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Limits of separation of a multi-capillary column with mixtures of volatile organic compounds for a flame ionization detector and a differential mobility detector

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ABSTRACT

The resolving power of a multi-capillary column (MCC) was evaluated using 14 mixtures of volatile organic compounds with known composition and complexity which was incremented stepwise up to 129 constituents. The number of constituents in these mixtures versus the number of components separated and detected with a flame ionization detector showed a proportional rise, with a decreasing slope, to 76 peaks after which a plateau was reached. This was improved 23.7% to 94 constituents, or 73% of all compounds in the mixture, after simplex optimization of carrier gas linear velocity, initial temperature and program rate. When the detection method was differential mobility spectrometry (DMS), additional selectivity was introduced through ion formation and separation. Fifty nine compounds were detected by DMS and 46 were separated by retention time; 13 were co-eluted and 7 of these were resolved by differential ion mobility (90% of all components ionized). A correlation of −0.412 between retention time for gas chromatography (GC) and differential mobility for DMS suggested a significant level of orthogonal character and the method of GC–DMS should not be seen as sequential only.

1. Introduction

The development of multi-capillary columns (MCCs) for gas chromatography (GC) was intended for increased mass loading on columns with thin films of stationary phase while linear isotherms were maintained [1,2]. In MCCs, up to a thousand capillaries are bundled together so that a substantial amount of stationary phase is found in the entire bundle though the phase ratios for individual capillaries can be comparable to conventional capillary columns. An added benefit with MCCs is the high volumetric flow of carrier gas, up to 60 mL min^{-1}, and resultant high speed separations [3,4]. Though MCCs have not attained the commercial availability or widespread acceptance of bonded-phase capillary columns, MCCs exhibit chromatographic efficiency high enough for applications with simple mixtures, often with the aid of selective detectors [3–13]. Examples include organometallic substances [5], explosives, drugs, and warfare agents [6,7], metabolic vapors from microorganisms or humans [8–10], polychlorinated biphenyls [11], aromatic hydrocarbons [12], and others [13]. There is no broad description of the chromatographic capabilities for MCCs with moderately or highly complex mixtures.

Chromatographic performance for MCCs has been described using analysis of theoretical designs [14], studies of liquid phase loading [15], and conventional measures of chromatographic performance [4,16], these provided limited practical values. Column efficiency with carrier gas velocity with flat so flows could be large, e.g., the minimum height equivalent to a theoretical plate (HETP) for alkanes and aromatics occurred at 12–36 cm s^{-1} and 12–96 cm s^{-1}, respectively for MCCs and a minimum HETP for organometallic compounds was 80–280 cm s^{-1} versus 20 cm s^{-1} for a conventional capillary column. Nonetheless, the separating power of MCCs with truly complex mixtures of volatile organic compounds is still undetermined. In studies here, flame ionization detection (FID) was used to provide an empirical measure of column performance with complex mixtures and differential mobility spectrometry, as detection method, was employed to determine the value of a second dimension to retention time.

Mobility based analyzers have been used as detectors in two of the main applications of MCCs, explosives detection [6–8] with the recently developed field dependent mobility, or differential mobility, spectrometry (DMS) and breath analysis [9,11] with traditional ion mobility spectrometry (IMS). In both mobility methods, analyzers are operated at ambient pressure with flows up to 300 mL min^{-1} or more, facilitating connection to capillary columns and particularly MCCs. Mobility based detectors provide a second dimension of analytical information based on characterization of gaseous ions formed from constituents in column effluent in ways analogous to mass spectrometers. This information for ions, however, is associated with mobility or differential mobility of ions rather than mass, as with mass spectrometry (MS). As with GC–MS, pre-separation

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Table 1
Retention behavior and column efficiency of MCC for volatile organic compounds. Chemicals are organized by group or category and were blended together to prepare mixtures of increasing complexity (Fig. 1). Compounds with same retention time in a mixture are co-listed in a row.

Compound	t_R (min)	Retention index	HETP (mm)	Asymmetry factor
n-Alcohols				
Ethyl alcohol	0.79	535.8	–	–
Propyl alcohol	1.44	622.1	0.617	1.778
Butyl alcohol	3.46	727.0	0.426	1.618
Amyl alcohol	7.78	841.1	0.146	1.556
Hexyl alcohol	11.89	939.6	0.062	–
Heptyl alcohol	15.55	1033.7	–	–
Octyl alcohol	18.88	1135.1	0.019	–
Nonyl alcohol	22.02	1231.8	0.031	–
Decyl alcohol	25.00	1322.4	0.024	–
2-Ketones				
2-Butanone	1.65	637.2	0.470	0.860
2-Hexanone	7.78	841.1	0.134	0.118
2-Heptanone	11.99	942.2	0.037	0.119
2-Octanone	15.77	699.1	0.030	–
2-Nonanone	19.22	1145.5	0.021	–
2-Decanone	22.39	1243.3	0.017	–
2-Undecanone	25.53	1338.5	0.025	–
2-Dodecanone	30.10	1477.6	0.053	–
n-Alkyl acetates				
Methyl acetate	0.90	557.2	0.669	1.501
Ethyl acetate	1.70	640.8	0.432	1.336
Butyl acetate	8.33	853.6	0.074	0.957
Amyl acetate	12.41	953.0	0.048	–
Hexyl acetate	16.05	1051.6	0.020	–
Heptyl acetate	19.40	1151.2	0.021	–
Octyl acetate	22.49	1246.2	0.028	–
Nonyl acetate	25.55	1339.1	0.028	–
Ethers				
tert-Butyl methyl ether	1.04	582.4	0.371	1.380
Isopropyl ether	1.28	611.0	0.369	1.110
n-Butyl methyl ether	1.56	631.2	0.372	1.148
tert-Amyl methyl ether	2.40	691.6	–	–
Propyl ether	2.54	700.5	–	–
Butyl ethyl ether	2.76	706.8	0.472	–
Butyl ether	10.15	895.5	0.076	1.109
Pentyl ether	17.42	1090.7	0.046	1.043
Hexyl ether	23.54	1278.2	0.025	–
n-Alkanes				
Pentane	0.60	500.0	0.771	1.569
Hexane	1.13	600.0	0.366	1.320
Heptane	2.52	700.0	0.383	1.086
Octane	5.99	800.0	0.144	0.990
Nonane	10.35	900.0	0.048	0.884
Decane	14.24	1000.0	0.036	0.922
Undecane	17.75	1100.0	0.025	0.965
Dodecane	20.97	1200.0	0.018	–
Tetradecane	27.55	1400.0	0.060	–
Benzene and alkylated benzenes				
Benzene	2.19	676.0	0.334	1.057
Toluene	5.35	781.6	0.268	1.059
m-Xylene, *p*-xylene	9.84	–	–	–
o-Xylene	10.89	913.8	0.080	0.969
Propylbenzene	13.18	972.8	0.040	1.053
1,3,5-Trimethylbenzene	13.78	988.1	0.046	1.065
1,2,4-Trimethylbenzene	14.75	1014.6	0.041	0.860
1,2,3-Trimethylbenzene	15.86	1046.2	0.042	–
trans-β-Methylstyrene	16.21	1056.0	0.040	–
Cylcoalkanes				
Methylcyclohexane	3.10	716.8	0.270	1.027
1,3-Dimethylcyclohexane (*cis* or *trans*)	4.97	770.6	0.269	1.010
Cycloheptane	5.79	794.2	0.249	–
1,3-Dimethylcyclohexane (*cis* or *trans*)	6.22	805.2	0.267	–
Ethylcyclohexane	7.45	833.5	0.149	0.922
cis-Cyclooctene	10.43	902.0	0.074	1.038
Cyclooctane	11.12	919.9	0.065	–
Propylcyclohexane	11.54	930.5	0.054	–
Butylcyclohexane	15.42	1033.6	0.026	1.063
Dicyclohexyl	24.33	1302.2	0.021	–

