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Indirect introduction of liquid samples in gas correlation chromatography

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ABSTRACT

An injection device, indirectly introducing liquid samples, for gas correlation chromatography is described. It introduces the liquid sample without disturbing the constant gas flow necessary for correlation chromatography. This is achieved by separation of the evaporation from the actual injection. An interesting feature of this system is the ease of performing correlation chromatography in a differential mode.

INTRODUCTION

Correlation chromatography (CC) or multiplex chromatography has been known for several decades. Compared with conventional chromatography, a lower detection limit can be achieved without preconcentration of the sample. Injections are performed according to a pseudo-random binary sequence (PRBS), containing $2^n - 1$ periods of which $I = 2^{n-1}$ injections (n being a positive integer). Theoretically the detection limit can be reduced by $\sqrt{(I/2)}$ when the injection time of a single injection is equal to the PRBS period time at the cost of a doubled analysis time. The reason is that the sequence time length has to be equal to or larger than the chromatogram time length, and at least two sequences have to be injected successively. After the first sequence, called the presequence, the detector signal becomes circular, and the detector signal of the second sequence can be used to calculate the so-called correlogram with *e.g.*, a cross-correlation procedure.

Much effort has been applied to develop these techniques for determining (very) low concentrations [1–13]. Most applications were published in the field of correlation gas chromatography (CGC) [1–3,6–9,13]. All CGC applications, however, concern gaseous samples, headspace samples or liquid samples that were made gaseous first. This is in contrast to the common practice in gas chromatography (GC), where in most methods liquid samples are injected as such. Up to now this direct introduction of liquid samples has not been used in CGC, as specific problems arise.

Apart from the large amount of solvent introduced by the semi-continuous injections, probably the most important problem is the appearance of a pressure pulse caused by the evaporation of the liquid. This evaporation pulse disturbs the constant gas flow for a certain period of time. In conventional GC an evaporation pulse occurs only once, at the start of the chromatogram. The detector may give a response and a few moments after the injection the GC system stabilizes again. The separation process itself is hardly disturbed, and a detector response, if present, is of no value because components had not yet

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arrived at the detector. In CGC, however, sample is injected semi-continuously. A disturbance of the gas flow with every injection is unacceptable, as it disrupts the stationary state of the system. For an optimally performing CC system, a stationary state is an important requirement.

In this paper, an injection device that does not disturb the stationary state of the system is described, being intermediate between the direct introduction of liquid samples and the introduction of gaseous samples. First the sample is (partly) evaporated, then the vapour of this sample is injected without disturbing the gas flow.

Liquid injection system

Fig. 1 shows a system for the indirect introduction of liquid samples in CGC. The important parts for CGC are the sample compartment located outside the gas chromatograph, the evaporation compartment and the injector. The evaporation compartment and the injector are located in an injector oven separated from the column oven. The sample and evaporation compartments are connected with a capillary used to introduce a liquid sample into the evaporation compartment. When the sample compartment is pressurized, liquid will be transported through the capillary from the sample compartment to the evaporation compartment. The temperature and the heat capacity of the evaporation compartment have to be high enough to evaporate the sample completely and immediately. The pressure of the evaporation compartment rises owing to the evaporation of the sample until an equilibrium is reached. When vapour is injected into the column, the pressure of the evaporation compartment falls. Liquid is transported through the capillary and evaporates owing to the high temperature until equilibrium is reached again. Only very small volumes of liquid need to be evaporated to replace a certain volume of gas because of the large difference in density between the liquid and gas phases.

As mentioned before, for CGC a constant gas flow through the GC column is required. It should not make any difference whether sample is injected or not. For this reason, it is necessary to tune the pressure of the nitrogen gas supply in such a way that the pressure in the evaporation compartment is equal to the pressure of the nitrogen carrier gas.

In the system described here, large amounts of vapour are injected (up to half of the time vapour may be injected). It can be expected that the separation conditions will be influenced and non-linearities will arise owing to the large differences in concentration of carrier gas and vapour, especially at the top of the column.

