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INCREASED SPEED OF ANALYSIS IN ISOTHERMAL AND TEMPERATURE-PROGRAMMED CAPILLARY GAS CHROMATOGRAPHY BY REDUCTION OF THE COLUMN INNER DIAMETER

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SUMMARY

It is shown theoretically that for an isothermal analysis the relationship of the retention time to the column diameter is $t_R \approx d_c^z$. The exponent z is determined by the column pressure drop and varies between $z = 1$ for high plate number columns and $z = 2$ for situations of low pressure drop. Equations derived for temperature-programmed conditions also lead to the same conclusion. The validity of the expressions was confirmed by experiments with columns of 30 and 50 μm internal diameter, installed in standard chromatographic equipment. With these small-diameter glass and fused-silica columns coated with non-polar stationary phases, plate numbers between 10^5 and 10^6 were obtained. A temperature-programmed run typically can be accomplished within 8 min on an 8 m $\times$ 50 μm column having over 10^5 plates. Several examples of high-speed, high-resolution analysis of complex samples are given.

INTRODUCTION

In recent years, capillary gas chromatography has become an important tool in analytical chemistry and has been applied to a wide range of routine applications. However, since the introduction of the technique in 1958 by Golay[1], there has been a demand for an increased speed of analysis. From a theoretical point of view, the reduction of the column inner diameter seems an obvious route towards shorter analysis times. The practical feasibility of this approach was convincingly demonstrated by Desty *et al.*[2] in 1962, but surprisingly this approach has received hardly any attention since then. In 1977, Gaspar and co-workers[3,4] reported on a novel injection technique, based on a "fluidic logic" pneumatic device. With this system an injection bandwidth of about 10 msec could be realized. Both the Desty and Gaspar groups obtained analysis times of the order of a few seconds on columns with inner diameters of 35 and 65 μm, respectively. However, the samples analysed were simple mixtures of lower hydrocarbons and the columns had low plate numbers (below 10^4).

In this paper, the relationship between the column diameter and the speed of analysis is investigated with emphasis on columns having over 10^5 theoretical plates.

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The performance of 50 and 30 μm I.D. columns under isothermal and temperature-programmed conditions is discussed. Separations of complex samples on such columns are shown.

THEORY

Isothermal conditions

In gas chromatography the retention time, t_R, of a compound can be described by

$$t_R = \frac{L(1 + k)}{\bar{u}} = \frac{HN(1 + k)}{\bar{u}} \tag{1}$$

where L is the column length, N the number of theoretical plates, H the plate height, $\bar{u}$ the average carrier gas velocity and k the capacity ratio.

In the following treatment it is assumed that the carrier gas velocity is maintained at the optimum value, $\bar{u}_{opt}$, for which the plate height is at a minimum, H_{min}. Expressions for $\bar{u}_{opt}$ and H_{min} can be found by differentiating the Golay/Giddings "plate height" equation[5]. If the term describing the resistance to mass transfer in the stationary phase is neglected, then

$$H_{min} = \tfrac{1}{2}\, d_c f_1 F(k)^{1/2} \tag{2}$$

$$u_{0,opt} = \frac{8\, D_{m,o}}{F(k)^{1/2}\, d_c} \tag{3}$$

$$\bar{u}_{opt} = u_{0,opt} f_2 \tag{4}$$

where d_c is the column inner diameter, u_0 the carrier gas velocity at the column outlet and $D_{m,o}$ the diffusion coefficient of the solute in the mobile phase at the column outlet pressure.

$$F(k) = \frac{11\,k^2 + 6\,k + 1}{3\,(k + 1)^2}$$

f_1 and f_2 are pressure correction factors, according to Giddings *et al.*[6] and to James and Martin[7], respectively:

$$f_1 = \frac{9}{8} \cdot \frac{(P^4 - 1)(P^2 - 1)}{(P^3 - 1)^2} \tag{5}$$

$$f_2 = \frac{3}{2} \cdot \frac{P^2 - 1}{P^3 - 1} \tag{6}$$

where $P = p_i/p_0$ is the ratio of the column inlet to the column outlet pressure. At $P \approx$

1, $f_1 = f_2 = 1$. When $P \gg 1$, f_1 will increase towards the maximum value of 9/8 and eqn. 6 can be simplified to

$$f_2 = \frac{3}{2P} \tag{7}$$

From eqns. 3, 4 and 7, it can be seen that $\bar{u}_{opt}$ is strongly affected by the column pressure drop. At $P \approx 1$, an inverse relationship between $\bar{u}_{opt}$ and d_c is found, since $f_2 = 1$. By contrast, at $P \gg 1$, $\bar{u}_{opt}$ is independent of d_c, as will be shown later. H_{min} is affected by P through f_1 (eqns. 2 and 5) and may be increased by a factor between 1 and 9/8.

The flow through a capillary column can be calculated from Poiseuille's law[8]:

$$u_0 = \frac{d_c^2 p_0 (P^2 - 1)}{64 \eta L} \tag{8}$$

where η is the dynamic viscosity of the mobile phase. Combination of eqns. 2, 3 and 8 leads to an explicit relationship between d_c and the column inlet and outlet pressures:

$$P_{opt}^2 - 1 = \frac{256 D_{m,o} \eta N f_1}{p_0 d_c^2} \tag{9}$$

At large values of P, $(P^2 - 1) \approx P^2$. P_{opt} and therefore the column inlet pressure, $p_{i,opt}$, are now seen to be inversely proportional to d_c provided that p_0 is kept constant.