Table 1 (*Continued*)

Compound	t_R (min)	Retention index	HETP (mm)	Asymmetry factor
Substituted ketones				
3-Methyl-2-butanone	2.57	701.5	0.419	1.149
tert-Butyl methyl ketone	3.84	738.1	0.337	1.058
Methyl isobutyl ketone	5.21	777.4	0.349	–
2-Methyl-3-pentanone	5.52	786.4	0.308	–
2,4-Dimethyl-3-pentanone	7.24	828.6	0.145	1.014
4-Heptanone	10.86	913.2	0.063	1.041
3-Heptanone	11.48	929.0	0.058	1.071
2,6-Dimethyl-4-heptanone	14.49	1007.1	0.037	0.947
5-Nonanone	18.23	1114.8	0.023	1.062
6-Undecanone	24.39	1303.9	0.019	0.995
Cycloalkanes II				
1-Methyl-1-cyclopentene	1.74	644.1	0.594	1.144
Methylenecyclohexane, 4-Methyl-1-cyclohexene	3.68	733.3	–	–
1,4-Dimethylcyclohexane (*cis* or *trans*)	4.91	768.9	–	–
1,1-Dimethylcyclohexane	5.19	777.0	0.309	–
trans-1,2-Dimethylcyclohexane	5.69	791.5	0.255	–
1,4-Dimethylcyclohexane (*cis* or *trans*)	6.05	801.5	0.228	–
cis-1,2-Dimethylcyclohexane	7.11	825.6	0.165	1.013
2,5-Dimethyl-2,4-hexadiene, ethylbenzene	9.49	880.2	–	0.934
Alcohols II				
tert-Amyl alcohol, isobutyl alcohol	2.38	690.2	–	–
Methyl propyl carbinol	4.17	747.6	0.293	1.125
3,3-Dimethyl-2-butanol	5.60	788.9	0.328	1.122
2-Methyl-1-butanol, isoamyl alcohol	6.16	803.9	–	–
4-Methyl-2-pentanol	6.85	819.6	0.140	1.074
2-Ethyl-1-butanol	10.54	905.0	–	–
dl-3-Heptanol	12.32	950.6	0.038	–
Alcohols III				
Isopropyl alcohol	0.82	541.5	0.645	1.345
tert-Butyl alcohol	0.98	572.3	0.505	–
sec-Butyl alcohol	1.80	648.2	0.403	1.216
2-Methyl-3-pentanol	7.17	827.1	0.131	1.026
3-Hexanol	8.33	853.6	0.109	–
2-Hexanol	8.65	861.0	0.101	–
2-Methyl-1-pentanol	10.30	898.9	0.063	1.016
2-Octanol	16.20	1055.9	0.025	0.984
Halogenated benzenes				
Chlorobenzene	8.93	867.4	0.103	1.015
1-Chloro-2-fluorobenzene	9.89	889.4	0.084	–
3-Bromofluorobenzene	11.75	936.0	0.060	1.201
4-Bromofluorobenzene	12.28	949.5	0.050	0.921
1-Bromo-2-fluorobenzene	13.31	976.0	0.047	1
Benzyl chloride	16.13	1053.8	–	–
1,2-Dichlorobenzene, iodobenzene	16.45	1063.1	–	–
1,2-Dibromobenzene	22.50	1246.4	0.027	–
Chlorocarbons				
Chloroform	1.83	650.4	–	–
1-Chlorobutane, 1,1,1-trichloroethane	1.94	658.3	–	–
1,2-Dichloroethane	2.23	678.9	0.441	1.126
1,2-Dichloropropane	3.20	719.5	0.322	1.140
1,1,2-Trichloroethane	6.64	814.9	0.165	1.089
1,1,1,2-Tetrachloroethane	9.36	877.3	0.083	1.080
1,1,2,2-Tetrachloroethane, 1,2,3-trichloropropane	13.12	971.1	–	–
Pentachloroethane	14.52	1008.0	0.030	0.947
Hexachloro-1,3-butadiene	21.78	1224.7	0.034	–
Esters II				
Isopropyl acetate	2.38	690.2	0.331	1.159
Isopropenyl acetate	2.83	709.0	0.340	1.167
tert-Butyl acetate	3.25	721.0	0.335	0.896
Methyl butyrate	3.99	742.4	0.339	1.071
dl-sec-Butyl acetate	5.57	787.9	0.242	1.122
Isobutyl acetate	6.30	807.2	0.187	0.986
Methyl valerate	8.44	856.2	0.105	0.974
Isoamyl acetate	10.72	909.6	0.057	1.037
Methyl salicylate	22.32	1241.1	0.021	1.063