Mainly for reasons of pressure tuning and changes in separation, first a more symmetrical system was developed, which is outlined in Fig. 2. In this system both the sample and reference compartments contain liquid; the reference compartment contains, *e.g.*, pure solvent and the other compartment contains the sample. Nitrogen as a carrier gas is replaced with solvent vapour. Nitrogen is only used to maintain an adjustable pressure. After equilibrium, both evaporation compartments will have the same pressure.

The system under consideration can easily be used in a differential CC mode, as described by Laeven *et al.* [14] for liquid chromatography.

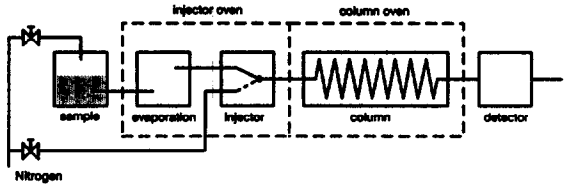

Fig. 1. Correlation gas chromatograph equipped with an indirect asymmetric device for liquid sample introduction.

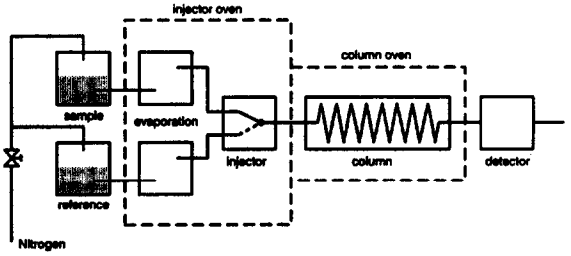

Fig. 2. Correlation gas chromatograph equipped with an indirect symmetrical device for liquid sample introduction.

When instead of pure solvent a known (standard) sample is used as a reference, only differences between the "unknown" sample and the other sample are measured.

A constant and equal pressure in both evaporation compartments can only be achieved when there is no significant pressure drop in one of the compartments when it starts to deliver gas to the chromatographic column. Assuming the evaporation of liquid is fast and a pressure drop due to a time consuming evaporation can be neglected, the pressure drop is negligible when the mass flow resistance of the capillary supplying the liquid is small compared with the mass flow resistance of the chromatographic column. The pressure drop over this liquid-supplying capillary can be described by the Hagen–Poiseuille law. This law is applicable for a laminar flow profile and an incompressible fluid:

$$\Delta P = \frac{8\Phi_m \eta l}{\pi r^4 \rho} \quad (1)$$

where:

ΔP = pressure difference (N m^{-2})
Φ_m = mass flow (kg s^{-1})
η = viscosity (kg m^{-1} s^{-1})
l = capillary length (m)
r = capillary radius (m)
ρ = density (kg m^{-3})

For gases eqn. 1 is not valid as they are compressible, the density ρ being dependent on pressure. However, to obtain a rough impression, eqn. 1 can be of limited use. When capillary GC columns are used, preferably the column inside diameter should not be larger than the diameter of the capillary supplying the liquid, as the pressure drop and the inside diameter are related to the fourth power. The length of the capillary supplying the liquid under normal conditions can easily be at least a factor of 100 smaller than that of a capillary GC column (which is usually 20 m or longer). The difference in density between liquids and gases is at least a factor of 100 when the pressure is low. Finally, the difference in viscosity can be a factor of 10–50 (28 for CS_2 liquid at 20°C and CS_2 vapour at 114°C [15]) between liquids and their vapour, depending on pressure and temperature. In most common cases the pressure drop over the capillary supplying the liquid can be small or negligible.

Separation/detection

In both systems described the separation conditions will change compared with conventional chromatography. In the first, asymmetric, system (Fig. 1), a large number of injections also introduce substantial amounts of solvent vapour. Depending on the actual amounts injected, up to 50% of the mobile phase is solvent vapour. This may give rise to non-linear chromatographic behaviour because of very large differences in concentration between sample, containing solvent vapour, and reference, containing carrier gas. The changed mobile phase composition of CGC compared with GC may also cause a separation difference between a single injection chromatogram and a correlogram. When the detector is sensitive to the solvent vapour, a very large solvent peak in the correlogram appears, which may cause so called correlation noise in the correlogram [14]. Correlation noise can be defined as noise present in the correlogram that does not originate from detector noise. This correlation noise caused by the solvent peak may disturb the determination of the other peaks, especially when the other peaks are small compared with the solvent peak.