A relationship between analysis time and column diameter is found by combining eqns. 1–4:

$$t_R = \frac{(k + 1) F(k) N}{16 D_{m,o}} \cdot \frac{f_1 d_c^2}{f_2} \tag{10}$$

When studying the effect of column diameter on analysis time, it is important to compare situations of identical resolution. In practice, this means that the columns must be operated with identical stationary phases, carrier gases, temperatures and column outlet pressures to ensure equal partition coefficients. If also the phase ratio, β, is kept constant then similar values of k are obtained. To a first approximation both the partition coefficient and k are assumed to be independent of pressure. If the above requirements are met, the same number of theoretical plates is needed to realize identical resolutions on columns of different diameter. Eqn. 10 then further simplifies to

$$t_R = c d_c^2 f_1 / f_2 \tag{11}$$

where c is a constant.

Thus the column pressure drop will have a considerable influence on the relationship between t_R and d_c, mainly via f_2. By use of eqns. 5, 6 and 9 the factor f_1/f_2 can be elaborated as a complex function of d_c. At a fixed value of N it is found that $t_R \approx d_c^z$, $1 \leqslant z \leqslant 2$. Two extreme situations can be discerned. At $P \approx 1$, $f_1/f_2 = 1$ and $z =$

2. Now the retention time is seen to decrease as the square of d_c. This dependence will be found when columns of limited plate number are studied[3]. At large values of P, f_1/f_2 can be approximated by $f_1/f_2 \approx \frac{3}{4} P$. According to eqn. 9, P_{opt} now is inversely proportional to d_c. Thus, the retention time will decrease in proportion to the column diameter. A large value of P in practice is found for columns of very large plate number.

Summarizing, it is concluded from eqn. 11 that reduction of the column diameter presents an attractive route for improving the speed of analysis in isothermal capillary gas chromatography, even for columns that are operated under a considerable pressure gradient.

Temperature-programmed conditions (constant-pressure mode)

Temperature programming has become very important in practical gas chromatography. In our opinion, this technique should therefore be given adequate attention when presenting a chromatographic theory. In the following theory it is demonstrated that expressions describing temperature-programmed situations may readily be obtained once the isothermal properties of a column are known.

The velocity distribution function, $F(x/L)$, of the carrier gas in an isothermally operated capillary column is described by

$$F(x/L) = \frac{u_x}{u_0} = \left[P^2 - \frac{x}{L} (P^2 - 1) \right]^{-1/2} \tag{12}$$

where x is the distance from the column inlet measured along the longitudinal axis and u_x, u_0 are local linear gas velocities at positions x and L, respectively.

Provided that the column inlet and outlet pressures are kept constant, the ratio u_x/u_0 is seen to be independent of temperature. The velocity distribution function will therefore remain unaffected when temperature programming is applied. For a compound that is retained, the local chromatographic velocity, v_x, can be defined by

$$v_x = \frac{u_x}{1 + k_x} = u_0 \cdot \frac{F(x/L)}{1 + k_x} \tag{13}$$

Both u_0 and k_x are functions of temperature as u_0 is dependent on the dynamic viscosity, η, and $k_x = K_x/\beta$, which is proportional to the partition coefficient, K_x. At two different isothermal column temperatures, T_0 and T_i, the local chromatographic velocities in a given column with phase ratio β are thus related by

$$\alpha_i = \frac{v_{x,T_i}}{v_{x,T_0}} = \frac{\eta_{T_0}}{\eta_{T_i}} \cdot \frac{\beta + K_{T_0}}{\beta + K_{T_i}} \tag{14}$$

For gases that show ideal behaviour, η and K are virtually independent of pressure. Therefore, α_i will be independent of the position x of the test compound. This is also true if the column is operated with a large pressure drop.

A relationship will now be derived between the isothermal retention time, t_R, and the retention temperature, T_R, that is obtained during a linear temperature-

programmed run, for a column that is operated at a constant inlet and outlet pressure. In order to facilitate the treatment, the temperature programme is assumed to be equivalent to a large number of small isothermal steps. The steps are of equal temperature height ∂T and of equal duration ∂t. The ratio $\partial T/\partial t$, must, of course, be equal to the programming rate, r, of the true linear programme. During step i of the programmed run, a test compound will move at the speed v_{x,T_i} between the coordinates x_{i-1} and x_i within ∂t units of time. According to eqn. 14, the same displacement will require $(\alpha_i \partial t)$ time units at the isothermal temperature T_0. Thus the compound can be spotted at the same position x_i in the column either after i programming steps or, for the isothermal run, when $t_i = \alpha_1 \partial t + \alpha_2 \partial t + \ldots + \alpha_i \partial t$ time units have elapsed. Obviously the isothermal run is completed when

$$(\alpha_1 + \alpha_2 + \ldots + \alpha_l)\partial t = t_{R,T_0} \tag{15}$$

Hence under programmed conditions the retention temperature, T_R, will be

$$T_R = T_1 + (l - 1)\partial T \tag{16}$$

where T_1 is the starting temperature of the programme. It can be seen from eqn. 14 that each coefficient $\alpha_1, \alpha_2, \ldots, \alpha_l$ will assume the same value for all columns that have the same phase ratios and stationary phases and are operated with the same carrier gases. From eqns. 15 and 16 it follows that the same retention temperature will be obtained on any of such columns when

$$r t_{R,T_0} = \text{constant} \tag{17}$$

Experimental data supporting the validity of this expression can be found in the literature, for capillary columns of conventional dimensions. By combining eqns. 1 and 17, for instance, it can be seen that r must be varied proportionally to the average carrier gas velocity and inversely proportionally to the column length, if the same retention temperatures are to be obtained on columns having the same β and stationary phase. Both conclusions are confirmed by observations of Grob *et al.*[9] and are even incorporated in their well known column quality test.

From eqn. 17, it can be concluded that columns of reduced inner diameter generally must be operated at an elevated programming speed. For the programmed run the retention time t_R^* is inversely proportional to the programming rate:

$$t_R^* = (T_R - T_1)/r \tag{18}$$

Therefore, with temperature-programmed conditions, reduction of the column diameter will result in the same increase in speed of analysis as with isothermal conditions. At $P \approx 1$ the analysis time t_R^* will be proportional to d_c^2 whereas at large values of P a linear dependence on d_c will be found.