of samples before DMS or IMS significantly simplifies response and spectral interpretation, so that GC–DMS (or GC–IMS) can be seen as a sequential or orthogonal measurement, though the relative contribution of these has not been determined. Combinations of gas chromatographs and mobility spectrometers were described over 30 years ago [17] and can be found in some prominent venues, such as the Volatile Organic Analyzer on-board the International Space Station [18]; nonetheless, complete and integrated mobility detec-

tors have only recently become available with GC–IMS and GC–DMS instruments.

The objective of this study was to measure quantitatively the chromatographic performance of an MCC by separating mixtures of volatile organic compounds with incremented number of constituents. Column conditions were also optimized to determine the effect of operating parameters and the contributions on analytical selectivity with a differential mobility spectrometer were determined.

2. Materials and Methods

2.1. Instrumentation

A Hewlett-Packard 5890A gas chromatograph was equipped with a splitless injector, a coiled multi-capillary column (OV-624, 1 m length, ~1000 capillaries, 40 μm I.D., 0.2 μm film thickness, Sibertech, Novosibirsk, Russia), and a FID system. Experimental parameters were injector temperature, 180 °C; detector temperature, 250 °C; initial oven temperature, 35 °C; initial time, 5 min; program rate, 5 °C min^{-1}; final temperature, 130 °C; and final time, 25 min. Other parameters included inlet pressure, 5.0 psig; split flow, 30 mL min^{-1}; and septum purge flow, 3 mL min^{-1}. The carrier gas was nitrogen obtained from a nitrogen generator (O_2N_2 Site Gas Systems, NMC1) and purified through molecular sieves.

The FID system was replaced after preliminary studies with a differential mobility spectrometer built at NMSU and described in detail [19,20]. The MCC was attached to the DMS system using a 40 cm length of aluminum clad capillary column (0.22 mm I.D.) and a Vu2 Union connector (Restek, Bellefonte, PA, USA). The aluminum clad column was passed from the oven to the detector through a heated (230 °C) transfer line of 6 mm O.D. stainless steel tubing. The DMS system was equipped with an ion source of 5 mCi of ^{63}Ni and was thermostated to 100 °C. Gas flow into the differential mobility spectrometer was air at 0.76 L min^{-1} and was obtained from a pure air generator and was further purified using a molecular sieve tower. Compensation voltages (CVs) were scanned from −10 to +30 V_{dc} repeatedly every 1.5 s throughout the elution time from 0 to 46.5 min.

All samples were analyzed using a Hewlett-Packard model 5971A gas chromatograph–mass spectrometer equipped with a capillary column (SPB-5, 15 m length, 0.3 mm I.D., 0.25 μm film, Supelco, Bellefonte, PA, USA) and splitless injector. Chromatographic conditions were: injector temperature, 200 °C; detector temperature, 250 °C; initial oven temperature, 10 °C; initial time, 3 min; program rate, 2 °C min^{-1}; final temperature, 120 °C; and final time, 0 min. Other parameters included inlet pressure, 2.0 psig and split ratio, 50:1. The carrier gas was bottled helium purified using a Model 8301Hydrox Purifier (Montgomeryville, PA, USA). Acquisition was in the scan mode. Mass spectra were scanned at a rate of 1.5 scans s^{-1} from 50 to 550 Da with an electron multiplier voltage of 1847 V.

2.2. Procedures

2.2.1. Preparation and analysis of mixtures

One hundred and twenty nine volatile organic compounds (VOCs) from 14 chemical classes (Table 1) were obtained from various manufacturers and used as received. Neat mixtures of these were prepared by chemical class with each mixture containing 8–10 compounds in equal amounts by mass. Stock solutions of all mixtures were prepared by dilution in anhydrous hexadecane (99+%) to ~100 ng μL^{-1} and were analyzed by GC–FID with the MCC. Composite mixtures were made using the neat mixtures, by stepwise combinations (Fig. 1), to form 14 composite mixtures of increasing number of constituents. These were also diluted in hexadecane and analyzed, as described above. Sample volumes for analysis were 1 μL.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	No. in mixture	No. of peaks
1	■														9	9
2	■	■													17	15
3	■	■	■												25	21
4	■	■	■	■											34	30
5	■	■	■	■	■										43	37
6	■	■	■	■	■	■									53	47
7	■	■	■	■	■	■	■								63	57
8	■	■	■	■	■	■	■	■							73	61
9	■	■	■	■	■	■	■	■	■						83	66
10	■	■	■	■	■	■	■	■	■	■					92	68
11	■	■	■	■	■	■	■	■	■	■	■				100	70
12	■	■	■	■	■	■	■	■	■	■	■	■			109	75
13	■	■	■	■	■	■	■	■	■	■	■	■	■		120	76
14	■	■	■	■	■	■	■	■	■	■	■	■	■	■	129	76

Fig. 1. Composition of mixtures and number of resolved peaks on MCC. Mixtures were (A) *n*-alcohols, (B) 2-ketones, (C) *n*-alkyl acetates, (D) ethers, (E) *n*-alkanes, (F) benzene and alkylated benzenes, (G) cycloalkanes, (H) substituted ketones, (I) cycloalkanes II, (J) alcohols II, (K) alcohols III, (L) halogenated benzenes, (M) chlorocarbons, and (N) esters II. Exact composition of each mixture is given in Table 1.

