be obtained, may make SFC the method of choice for many separations. Present limitations upon capillary SFC stem primarily from limited column technology and the non-availability of sufficiently stable or chemically bonded stationary phases.

The development of a reliable SFC–MS interface can be expected to result in the increased application of SFC, particularly as improved and alternative capillary columns become available. This work has demonstrated that the mass spectrometer is

a nearly ideal capillary column SFC detector, providing comparable or greater sensitivity than alternative methods in addition to high selectivity. We have also shown that non-volatile high-molecular-weight compounds can be efficiently detected and analyzed using the capillary SFC–MS instrumentation. The detection of such compounds illustrates the successful application of a short capillary restriction for injection of non-volatile molecules into the ionization region. Efforts are being made to simplify the interface by the production of improved restriction devices.

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REFERENCES

1 W. H. McFadden, *J. Chromatogr. Sci.*, 17 (1979) 2–17.
2 P. J. Arpino and G. Guiochon, *Anal. Chem.*, 51 (1979) A682–A701.
3 W. H. McFadden, *J. Chromatogr. Sci.*, 18 (1980) 97–115.
4 N. J. Alcock, C. Eckers, D. E. Games, M. P. L. Games, M. S. Lant, M. A. McDowall, M. Rossiter, R. W. Smith, S. A. Westwood and H.-Y. Wong, *J. Chromatogr.*, 251 (1982) 165–174.
5 M. Dedieu, C. Juin, P. J. Arpino, J. P. Bounine and G. Guiochon, *J. Chromatogr.*, 251 (1982) 203–214.
6 M. N. Myers and J. C. Giddings, *Separ. Sci.*, 1 (1966) 761.
7 S. T. Sie, W. Van Beersum and G. W. Rijnders, *Separ. Sci.*, 1 (1966) 459.
8 R. E. Jentoft and T. H. Gouw, *J. Chromatogr. Sci.*, 8 (1970) 135.
9 E. Klesper, *Angew. Chem. Int. Ed. Engl.*, 17 (1978) 738.
10 T. H. Gouw and R. E. Jentoft, *Advan. Chromatogr.*, 13 (1975) 1–40.
11 L. G. Randall and A. L. Wahrhaftig, *Anal. Chem.*, 50 (1978) 1705–1707.
12 L. G. Randall, *Ph. D. Thesis*, University of Utah, 1979.
13 L. G. Randall and A. L. Wahrhaftig, *Rev. Sci. Instrum.*, 52 (1981) 1283–1295.
14 S. R. Springston and M. Novotny, *Chromatographia*, 14 (1981) 679–684.
15 M. Novotny, S. R. Springston, P. A. Peaden, J. C. Fjeldsted and M. L. Lee, *Anal. Chem.*, 53 (1981) A407–A414.
16 P. A. Peaden, J. C. Fjeldsted, M. L. Lee, S. R. Springston and M. Novotny, *Anal. Chem.*, 54 (1982) 1090–1093.
17 P. A. Peaden, B. W. Wright, M. L. Lee, T. J. Stark, B. A. Newton and P. L. Larson, *Anal. Chem.*, in preparation.
18 K. Grob, G. Grob and K. Grob, Jr., *J. Chromatogr.*, 211 (1981) 243–246.
19 K. Grob and G. Grob, *J. Chromatogr.*, 213 (1981) 211–221.
20 F. J. Van Lenten and L. D. Rothman, *Anal. Chem.*, 48 (1976) 1430–1432.
21 R. A. Yost and C. G. Enke, *J. Amer. Chem. Soc.*, 100 (1978) 2274–2275.
22 M. A. Baldwin and F. W. McLafferty, *Org. Mass Spectrom.*, 7 (1973) 1355–1354.
23 K. H. Schäfer and K. Levsen, *J. Chromatogr.*, 206 (1981) 245–252.
24 P. J. Arpino, P. Krien, S. Vajta and G. Devant, *J. Chromatogr.*, 203 (1981) 117–130.
25 J. D. Henion and T. Wachs, *Anal. Chem.*, 53 (1981) 1963–1965.
26 P. Krien, G. Devant and M. Hardy, *J. Chromatogr.*, 251 (1982) 129–139.