Instrumental contributions

Often the variance, σ_m^2, that is actually measured for a peak leaving the column will differ appreciably from

$$\sigma_c^2 = t_R^2/N \tag{19}$$

where σ_c^2 is the variance that will originate from the chromatographic processes

taking place inside the column. The following rule of additivity of variances is generally valid:

$$\sigma_m^2 = \sigma_c^2 + \sigma_{ec}^2 \tag{20}$$

where σ_{ec}^2 accounts for the extra-column contributions that may arise from injection bandwidth, detector cell volume, dead volumes and time constants of the electronic equipment, etc. According to eqns. 11 and 19, σ_c^2 will decrease when the column inner diameter is reduced while N is held constant. For very rapid analyses using short columns (t_R proportional to d_c^2), it can be seen from eqn. 20 that the peak width values are determined mainly by instrumental factors. To prevent this situation, σ_{ec}^2 must be lowered in proportion to σ_c^2. Specially designed injection and detection equipment having low time constants are therefore needed, as has been reported by Gaspar *et al.*[3]. In our philosophy[10], the use of modern commercial instruments without modification in combination with columns of high plate number is of more practical interest. If the decrease in column diameter is accompanied by an appropriate increase in the plate number, then σ_c^2 will approximately remain unchanged. The gain in analysis speed is thus traded off against increased separating power and σ_{ec}^2 need not to be lowered by complicated instrumental designs.

Columns with high plate numbers

The theory given in the first section will now be extended to long narrow-bore columns that require a large pressure gradient. As $P \gg 1$, eqns. 2 and 9 can be rewritten as

$$P_{opt} = \frac{1}{d_c}\left(\frac{288\, D_{m,0}\, \eta\, N}{p_0}\right)^{1/2} \tag{21}$$

$$H_{min} = \tfrac{9}{16} \cdot d_c\, F(k)^{1/2} \tag{22}$$

If the column outlet is kept at atmospheric pressure then combination of eqns. 3, 4, 7 and 21 leads to an expression for $\bar{u}_{opt}$ that is independent of the column diameter!:

$$\bar{u}_{opt} = \left[\frac{10^5\, D_m}{2\, \eta\, N\, F(k)}\right]^{1/2} \tag{23}$$

where D_m is the diffusion coefficient in the mobile phase at 1 bar (10^5 N m^{-2}).

Values of $(\eta\, D_m)^{1/2}$ and $(D_m/\eta)^{1/2}$ are given in Table I for three commonly used carrier gases. From a chromatographic point of view hydrogen is undoubtedly the most attractive choice for the carrier gas. Hydrogen is seen to have the largest value of $(D_m/\eta)^{1/2}$ and thus will allow the highest speed of analysis. Helium is slower by a factor 1.6 and nitrogen by a factor 2.8. The value of $(\eta\, D_m)^{1/2}$ and thus the required column inlet pressure is lower for hydrogen than for helium. Nitrogen is seen to require the lowest operating pressure, owing to its low optimal speed.

In practice, the applicability of narrow-bore columns with large plate numbers will be limited by the required inlet pressure and/or by the allowable analysis time.

TABLE I

PHYSICAL DATA FOR DIFFERENT CARRIER GASES

Carrier gas	D_m ($\times 10^{-6}$ m^2 sec^{-1})	η ($\times 10^{-6}$ N sec m^{-2})	$(D_m/\eta)^{1/2}$	$(\eta D_m)^{1/2}$
Hydrogen	36.5	10.3	1.88	19.4
Helium	29.7	22.9	1.14	26.1
Nitrogen	9.0	20.8	0.66	13.7

The maximum number of plates that can be realized without surpassing a maximum inlet pressure, $p_{i,max}$, or a maximum column dead time, $t_{m,max}$, can be found from eqns. 1, 21, 22 and 23. When values taken from the literature are entered for all constants, a graph of N *vs.* d_c can be constructed, as shown in Fig. 1. The shaded area indicates that plate numbers of $N > 10^6$ can be obtained without violating the limitations $p_{i,max} < 50$ bar (curve 1) and $t_{m,max} < 10$ min (curve 2), with hydrogen as the carrier gas when d_c is between 20 and 170 μm. A maximum of $2.7 \cdot 10^6$ plates may be generated at the optimum d_c value of 35 μm.

EXPERIMENTAL

Glass capillary columns of I.D. 50 μm and 0.3 mm and O.D. about 0.9 mm were drawn from borosilicate tubing (Duran 50, Schott, Wertheim, G.F.R., or Hypersil, Corning, Corning, NY, U.S.A.) on a home-made precision drawing apparatus. Fused-silica columns of I.D. 30 μm and O.D. 0.2 mm were obtained from SGE (Melbourne, Australia). The empty columns were rinsed several times with

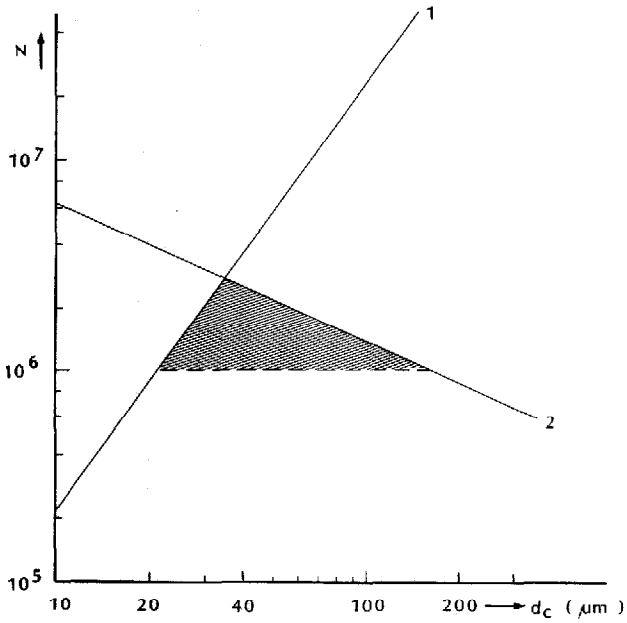

Fig. 1. Column diameter *versus* maximum attainable plate number. For discussion, see text.