2.2.2. Processing of chromatograms and optimization of parameters

Chromatograms were deconvoluted using PeakFit 4.0.5 (SPSS, Chicago, IL, USA). When a peak could be computationally deconvoluted using PeakFit software into two constituents, both compounds were included in the number of components separated. Optimization was made using MultiSimplex 2.1.3 (Grabitech Solutions, Sundsvall, Sweden). Three control variables were linear flow velocity of carrier gas, initial temperature and program rate. The step sizes and reference values for these were initial temperature (°C), 8, 35; program rate, (°C min^{-1}) 2, 5; and linear velocity of carrier gas (m min^{-1}), 0.3, 3.1. The response variable was the number of resolved peaks and the goal was to maximize the number of resolved peaks.

2.2.3. GC–DMS analysis of optimized parameters with MCCs

Spectra for both positive ions and negative ions were obtained from GC–DMS analysis of all mixtures using 0.3–1 μL of solutions with optimized chromatographic parameters. Spectra were extracted into spreadsheets of ion intensity at 410 columns for compensation voltage axis ranged from −10 to +30 V.

3. Results and discussion

3.1. Separations of mixtures with MCC and FID

Chromatograms for homologous series for *n*-alkyl acetates and *n*-alcohols and for a mixture of benzene with alkylated-benzenes are shown in Fig. 2 and retention behavior with chromatographic terms are listed in Table 1. Relative retention and identities of peaks were verified with the injection of individual standards. Baseline separation was obtained for major constituents in each homologous series (Fig. 2A and B), though not uniformly so as observed with alkylated benzenes in Fig. 2C. Chromatographic efficiencies ranged from 0.017 to 0.771 mm in HETP at 9.0 mL min^{-1} and these were later improved by 26% or greater with flows of 33 mL min^{-1}. Relative retention was not influenced by flow rate and studies were

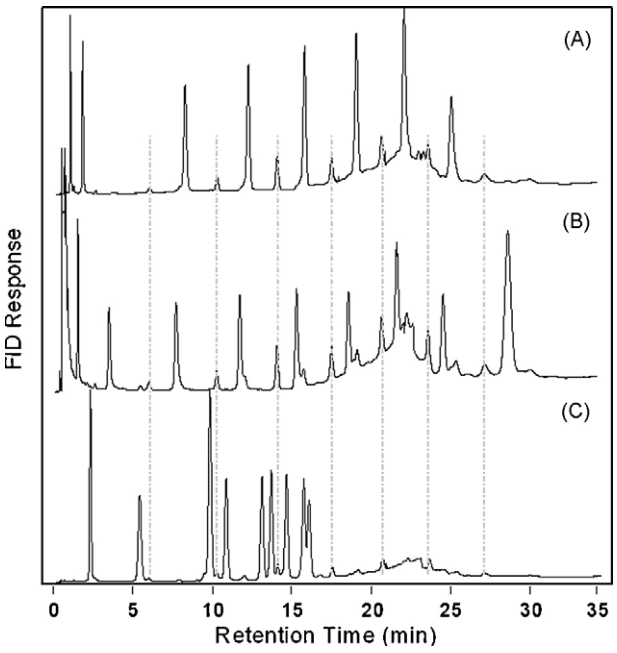

Fig. 2. Chromatograms from separations of homologous series of (A) *n*-alkyl acetates, (B) *n*-alcohols and (C) benzene with alkylated benzenes using multi-capillary column. Mixtures also contain minor amounts of *n*-alkanes originating in hexadecane, the solvent.

continued with mixtures where the number of constituents in a sample was increased stepwise to a total of 129 compounds.

As the complexity of mixtures was increased (Fig. 1), the number of compounds unresolved was proportionally increased. For example, 17 constituents were observed as only 15 peaks (Fig. 3D) from a mixture of ketones and alcohols. Baseline separation was obtained for *n*-propanol and 2-butanone while partial separation was observed for *n*-heptanol:2-octanone, *n*-octanol:2-nonanone, *n*-nonanol:2-decanone, and *n*-decanol:2-undecanone. Unresolved pairs included *n*-petanol:2-hexanone and *n*-hexanol:2-heptanone. Additional increases in complexity of samples produced chromatograms with an increase in number of constituents not resolved (Figs. 3C, B and 1). This relationship was linear between 8 and 60 constituents with a slope of ~1:0.9 (Fig. 4B) and decreased to 1:0.7 after 60 constituents. A plateau was approached after 105 chemicals and altogether only 76 of 129 components were resolved before optimization of parameters.

3.2. Optimization of parameters for separations

Parameters treated using simplex optimization were carrier gas linear velocity, initial temperature and program rate and the simplex optimization was operated to maximize the number of peaks resolved. Reference values and step sizes for these three variables were chosen from preliminary experiments and the number of resolved peaks was increased after nine steps by 19.7% (Fig. 4A) and this was increased slightly in the following 12 trials to a final number of 94 peaks or a 23.7% improvement over the non-optimized chromatographic conditions. Optimum conditions were carrier gas linear velocity of 5.64 cm s^{-1}, initial temperature of 18 °C and program rate of 4 °C min^{-1} and the number of VOCs resolved was 94, or 73% of all compounds.

3.3. Enhanced separation with a differential mobility detector

An alternative to computational deconvolution of peaks is the use of detectors where a second dimension of measurement could aid resolution and an FID system was replaced by a DMS system. In a DMS system, a first layer of separation occurs in the ionization step where a substance (M) is ionized through chemical reactions with [$H^+(H_2O)_n$ where n is principally 2 here], forming MH^+ and M_2H^+ ions [21]. Only 59 of all substances were ionized in positive polarity with moisture of 1 ppm in the supporting atmosphere. Chemicals showing no or very low response were alkanes, cycloalkanes, aromatic hydrocarbons, halogenated aromatic hydrocarbons, and chlorocarbons and these were excluded from further chromatographic consideration. The second dimension of selectivity in a DMS system is ion characterization and separation in a 1 Mz asymmetric waveform. In the DMS spectra, protonated monomers (MH^+) appear from 1 to 10 V in compensation voltage (E/N values of 0.117 to 1.171 Td) and the proton bound dimers (M_2H^+) appear at CV values of 0.5 to −3 V (E/N values of −0.059 to −0.351 Td). Increased ion mass or size leads to systematic shifts in protonated monomer and proton bound dimer as described [22]. The effects of functional groups are also seen in comparison of ketones and acetates and alcohols where tendency to solvate the ion governs the CV value. Proton bound dimers are largely governed by ion drag, exhibit lessened dependences on electric field, and appear in a CV band near zero E/N.