The second, symmetrical, system (Fig. 2) differs even more from a conventional chromatographic system. The mobile phase only consists of liquid vapour. Instead of, *e.g.*, nitrogen, solvent vapour is used as the carrier gas. The use of solvent vapour as a carrier gas has been reported previously [16–21]. Large concentration differences between solvent vapour and mobile phase are eliminated. Therefore, non-linear chromatographic behaviour will not appear as quickly in this symmetrical system as in the other asymmetric system.

The detector must be able to cope with the large amounts of vapour involved. Therefore, if possible, a solvent is used that gives only a very small detector signal or does not respond at all. Another possibility is to use a differential detector, such as a heat conductivity detector.

EXPERIMENTAL

An existing CGC system, developed and tested for CC [22] in our laboratory, was used for the experiments. This system was modified to an indirect symmetrical liquid injection system as outlined in Fig. 2. Table I lists the equipment. As the injection device a pair of MOVPT-1/100 pneumatic needle valves (Scientific Glass Engineering) were used, controlled by a computer with an optocoupler as a circuit breaker. The valves were connected to the column by a 0.8-mm T-piece (Valco). The evaporation compartments, laboratory-made 300-cm^3 glass vessels, were connected to the needle valves by a 3 cm × 1.6 mm O.D. steel capillary. Glass vessels, as described above, were also used as sample and reference compartments. A piece of steel capillary connected the inlet of the sample and reference compartment to the nitrogen gas supply, without a significant pressure drop.

Fused-silica capillaries (50 cm × 0.2 mm I.D.) were connected between the sample compartment and its evaporation compartment and the reference compartment and its evaporation compartment. The injector oven, containing the injection device and the evaporation compartments, was a rebuilt temperature-controlled PV 4000 GC oven (Philips). The separations were performed on a 50 m × 0.32 mm I.D. open-tubular GC column, coated with 1.13-μm CP-Sil 5 CB (Chrompack). Table II gives the separation conditions.

Three samples were prepared; Table III gives the volume fractions of the compounds in carbon disulphide. 2-Methyl-2-butanol was purchased from BDH and other chemicals from Merck.

TABLE I

LIST OF EQUIPMENT

Apparatus	Type
GC	Packard Becker Model 421 with flame ionization detector
Injector	Laboratory-made
i–v converter	Atlas MAT DC60CH
Filter	24-dB low-pass filter, laboratory made
CC computer	Tulip dc386 with DAS-16 DAC/ADC controlled by Assyst
Data-handling computer	HP-9000/350

TABLE II

CHROMATOGRAPHIC CONDITIONS

Gas	Pressure (10^5 kPa)	Temperature control	Temperature (°C)
H_2	0.6	Injector	118
N_2	1.9	Column	110
Air	1.4	Detector	180

TABLE III

VOLUME FRACTION OF COMPOUNDS

Compound	Volume fraction (ml l^{-1})		
	1	2	3
Ethanol	0.5	0.5	0.5
2-Propanol	0.5	0.6	0.5
1-Propanol	0.5	0.5	0.5
2-Butanone	0.5	0.5	0.6
2-Methyl-2-butanol	0.5	0.5	0.5

The CC experiments were carried out with a PRBS of 511 elements and a clock period (the time length of one element) of 0.3 s. The data were collected with equal sampling time periods. A filter frequency of 1.2 Hz was chosen to avoid aliasing. To produce a correlogram at least two PRBSs were injected and the data collected during the last injection sequence were used to calculate the correlogram. For single-injection experiments, the data sampling period and filter frequency were chosen to be equal to those in the CC experiments.

RESULTS AND DISCUSSION

As already mentioned, the experiments were performed with the indirect symmetrical liquid injection system. A single-injection chromatogram (Fig. 3), a normal correlogram (Fig. 4a), an inverse-bit correlogram (Fig. 4b) and the inverse-bit subtracted from the normal correlogram (Fig. 4c) are shown for sample mixture 1 against a reference of pure carbon disulphide.