methanol and methylene chloride and then dried by passing nitrogen through them at ambient temperature. A 70 m × 50 μm I.D. column was dynamically coated by passing through it a solution of 20% (v/v) of OV-101 in pentane at a speed of 3.5 cm/sec. All other columns were filled with a solution of 0.8% (v/v) of SE-30 in pentane and were coated by the static method as described by Rutten and Rijks[11]. Using a lamp, the evaporation process in the glass columns could be observed.

All experiments were carried out on a Fractovap 2900 gas chromatograph (Carlo Erba, Milan, Italy) equipped with a split/splitless injector and a flame-ionization detector (FID). The chromatograph was modified with a Veriflow IR 503 (Veriflo, Richmond, CA, U.S.A.) pressure regulator for the high inlet pressures required. With a split mode injection the carrier gas flow-rate remained stable within 0.2% at all pressure levels up to 20 bar. The ends of the glass columns were straightened by gentle heating in an electrical device (Pierce Eurochemie, Rotterdam, The Netherlands). The column inlet was positioned in the centre of the 2 mm I.D. glass liner. The column outlet almost reached the flame. Reliable seals were obtained with graphite ferrules, provided that the bore of the ferrule closely fitted the outer diameter of the column. Ferrules made out of Viton or PTFE were not used as they gave problems during use.

By addition of nitrogen (40 ml/min) to the hydrogen supply, the detector sensitivity increased by 40%. According to the specifications, the time constants of the electrometer amplifier were 50 msec for the 1-V integrator output and about 150 msec for the 10-mV recorder output. The recorder (Leeds & Northrup, North Wales, PA, U.S.A.) used for the plate height measurements had a time constant of 150 msec.

An SP4100 computing integrator (Spectra-Physics, Santa Clara, CA, U.S.A.) was used for data handling and was operated at a sampling frequency of 50 Hz and at a resolution of 0.05 μV sec.

Most chromatograms shown in this paper were obtained with an attenuator setting giving $8 \cdot 10^{-12}$ A f.s.d. The noise level was about 10^{-14} A. Only the split mode injection was used. The injector and the detector temperatures were set at 225 and 250°C, respectively. Helium was used as the carrier gas on most columns. For the 70 m × 50 μm I.D. column, nitrogen had to be used as the inlet pressure needed for helium (40 bar) exceeded the pressure limits of our equipment. Oven temperature data are given with the chromatograms.

RESULTS AND DISCUSSION

Information on the performance of the chromatographic system was obtained from a study on the relationship between the column plate height and the average carrier gas velocity. *H versus* $\bar{u}$ curves were assessed for four non-polar columns of about 50 μm I.D. and 6.5–8.6 m long. When operated near to $\bar{u}_{opt}$ these columns produced over 16,000 theoretical plates per metre. At $k < 5$ the coating efficiency was highly dependent of the time constant of the recorder used. At $k > 8$ the experimental values for H_{min} were within 30% of the theoretically predicted values. With nitrogen as the carrier gas the coating efficiencies were found to be about 6% higher than with helium. The measured $\bar{u}_{opt}$ values ranged between 28 and 36 cm/sec with helium and between 16 and 24 cm/sec with nitrogen. When these H_{min} and $\bar{u}_{opt}$ values are compared with values that normally are obtained with conventional 0.25 mm I.D. col-

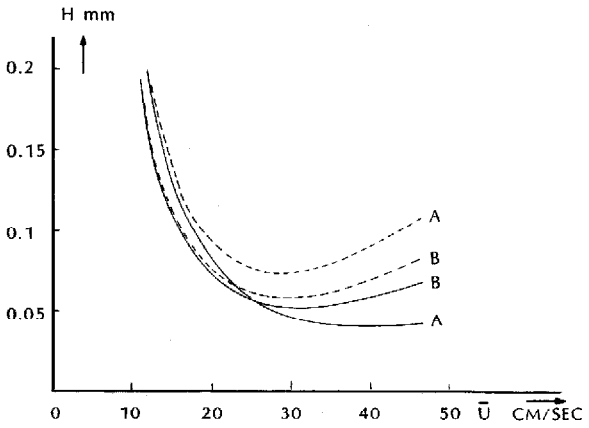

Fig. 2. Calculated (solid lines) and measured (broken lines) curves of H *versus* $\bar{u}$ obtained on an 8.5 m × 50 μm I.D. column using helium as the carrier gas. Test compounds: (A) *n*-decane; (B) *n*-tetradecane.

umns, then it is easily verified from eqns. 1 and 2 that for columns with a plate number of about 150,000 the analysis time in practice will decrease in proportion to the column diameter, as is predicted by theory.

In Fig. 2, typical H *versus* $\bar{u}$ curves are shown for *n*-decane ($k = 1.7$) and *n*-tetradecane ($k = 18$), measured at 115°C. Helium was used as the carrier gas. A comparison was made with the H *versus* $\bar{u}$ curves that where calculated from the "plate height" equation[5] according to the Golay and Giddings groups. Values for the diffusion coefficients of both compounds in the gaseous phase[12] and in the stationary phase[13] were taken from the literature. Only at low values of $\bar{u}$ are the experimental data seen to be in close agreement with theory. At increased values of $\bar{u}$ marked deviations are found, which apparently are due to band broadening contributions arising from the injection and detection equipment. These "extra-column" effects are seen to shift the minima in the experimental plate height curves towards higher values of H_{min} and lower values of $\bar{u}_{opt}$, thus in two ways counteracting the expected gain in analysis time.