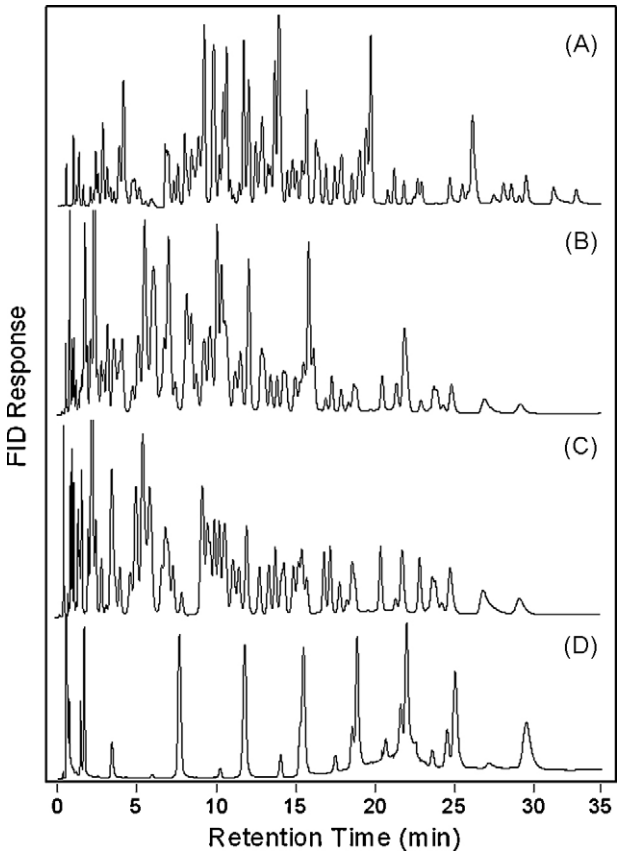

Fig. 3. Chromatograms from separation with MCC of mixtures number 14 (B), 10 (C) and 2 (D). Composition of these mixtures is referenced to Fig. 1. The chromatogram in (A) is after simplex optimization of parameters.

Results from analysis of DMS spectra are shown in Table 2 in lists of compensation voltage for protonated monomers and proton bound dimers and a plot of ion mass versus CV is shown in Fig. 5. In the plot, CV for protonated monomers was proportional (14 V to 2 V) to ion mass (100–220 Da, assuming two waters of hydration) with some scatter between chemical families. A similar pattern was observed with the proton bound dimers through the CV scale is compressed to only 2.2 V (−1.9 to 0.3). Peak widths of product

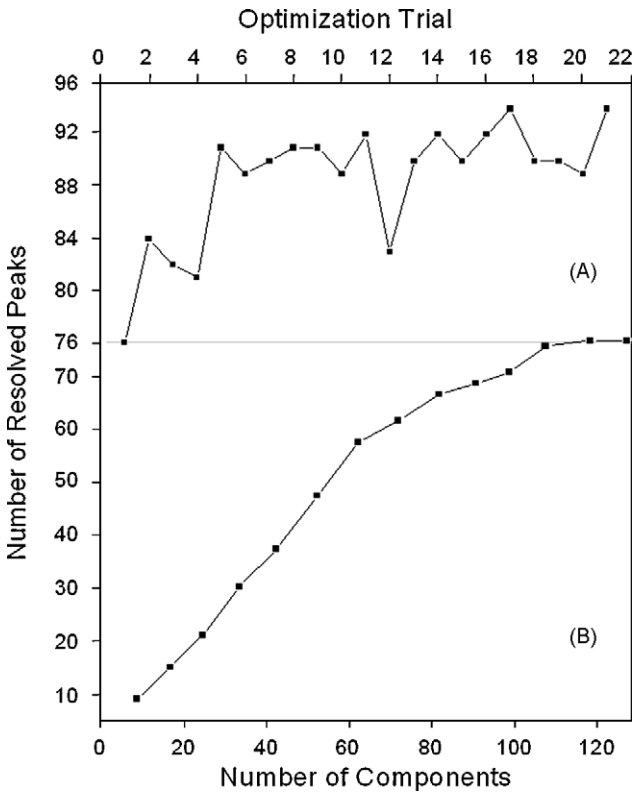

Fig. 4. Number of resolved peaks versus constituents in mixture from separation with an MCC before optimization (B) and during simplex optimization of parameters (A). Note separate *x*-axes and scaling on *y*-axis.

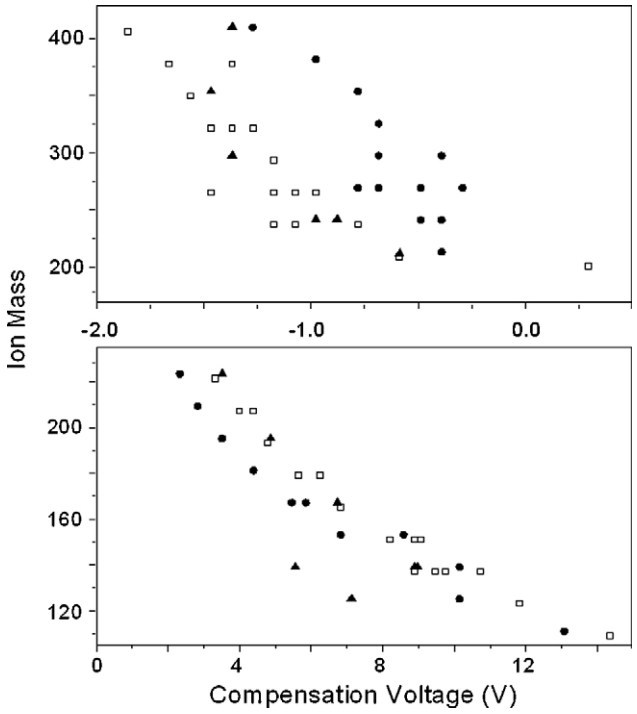

Fig. 5. Plots of ion mass versus CV value for all chemicals showing response in positive polarity with DMS detector. Chemical groups are: (●) esters; (▲) ethers; and (■) ketones.