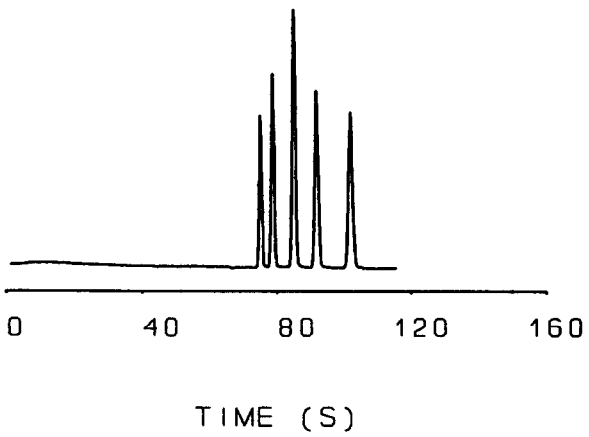

Fig. 3. Single-injection chromatogram obtained with the symmetrical system. A mixture of ethanol, 2-propanol, 1-propanol, 2-butanone and 2-methyl-2-butanol in carbon disulphide was analysed with carbon disulphide functioning as the carrier gas.

Carbon disulphide vapour functions as a carrier gas and has a low detector (flame ionization detector) response. The inverse-bit correlogram is obtained by inverting the injection-bits of the PRBS. A "1" represents "no injection" instead of an "injection" in case of a normal correlogram, and a "0" represents an "injection" instead of "no injection" [22].

The small peaks at 143, 147, 153, 6 and 16 s in the correlogram and the inverse-bit correlogram (Fig. 4a and b) are ghost peaks of the five main eluting components. The average time difference between a component peak and its corresponding ghost peak is 236.2 clock periods or 70.9 s. This corresponds very well with a theoretical expected value of 237 clock periods (71.1 s) for a first-order non-complementary ghost peak [22], also known as a λ3 ghost peak. This λ3 ghost peak may appear when a memory effect is present in the injection sequence. Comparing the normal correlogram with the inverse-bit correlogram, the sign of the ghost peaks with respect to the main peaks has changed. Theoretically, this is expected for first-order non-complementary ghost peaks. The ghost peaks disappear when the inverse-bit correlogram is subtracted from the normal correlogram in Fig. 4c. The noise level in Fig. 4c has been considerably reduced. Probably other small non-complementary effects are also present, as they are neutralized with subtraction [22,23]. Reproducible small pressure variations and injection errors due to the small clock period (the injector could not cope with smaller clock periods) might have caused these reproducible effects.

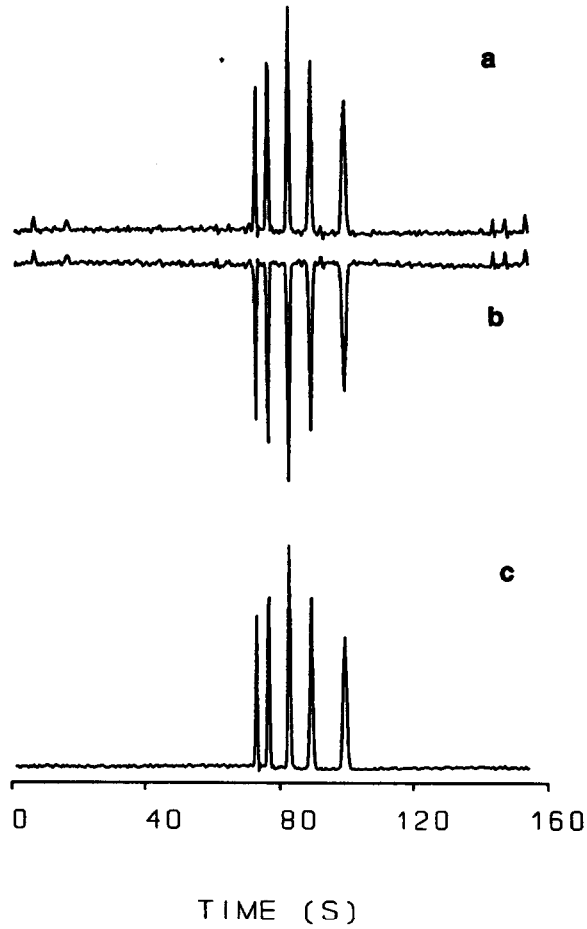

Fig. 4. (a) Correlogram, (b) inverse-bit correlogram and (c) the correlogram subtracted from the inverse-bit correlogram. The system used and the mixture analysed are identical with those in Fig. 3.