It has been shown by Gaspar *et al.*[4] that the variance contributions that orig-

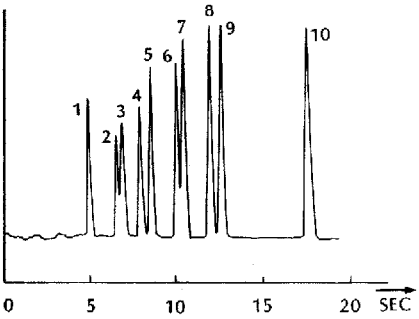

Fig. 3. Separation of a synthetic mixture of hydrocarbons at 25°C on a 3 m × 30 μm I.D. fused-silica column coated with a 0.05 μm film of SE-30. Carrier gas: hydrogen at 14 bar. Peaks: 1 = *n*-pentane; 2 = 4-methylpentene-1; 3 = 2,3-dimethylbutane; 4 = 2-methylpentene-1; 5 = *n*-hexane; 6 = methylcyclopentane; 7 = 2,4-dimethylpentane; 8 = benzene; 9 = cyclohexane; 10 = *n*-heptane.

inate from extra-column sources can be accounted for by adding to the Golay equation an extra term which is proportional to $\bar{u}^2$. This modified equation was fitted to the data presented in Fig. 2. Values were obtained of $\sigma_{ec} = 0.15$ sec for *n*-decane and $\sigma_{ec} = 0.5$ sec for *n*-tetradecane. A value of 0.15 sec is in good agreement with the time constant of the amplifier–recorder system. The significantly larger value for *n*-tetradecane can probably be attributed to retarded evaporation of this compound at elevated pressures. The mechanism of this phenomenon, which may occur when the saturated vapour pressure of a compound is considerably below the actual injector pressure, has recently been described by Jonker[14].

For the 50 μm I.D. columns that are discussed above, the slight increase in H_{min} which is due to the time constants of the chromatographic system appears acceptable when compared with the large improvement in analysis speed. The contributions of the equipment, however, may easily become dominant, as is demonstrated in Fig. 3. Here the separation within 20 sec of a synthetic mixture of hydrocarbons on a 3 m × 30 μm I.D. fused-silica column with hydrogen as the carrier gas is shown. For all compounds, less than 20,000 theoretical plates were obtained. However, with the same column about 90,000 plates (coating efficiency, C.E. = 80%) were measured for compounds eluting at $k > 10$ with nitrogen as the carrier gas.

For temperature-programmed situations the relationship between the column diameter and the speed of analysis was investigated from retention temperature measurements on two columns of different length and diameter (8.3 m × 50 μm I.D. and 40 m × 0.3 mm I.D.) with helium as the carrier gas. Both columns were coated with SE-30 and had nearly the same phase ratio values. First the columns were compared isothermally. At 100°C it was observed that k values were about 6% larger on the 50 μm I.D. column. Average carrier gas velocities were close to the $\bar{u}_{opt}$ values and were adjusted such that the retention times on the 50 μm I.D. column were shorter by a factor of 6.0. A mixture of straight-chain hydrocarbons was then analysed on both columns with a linear temperature programme from 50 to 220°C. The retention temperatures of these compounds were assessed for several programming rates. The results are presented in Table II. Equal retention temperatures are seen to

TABLE II

RETENTION TEMPERATURES OF STRAIGHT-CHAIN HYDROCARBONS MEASURED WITH LINEAR TEMPERATURE-PROGRAMMED CONDITIONS FOR SEVERAL PROGRAMMING RATES AND ON TWO COLUMNS OF 0.3 mm AND 50 μm I.D.

Column	*Programming rate* (°C min^{-1})	*Retention temperature* (°C)				
		n-C_8H_{18}	n-$C_{10}H_{22}$	n-$C_{12}H_{26}$	n-$C_{14}H_{30}$	n-$C_{16}H_{34}$
40 m × 0.3 mm I.D.	2	71.2	97.5	128.0	156.2	181.4
	4	85.7	116.9	149.2	178.2	203.9
	6	97.1	130.9	164.5	194.4	*
8.3 m × 50 μm I.D.	5	60.5	80.3	108.3	135.8	160.4
	10	68.9	95.1	126.0	154.3	179.6
	15	75.8	104.8	136.4	164.9	190.4
	20	81.8	112.5	144.8	173.8	200.3
	25	87.1	119.0	151.8	183.9	216.3

* Elution occurred after the temperature programme was stopped.