Table 2
Compensation voltages of chemicals which were ionized and characterized with a differential mobility detector. E/N values can be obtained using the formula $E/N = 2.828 \times E/(273.16 \times P/T)$, in which E is V cm^{-1}, P is in Torr and T is in K.

Compound	Compensation voltage (V)	
	Proton bound dimer	Protonated monomer
2-Ketones		
2-Butanone	0.293	14.355
2-Hexanone	−0.781	9.766
2-Heptanone	−0.977	8.203
2-Octanone	−1.172	6.836
2-Nonanone	−1.367	5.664
2-Decanone	−1.562	4.785
2-Undecanone	−1.66	4.004
2-Dodecanone	−1.855	3.32
n-Alkyl acetates		
Methyl acetate		13.086
Ethyl acetate	−0.391	10.156
Butyl acetate	−0.684	6.836
Amyl acetate	−0.684	5.469
Hexyl acetate	−0.684	4.395
Heptyl acetate	−0.781	3.516
Octyl acetate	−0.977	2.832
Nonyl acetate	−1.27	2.344
Ethers		
tert-Butyl methyl ether		7.129
Butyl methyl ether	−0.586	
tert-Amyl methyl ether		5.566
Propyl ether	−0.879	8.984
Butyl ethyl ether	−0.977	8.887
Butyl ether	−1.367	6.738
Pentyl ether	−1.465	4.883
Hexyl ether	−1.367	3.516
Substituted ketones		
3-Methyl-2-butanone	−0.586	11.816
tert-Butyl methyl ketone	−1.172	8.887
Methyl isobutyl ketone	−1.074	9.473
2-Methyl-3-pentanone	−1.074	10.742
2,4-Dimethyl-3-pentanone	−1.465	9.082
4-Heptanone	−1.074	8.887
3-Heptanone	−1.172	8.887
2,6-Dimethyl-4-heptanone	−1.465	6.25
5-Nonanone	−1.27	6.25
6-Undecanone	−1.367	4.395
Esters II		
Isopropyl acetate	−0.391	
Methyl butyrate	−0.488	10.156
dl-sec-Butyl acetate	−0.488	
Isobutyl acetate	−0.293	
Methyl valerate	−0.781	8.594
Isoamyl acetate	−0.391	5.859

ions were all ~1.5 V wide at half height. This second dimension of selectivity can have practical value in aiding resolution of convolved peaks as described below.

Another aspect of a DMS system is the dependence of vapor concentration in the analyzer of ion profiles, seen largely as the position of the distribution between protonated monomer and proton bound dimer. This is seen in Fig. 6 for the mixture of 2-ketones. As the vapor level in effluent increases in the detector, protonated monomer first appears and is rapidly displaced or supplanted with a proton bound dimer as vapor levels increase further to the chromatographic peak maximum. As the vapor level decreases on the tailing side of the GC peak, the proton bound dimer decreases in intensity and the protonated monomer reappears. This is seen as a dual peak pattern at the same CV value on either side of the GC peak maximum. This will be observed only when vapor levels are high enough to form a proton bound dimer and otherwise, only a protonated monomer peak in a simple single peak pattern will be observed. This introduces an additional level of complexity in

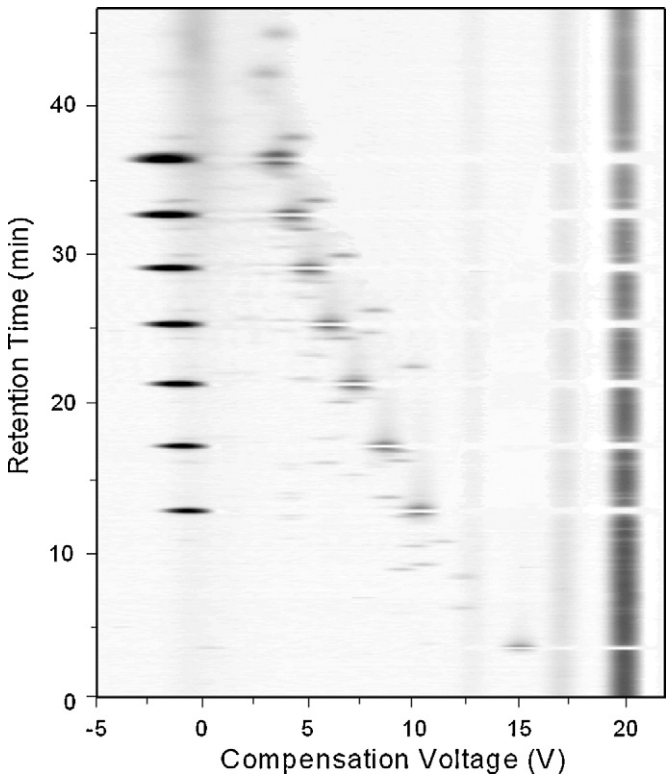

Fig. 6. Contour plot from GC–DMS analysis of mixture of 2-ketones. Retention times and CV values can be found in Tables 1 and 2, respectively.