Comparing the retention times of the single-injection chromatogram with the correlogram, the components of the single injection elute on average 2.1 s later. This phenomenon has been observed and explained before in CC [23]. Owing to the many injections, the concentration level of the components is relatively high all over the column during a CC experiment, whereas

during a single injection this is not the case. These high concentrations act as a modifier of the mobile phase, making the components elute sooner. In this instance, however, it cannot explain the retention time shift, as exactly the same shift is also observed in the experiments below, where high component concentrations are present both in the sample and in the reference.

An undesired pressure drop in the evaporation compartments can explain this phenomenon and it is assumed that this causes the retention shift. When a pressure drop in the evaporation compartments is caused by the supply of gas to the column, during a CC experiment the pressure drop will be approximately the same in both the sample and reference compartments, as the injector often switches from sample to reference and both evaporation compartments supply gas to the column for an equal amount of time. In a single-injection experiment, most of the time the gas is supplied by the reference evaporation compartment. Assuming the pressure drop in this compartment is small compared with the total pressure over the column, it can be estimated to be approximately double the pressure drop in the CC experiments. The observed time shift was 2.1 s (this equals a time shift of ±2.5%). When the preceding assumptions are correct, and it is also assumed that within a small pressure range the column pressure is inversely related to the retention time, a pressure drop of ±2.5% is expected for CC experiments and ±5% for a single-injection chromatogram.

Differential CC experiments are shown in Figs. 5 and 6. Sample mixture 2 was measured against reference mixture 3. A single-injection chromatogram (Fig. 5), a normal correlogram (Fig. 6a), an inverse-bit correlogram (Fig. 6b) and the inverse-bit subtracted from the normal correlogram (Fig. 6c) are shown. The same ghost peaks appear as described before at exactly the same places relative to the main components. They also are identified as first-order non-com-

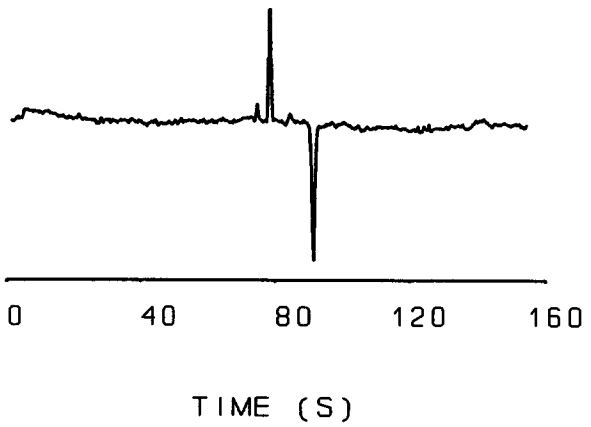

Fig. 5. Differential single-injection chromatogram obtained with the symmetrical system. A mixture of ethanol, 2-propanol, 1-propanol, 2-butanone and 2-methyl-2-butanol in carbon disulphide was analysed (sample). A mixture with the same components present in equal or changed amounts was used as the carrier gas (reference).