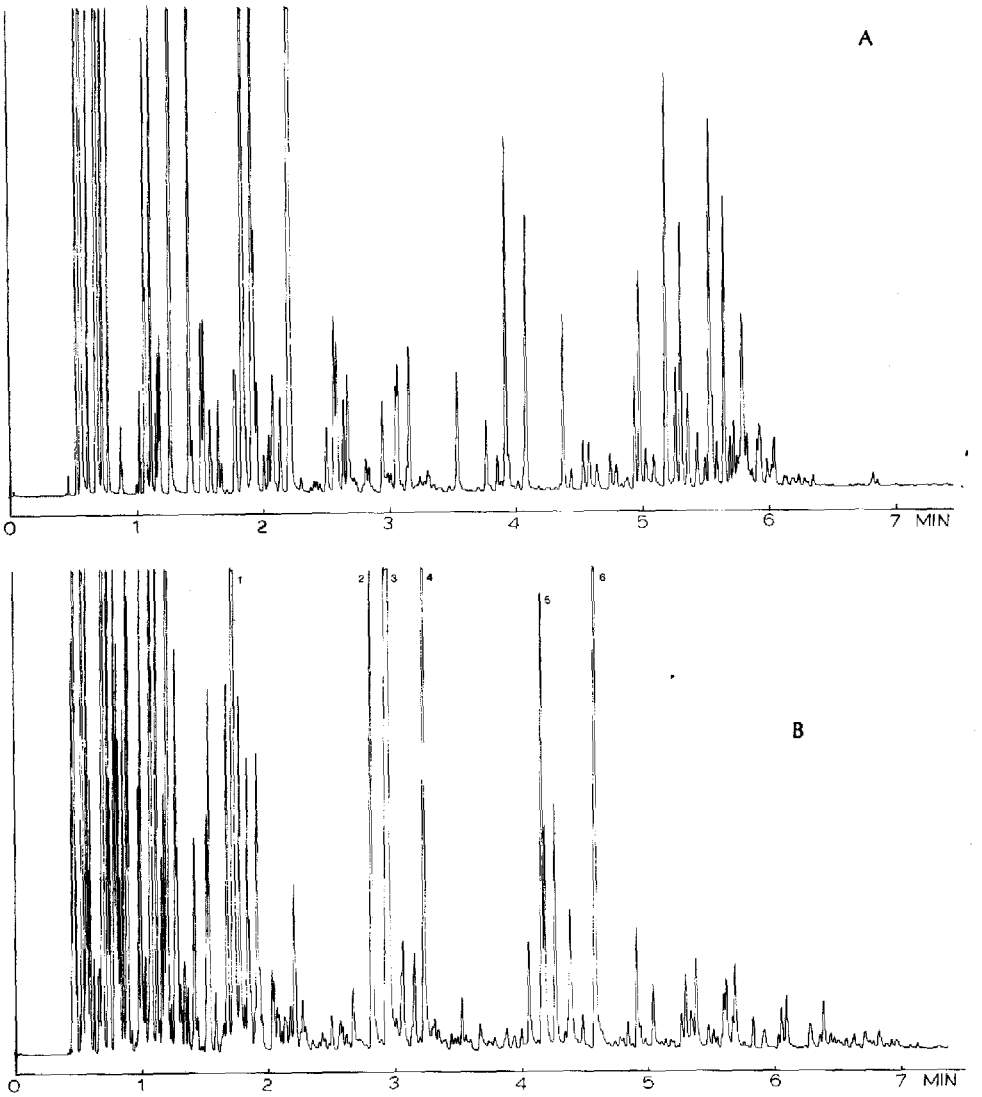

Fig. 4. Chromatogram of (A) a hydrocarbon fraction prepared from plant matter and (B) of super-grade gasoline on an 8 m × 50 μm I.D. SE-30 coated column. Carrier gas: helium at 12 bar. Oven temperature programmed from 30 to 60°C at 10°C/min, then to 130°C at 15°C/min. Peaks: 1 = toluene; 2 = ethylbenzene; 3 = *m*-/*p*-xylene; 4 = *o*-xylene; 5 = 1-methyl-3-ethylbenzene; 6 = 1,2,4-trimethylbenzene.

occur when the programming rate, r, for the 50 μm I.D. column is about six times larger than the programming rate for the 300 μm I.D. column. In consequence, the analysis times on the 50 μm I.D. column are shorter by a factor of 6. This observation is in good agreement with theory (*cf.*, eqns. 17 and 18). Reduction of the column diameter is seen to give the same gain in the speed of analysis for both isothermal and temperature-programmed runs.

Columns of 50 μm I.D. having about 150,000 theoretical plates were success-

fully used in the analysis of complex samples. A separation of gasoline, for instance, took about 7 min using helium as the carrier gas. In Fig. 4 the chromatogram of super-grade gasoline is compared with that of a hydrocarbon fraction with a similar boiling-point range that was obtained by catalytic conversion of plant matter. The bio-product is obviously not a good substitute for gasoline as a motor fuel as all important olefinic and aromatic compounds are missing.

The use of conventional capillary columns with plate numbers in excess of, say, 300,000 is known to be seriously limited by their inherent long analysis time. Reduction of the column inner diameter, as shown before, is therefore of great potential interest for overcoming this disadvantage. An attempt was made to obtain such an