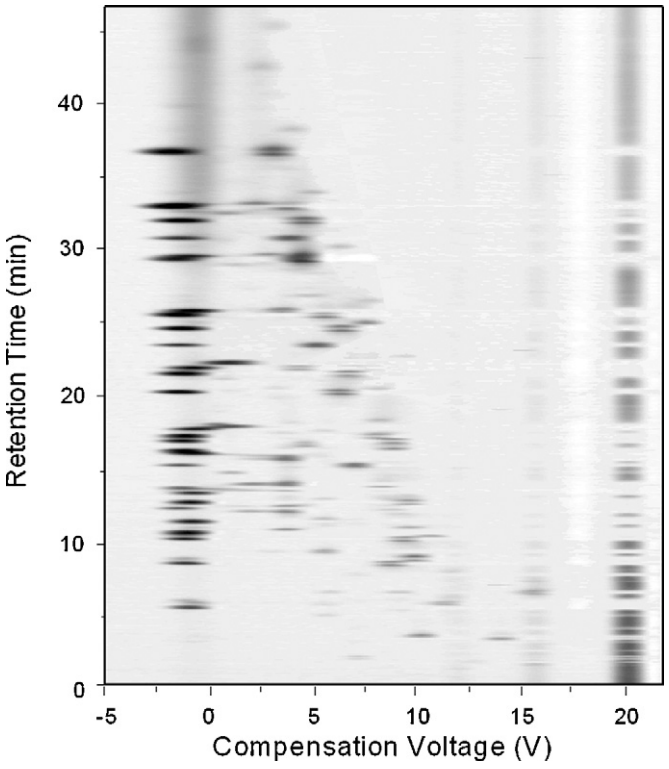

Fig. 7. Contour plot from GC–DMS analysis of the complex mixture with 59 of 129 chemicals ionized. Retention times and CV values can be found in Tables 1 and 2, respectively.

a GC–DMS analysis while simultaneously disclosing concentration directly in a calibrated instrument.

A measurement by GC–DMS can be described using contour or topographic plots [19,20] and a plot for the complete mixture of these studies is shown in Fig. 7 (the peak at +19.1 V is the reactant ion peak). The appearance of a chemical in the effluent results in formation of the product ions from charge available with the reactant ion. Since kinetics of formation of the reactant ion are slow compared to the depletion to form product ions, losses in intensity are observed with elution of a chemical. As seen in Fig. 7, the differences in retention time for chemicals also are seen in differences in CV values as given in Table 2. These form the pattern in Fig. 7 suggesting analytical resolution can be enhanced with the detector.

Thirteen instances were found in the measurement (Fig. 7) where chromatographic separation was insufficient to resolve components in a peak and separations could be seen in the compensation voltage axis within DMS spectra for seven of these convolved peaks. Thus, DMS spectra were obtained from a GC peak at 3.5 min which showed limited resolution (Fig. 8A) and protonated monomers for 2-butanone and ethyl acetate were seen at characteristic compensation voltages. As anticipated from the relationship between molar mass of the ion and CV values, the protonated monomers were easily recognizable and baseline resolved; protonated dimers were less so. Six other examples of this type of detector-enhanced resolution were found and the number of compounds detected was 53 of 59 or 90% compared to 73% with FID. At a comparable number of compounds, the GC was 46 compounds of

Table 3
List of peaks resolved by GC and chromatographically unresolved peaks separated in the compensation voltage axis by DMS.

Range of retention times (min)	No. of components	No. separated by retention	No. separated with aid of DMS	No. not separated with GC–DMS
0–2	3	3		
2–4	4	4		
4–6	6	3	1	2
6–8	1	1		
8–10	4	4		
10–12	6	4		2
12–14	7	7		
14–16	5	5		
16–18	5	2	3	
18–20	1	1		
20–22	4	4		
22–24	1	1		
24–26	4	4		
26–30	3		1	2
30–40	5	3	2	
Total	59	46	7	6

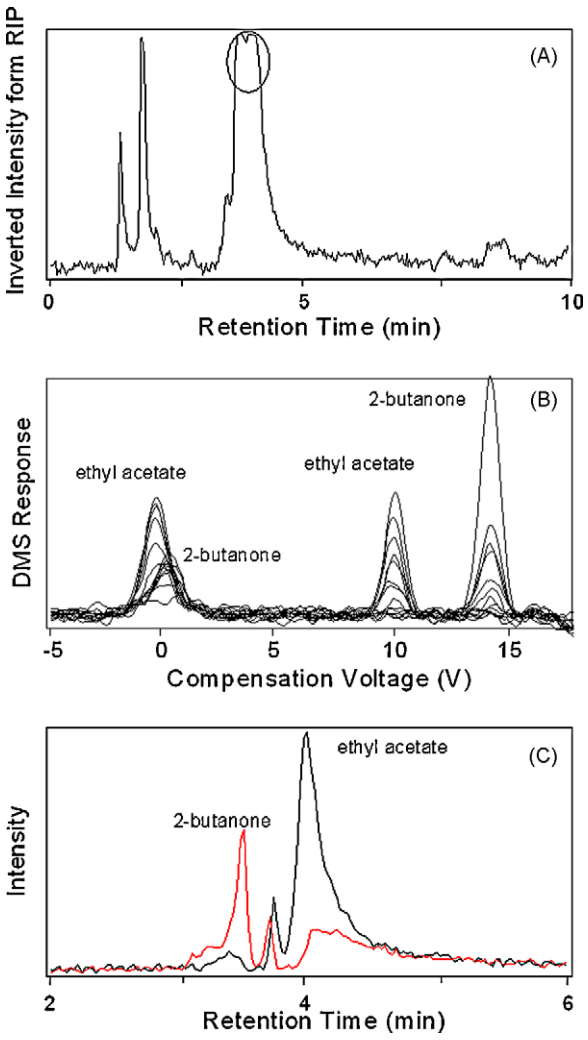

Fig. 8. Example where resolution is enhanced with DMS where co-elution of ethyl acetate and 2-butanone are detected by differential mobility. Multiple spectra obtained over the elution profile of the peak (A) are overlapped (B) and drawn from throughout the elution profile. The ion plots for protonated monomer of each chemical are shown in frame C.

59 or 78% as shown in Table 3. Nearly half of all unresolved peaks in the chromatographic timescale were resolved in the DMS axis and this could be improved further with either a different separation voltage or a programmed separation voltage that increases with increased chromatographic retention [23]. This possibility is influenced by ion formation, which is competitive in these detectors. Thus, suppression of response is possible then there may be a large excess of chemicals with comparable ionization properties; in such instances, resolution is dependent wholly on chromatography.