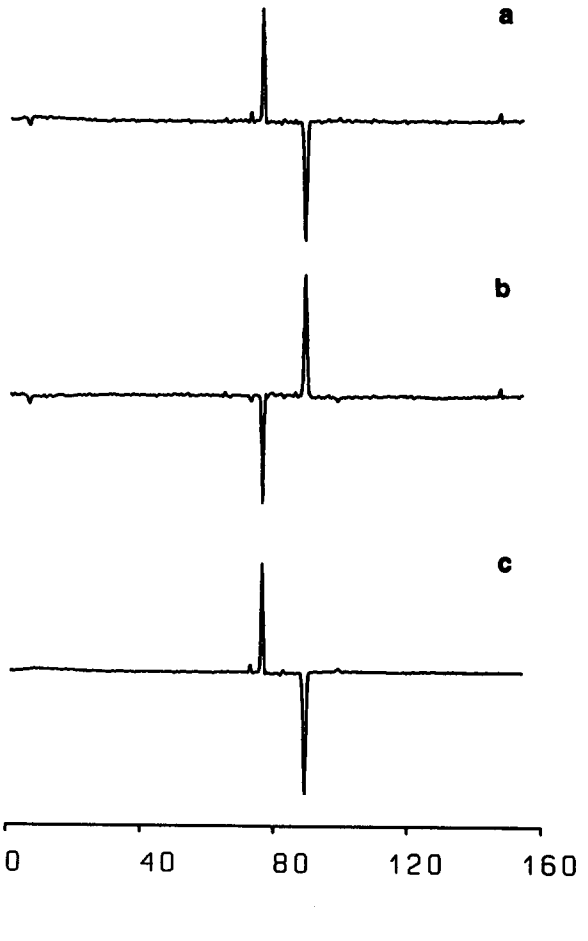

Fig. 6. Differential correlograms. (a) Correlogram, (b) inverse-bit correlogram and (c) the correlogram subtracted from the inverse-bit correlogram. The system used and the mixtures analysed are identical with those in Fig. 5.

plementary (λ3) ghost peaks; the ghost peaks disappear when the inverse-bit correlogram is subtracted from the normal correlogram (Fig. 6c). The positive peak in Figs. 5 and 6 relates to the extra 0.1 ml l^{-1} of 2-propanol in mixture 2 relative to mixture 3. The opposite is valid for butanone: mixture 2 contains 0.1 ml l^{-1} less than mixture 3, so a negative peak appears in the chromatogram and correlogram. The other three components are hardly present in the correlogram, except possibly for ethanol. Taking the peak heights in Figs. 3–6 concerning ethanol and 2-propanol into consideration, the ethanol content in mixture 2 is estimated to be 0.01 ml l^{-1} higher compared with mixture 3.

CONCLUSIONS

The results demonstrate that the indirect introduction of liquid samples in CGC is not only possible in theory but also in practice. An existing CGC system can be extended without much difficulty to the use of indirect liquid injection. For this purpose the injector together with the evaporation compartments have to be placed in an injector oven apart from the column oven in order to maintain separate temperature control. Experiments show that even if a small pressure drop in the evaporation compartments is present during the CC process, still very reasonable results can be obtained with CGC. Both evaporation compartments will have approximately the same pressure drop, as there is a continuous switching due to the PRBS injection pattern. If needed, the pressure drop can be decreased by using a capillary with a larger diameter to supply the liquid to the evaporation compartment. When an injection device is developed especially dedicated for indirect liquid sample introduction in CGC, special attention has to be paid to preventing a significant pressure drop.

Compared with conventional GC, the system has been changed. The carrier gas consists completely of solvent vapour when a symmetrical system is used. One should be aware of the fact that the separation may change, which might complicate the analyses. On the other hand, an extra dimension is added when the content of a solvent (mixture) is used to optimize the separation. A solvent (mixture), however, always has to be chosen in agreement with the detector in order to avoid a non-linear detector response or an overloaded detector.

One of the main advantages of the symmetrical system is the possibility of determining differences in concentration that are small with respect to the total concentration between two samples using differential CC. It can therefore be a powerful tool for monitoring the concentrations of various components in process control. A process sample can be measured against an "optimum" reference sample. The level of the components present in this reference sample can be chosen in such a way that it represents the optimum process conditions. The resulting correlogram will only show the components of the process sample that have a different concentration level with respect to the reference sample, and only differential peaks (positive or negative) appear in the correlogram. Because of the multiplex advantage of CC, more accurate results may be obtained compared with conventional chromatography. Differences between a sample and an (optimum) reference sample that can hardly be distinguished or not at all by conventional chromatography can be determined accurately using differential CC. Therefore, the introduction of an indirect liquid injection system for CGC opens up a new field of applications in CC, which could not previously be achieved.

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