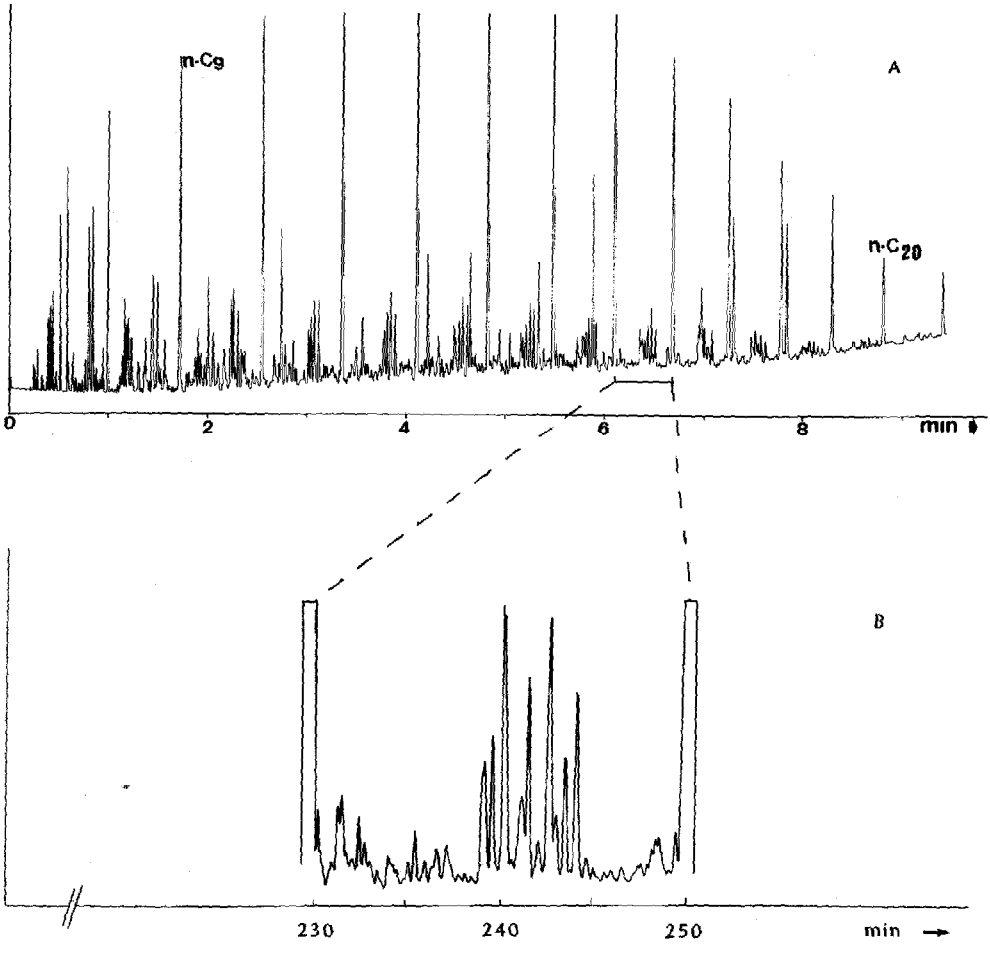

Fig. 5. (A) Chromatogram of a condensate of crude natural gas on a 3 m × 30 μm I.D. fused-silica column having 10^5 theoretical plates, programmed from 32 to 200°C at 20°C/min. Carrier gas: helium at 9 bar. (B) Chromatogram of the C_{15}/C_{16} fraction of the same sample obtained with a 70 m × 50 μm I.D. column, having 10^6 theoretical plates, programmed from 45 to 200°C at 0.6°C/min. Carrier gas: nitrogen at 22 bar.

improved column by coating a 70 m × 50 μm I.D. capillary with a 0.1 μm film of OV-101. With nitrogen as the carrier gas $1.1 \cdot 10^6$ theoretical plates were obtained with *n*-tetradecane at $k = 3.5$. The coating efficiency is about 55%. For the optimum carrier gas velocity, a value of $\bar{u} = 6.7$ cm/sec is predicted by eqn. 23. A value of $\bar{u}_{opt} = 5.6$

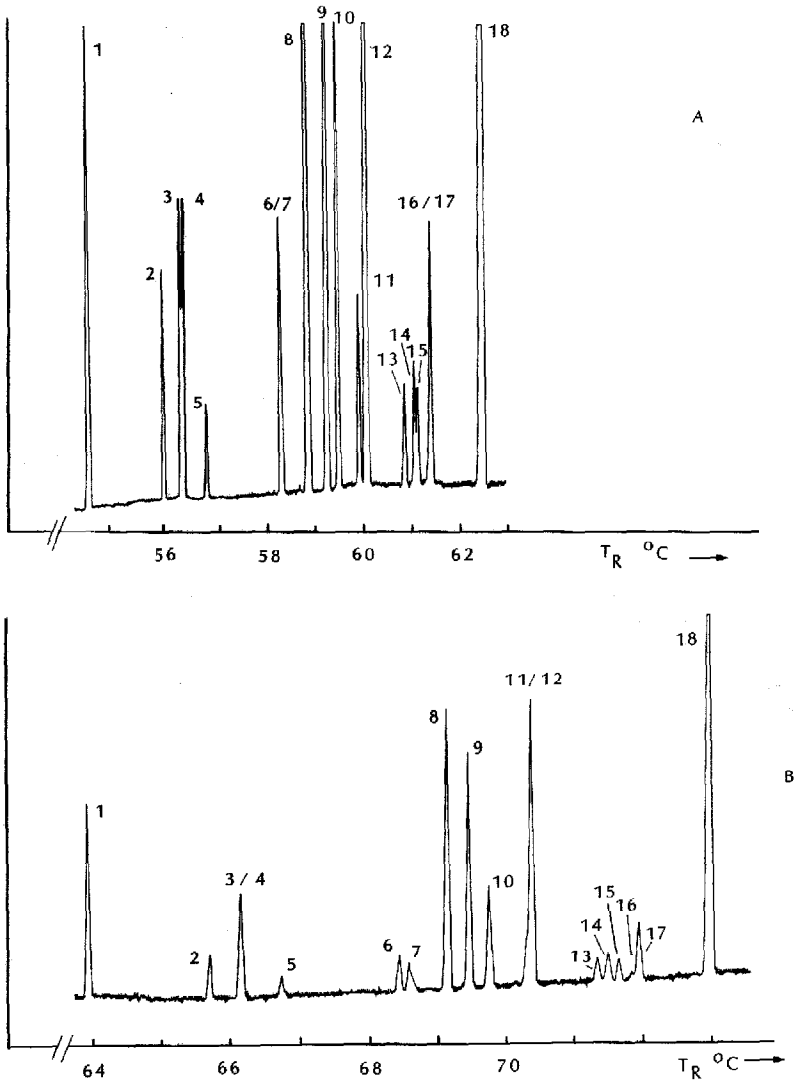

Fig. 6. Temperature-programmed separation of the C_6/C_7 fraction of a natural gas condensate, demonstrating the efficient exploitation of small dI/dT differences by the 70 m × 50 μm I.D. column used. Carrier gas: nitrogen at 22 bar. Oven temperature programmed from 35 to 200°C at (A) 0.7°C/min or (B) 1.0°C/min. Peaks: 1 = *n*-hexane; 2 = 2,2-dimethylpentane; 3 = methylcyclopentane; 4 = 2,4-dimethylpentane; 5 = 2,2,3-trimethylbutane; 6 = 3,3-dimethylpentane; 7 = benzene; 8 = 2-methylhexane; 9 = cyclohexane; 10 = 2,3-dimethylpentane; 11 = 1,1-dimethylcyclopentane; 12 = 3-methylhexane; 13 = 1-*cis*-3-dimethylcyclopentane; 14 = 3-ethylpentane; 15 = 1-*trans*-3-dimethylcyclopentane; 16 = 1-*trans*-2-dimethylcyclopentane; 17 = 2,2,4-trimethylpentane; 18 = *n*-heptane.

cm/sec was measured, requiring an inlet pressure of 22 bar. According to eqn. 20 the separation power of this particular column will not be adversely affected by the time constants of our chromatographic equipment.