A central question is how orthogonal GC and DMS are from differences in the mechanism of characterization and separation; although differences exist, the principles used in GC and DMS are not totally independent of each other. For example, large molecules with long retention times also have low differential mobilities and hence appear near compensation voltages of zero. The orthogonality and practical peak capacity in GC–DMS were determined mathematically using geometric approach first designed for GC–GC [24]. This was not directly applicable since the entire range for DMS spectrum is not useable as protonated monomers and proton bound dimers appear only on one side of the RIP, as seen in Figs. 6 and 7. Theoretical peak capacity in either dimension was estimated from the ratio of the axis range to average peak width

Table 4
Parameters of GC–DMS orthogonality calculation for 2-ketones.

DMS	Effective compensation voltage range (V)	24.50
	Peak base width	1.73
	Theoretical peak capacity N1	14.20
GC	Retention time range (min)	46.50
	Peak base width	0.45
	Theoretical peak capacity N2	104.09
2 D theoretical peak capacity Nt		1477.64
correlation		−0.4120
β		1.1462
α'		1.4352
α		0.3875
γ		0.0364
Practical peak capacity Np		1239.72
Loss of peak capacity		237.92
Loss of peak capacity %		16.10

in that dimension where average peak width in DMS dimension was estimated as almost four times that in GC dimension. Theoretical peak capacity in GC dimension is 104 and this is higher than that obtained using empirical approach (i.e., 76). The reason for this is that components in the actual complex mixture were randomly positioned, not evenly lined up in the chromatogram. The two dimensional theoretical peak capacity was then determined as the product of one dimensional theoretical peak capacities. The correlation between two dimensions was calculated to evaluate orthogonality using a peak spreading angle. Practical peak capacity of GC–DMS was then determined based on peak spreading angle. The resultant values of these calculations for the 2-ketone mixture are listed in Table 4 and the correlation of −0.412 implies significant orthogonality between GC and DMS. Only 16.1% of theoretical peak capacity was lost due to correlation. In theory, the combination of GC and DMS increases peak capacity to 1240 which is more than ten times the GC dimension alone; however, such performance cannot be expected practically due to peak overlap in some space and multiple product ion in the DMS dimension, reducing the maximum number of chemical components which can be resolved theoretically by GC–DMS to 620, and this is about half of the practical peak capacity.

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References

[1] M.J.E. Golay, Chromatographia 8 (1975) 421.
[2] V.P. Soldatov, A.P. Archakov, A.P. Efimenko, I.I. Naumenko, S.K. Kulov, G.P. Romanov, M.N. Popov, USSR Pat. 1 635 128 (1991).
[3] Y. Wen, H. Zhang, R. Fu, Sepu 16 (1998) 137.
[4] J.I. Baumbach, G.A. Eiceman, D. Klockow, S. Sielemann, A. von Irmer, Int. J. Environ. Anal. Chem. 66 (1997) 225.
[5] R. Lobinski, V. Sidelnikov, Y. Patrushev, I. Rodriguez, A. Wasik, Trends Anal. Chem. 18 (1999) 449.
[6] I.A. Buryakov, Y.N. Kolomiets, J. Anal. Chem. (Translation of Zh. Anal. Khim.) 58 (2003) 944.
[7] I.A. Buryakov, J. Chromatogr. B 800 (2004) 75.
[8] V. Ruzsanyi, J.I. Baumbach, S. Sielemann, P. Litterst, M. Westhoff, L. Freitag, J. Chromatogr. A 1084 (2005) 145.
[9] W. Vautz, J.I. Baumbach, Eng. Life Sci. 8 (2008) 19.
[10] J.I. Baumbach, W. Vautz, V. Ruzsanyi, L. Freitag, Mod. Biopharm. 3 (2005) 1343.
[11] E. Bolzacchini, S. Meinardi, M. Orlandi, L. Radice, B. Rindone, R. Belloli, Laboratorio 2000 11 (1997) 20.
[12] J.I. Baumbach, S. Sielemann, Z. Xie, H. Schmidt, Anal. Chem. 75 (2003) 1483.
[13] G. Walendzik, J.I. Baumbach, D. Klockow, Anal. Bioanal. Chem. 382 (2005) 1842.
[14] M. Van Deursen, M. Van Lieshout, R. Derks, H. Janssen, C. Cramers, J. High Resolut. Chromatogr. 22 (1999) 119.
[15] V.P. Zhdanov, V.N. Sidelnikov, A.A. Vlasov, J. Chromatogr. A 928 (2001) 201.

[16] M. Van Lieshout, M. Van sen, R. Derks, H. Janssen, C. Cramers, J. Microcol. Sep. 11 (1999) 155.
[17] M.J. Cohen, F.W. Karasek, J. Chromatogr. Sci. 8 (1970) 330.
[18] P.V. Johnson, L.W. Beegle, H.I. Kim, G.A. Eiceman, I. Kanik, Int. J. Mass Spectrom. 262 (2007) 1.
[19] G.A. Eiceman, B. Tadjikov, R.G. Ewing, E.G. Nazarov, E. Krylov, R. Miller, Analyst 129 (2004) 297.
[20] S. Prasad, H. Schmidt, M. Wang, R. Güth, J.V. Rao, G.B. Smith, G.A. Eiceman, Analyst 131 (2006) 1216.
[21] G.A. Eiceman, Z. Karpas, Ion Mobility Spectrometry, CRC Press, Boca Raton, FL, 2005, p. 95.
[22] G.A. Eiceman, E.G. Nazarov, R.A. Miller, E. Krylov, A. Zapata, Analyst 127 (2002) 466.
[23] M. Basanta, D. Singh, S. Fowler, I. Wilson, R. Dennis, C.L.P. Thomas, J. Chromatogr. A 1173 (2007) 129.
[24] Z. Liu, D.G. Patterson, M.L. Lee, Anal. Chem. 67 (1995) 3840.