This column was used for studies of a condensate from crude natural gas of Dutch origin. Part of the chromatogram showing the C_{15}/C_{16} fraction is given in Fig. 5B. For comparison the full chromatogram up to n-C_{20} is shown in Fig. 5A. An analysis time of 9 min was needed on a 3 m × 30 μm I.D. fused-silica column of about 10^5 plates. Despite the large separating power of the 70-m column, only overlapping peaks are obtained for the C_{15}/C_{16} fraction. In contrast, the Trennzahl of the column exceeds the number of compounds present in the low-boiling fraction of the condensate. In this region most substances may be expected to elute as well separated peaks. In Fig. 6 two chromatograms are shown of the fraction between n-hexane and n-heptane. Despite the plate number of $N = 10^6$ it is again seen that peak overlap cannot be avoided and that complete resolution is not usually realized within a single chromatographic run. Peaks formed by two overlapping compounds (*e.g.*, pairs 3–4 and 6–7) may still have a Gaussian shape.

In Fig. 6 it is also demonstrated that columns with high plate numbers allow a very efficient exploitation of the small differences in the dI/dT values of compounds with coinciding Kováts retention indices. In this example the overlapping substances could be separated by a change in the elution temperature of about 10°C. Columns of 50 μm I.D. with high plate numbers are apparently well suited for the analysis of low-boiling mixtures. With hydrogen as the carrier gas, less than 30 min are needed for the separation of compounds eluting before n-octane. Reliable information regarding peak purity and compound identity can be obtained when the sample is analysed at several slightly different temperatures.

In our laboratory, columns with I.D. 30–60 μm and having about 10^5 theoretical plates have given promising results. Their chromatograms compare well with results obtained on 0.25 mm I.D. columns for both isothermal and temperature-programmed applications. The columns can be handled without too many difficulties. For their operation modern standard chromatographic equipment can be used. Apart from replacement of the carrier-gas-pressure regulator, no major modifications to the gas chromatograph are needed.

All chromatograms presented in this paper were obtained from columns that were simply rinsed before coating. Column deactivation therefore was not satisfactory. Recently, deactivation methods such as leaching, silylation and polysiloxane degradation have been successfully applied to columns of 50 μm I.D. Methods taken from the literature, however, initially led to serious problems and had to be adapted in some instances. Well deactivated 50 μm I.D. columns have been prepared that were used for the analysis of free phenols and essential oils. Cross-linking of the stationary phase with organic peroxides was found to give very stable non-polar films. Therefore, this technique is now routinely used. In a forthcoming paper, preparation methods for 50 μm I.D. columns will be discussed in more detail.

In capillary gas chromatography, a large sample capacity and a high speed of analysis are known to be conflicting demands because these parameters are related to the column diameter in an opposite sense. The loadability of 50 μm I.D. columns is therefore necessarily low. For an SE-30 coated column of 8 m × 50 μm I.D., peak overloading was observed with about 1 ng of n-tetradecane. Although reduction of

the column diameter is accompanied by an improvement in the detection limits, narrow-bore columns are found to have a decreased "dynamic range". The analysis of mixtures in which substances are present at very different concentration levels may require overloading of the main peaks. Sample amounts between 0.02 and 2 ng seem to be a good working range for columns of 50 μm I.D. The FID currents that are generated by these amounts are generally below 10^{-11} A, which sets stringent requirements on the noise level. Fortunately, the bleeding from a 50 μm I.D. column is extremely small. Even at very sensitive electrometer settings very good baseline stability is found.

Several techniques can be used for the introduction of a sample on to a narrow-bore column. Syringe injections of 0.1–1 μl can easily be performed at pressures up to 25 bar. For the split mode injection a splitter flow of 0.3–1 l/min is normally required, as the column must not be overloaded, and the injection bandwidth must be kept small. Despite the discriminative characteristics of a splitter, acceptable quantitative results have been obtained on 50 μm I.D. columns when an internal standard method was used. With a solution containing a series of straight-chain hydrocarbons a coefficient of variation of 2.5% was measured for the relative areas of two consecutive homologues.

Highly diluted samples are best introduced into a 50 μm I.D. column by closing the splitter until 30 sec after injection. The "solvent effect"[15] is then utilized to reduce the bandwidth. The term "splitless injection"[15] should not be used for this method, as only a small percentage of the injected sample is transferred to the column. The technique has been applied successfully to the analysis of derivatized sera of uraemic patients[10] and to the profiling of urinary steroids. "On-column" introduction of liquid samples into a 50 μm I.D. column has not been tried.

A high speed of analysis requires fast data handling. Our gas chromatograph was therefore coupled to an SP4100 microprocessor-based programmable integrator. The high resolution of the V/F converter of 0.05 μV sec guarantees correct digital representation even of the smallest peaks. The 50 Hz sampling rate is sufficient for all but the fastest signals, because according to information theory about 20 data points are needed for an unambiguous representation of a chromatographic peak. Simple chromatograms from a 50 μm I.D. column were found to be handled well by the integrator, also from a quantitative point of view. However, when complex chromatograms, *e.g.*, of gasoline, had to be integrated then parts of the chromatogram were omitted by the plotter and post-run calculations and printing of the results took twice the analysis time.

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