Journal of Chromatography, 473 (1989) 27–35
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

CHROM. 21 461

FACTORIAL OPTIMIZATION FOR FLOWS IN THE HALL ELECTROLYTIC CONDUCTIVITY DETECTOR

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(First received September 14th, 1988; revised manuscript received March 2nd, 1989)

SUMMARY

Statistical optimization of flows is carried out for a Hall electrolytic conductivity detector (HECD). Yates' method was used to quickly estimate main factors affecting HECD response to organochlorine. Also, more detailed evaluation of variations of HECD response for three flow variables was performed via central composite design factorial experiments. Corresponding three-factor, three-level factorial experiments provided data for least-squares regression analyses. The resulting fitted-polynomial yielded an appropriate mathematical model of the HECD response surface for the corresponding three dimensions in flow-space.

Optimum values for three detector flows are thereby selected from the response surface to provide maximum HECD sensitivity, *i.e.*, response to organochlorine in the halogen mode. Supplemental data then allow for flow optimization with respect to other criteria, *e.g.*, signal-to-noise ratios and resolution of eluates.

INTRODUCTION

Hall electrolytic conductivity detector (HECD) sensitivity can be influenced by many variables. Selection of HECD reactor temperature affects detector response, and depends upon eluites to be detected[1]. Also, flow-rates for carrier gas, reaction gas and conductivity solvent are important parameters affecting HECD response[2–4].

Carrier gas, often helium which contains gas-phase eluates, is introduced to the high-temperature HECD reactor from the chromatographic column. Hydrogen, the reaction gas, to produce $HCl_{(g)}$ for the halogen mode, is added to the carrier gas prior to exposure to the reactor's nickel catalyst. Reactor effluents containing carrier gas, hydrogen, $HCl_{(g)}$ and other reactor products mix with buffered *n*-propanol in the gas–liquid contactor; the gas–liquid separator then isolates the flowing liquid phase from undissolved gases for electrometric measurements of dissolved Cl^- in the analytical cell. The two gas flows and the flow of the liquid through these mixing,

0021-9673/89/$03.50

separation and measurement regions of the differential conductivity cell significantly affect HECD response.

In this work factorial experiments were conducted to obtain mathematical models representing HECD response surfaces which estimate effects of carrier gas flow, reaction gas flow and conductivity solvent flow upon HECD sensitivity[5]. These three flow variables, or factors[6], were deliberately varied in a controlled fashion and corresponding HECD response factors were determined. A second-order multiple regression model was used to estimate the relationship between the three factors and the response surface[7]. This regression model and Yates' method of analysis[6] were employed to evaluate the main effects for each factor, *i.e.*, variations of the average response factor as a single flow variable changes. The interaction effects were also calculated for each combination of pairs of flows[6]. Optimized flow settings were then estimated for achieving maximum detector sensitivity for the HECD system. Results of this study are reported herein for both packed and capillary gas chromatographic (GC) systems with a HECD.

Other variables may also affect HECD sensitivity such as conductivity cell temperature, reactor catalyst integrity, eluate peak shape, background conductance and solvent pH. These variables were not evaluated in this study because previous work has shown these variables to change slowly with time or cause only minor changes in HECD response factors[7,8].

EXPERIMENTAL

Reagents

1-Chlorooctane (>99%) (1COA) was purchased from Aldrich. Resi-analyzed grade *n*-hexane and propanol were purchased from J. T. Baker. Dilutions of 1-chlorooctane in hexane were used as injected aliquots for these studies.

Instrumentation

A Tracor Model 560 gas chromatograph equipped with a Tracor Model 700A HECD was used for these studies. Packed-column separations were done with a 2 m × 2 mm I.D. glass column, packed with 3% OV-17 on 100–120 mesh Supelcoport. For capillary column separations the HECD was interfaced with a J&W Scientific 30 m × 0.32 mm I.D. fused-silica capillary column with 0.25-μm DB-5 bonded phase.

The HECD reactor assembly was adapted for capillary systems for some of this work. A 4 in. × 1/4 in. O.D. × 1 mm I.D. glass insert was placed into the HECD column interface and anchored with a 1/4-in. graphite ferrule. A 1/4 in. O.D. to 1/16 in. O.D. stainless-steel Swagelok reducing union, modified for make-up gas introduction, was attached to the other end of the glass insert. The capillary column was passed through the reducing union into the flow channel of the glass insert and located such that the termination of the capillary column was about 1 mm from the entrance to the nickel catalyst reaction tube. The capillary column was anchored by a 0.8 mm to 1/16 in. O.D. graphite ferrule at the reduction union.

An SGE OCI-3 on-column injector and syringe were used to deliver sample injection volumes onto the capillary column. Hydrogen carrier gas flow was set with the precision flow-control valve provided with the on-column injector. Hydrogen

make-up gas for capillary separations was introduced through the modified Swagelok reducing union and the reaction gas inlet. The HECD conductivity solvent, *n*-propanol, was delivered by the metering pump provided with the HECD.

The HECD was used in the halogen mode for these studies. A nickel-catalyst reactor temperature of 950°C was used, as recommended for chlorinated hydrocarbon analyses[1]. A Hewlett-Packard Model 3390A integrator was used to measure HECD peak areas and retention times.

Procedures

Gas flow-rates were measured with a soap-bubble meter and a stopwatch at the differential conductance cell exit. Solvent flows were measured with a 10-ml graduated cylinder at the same cell outlet. The following procedure was used to set and monitor the three flows: (a) solvent flow was turned off, (b) reactor gas flow was turned off, (c) vent valve was closed, (d) carrier gas flow was adjusted and measured, (e) reaction gas flow was adjusted and the carrier gas plus reaction gas flow was measured, (f) solvent flow was adjusted and measured.

A volume of 1 μl of a 1-chlorooctane solution (59 nmol Cl/ml) in *n*-hexane was repeatedly injected and separated at 65°C for each set of flow conditions evaluated. Peak areas for 1-chlorooctane from chromatograms for each set of flow conditions were used according to the central composite factorial experiment described below. The baseline noise was always small relative to peak areas for these experiments.

Factorial experimental design

Factorial experiments allow the main effects and interaction effects within a multivariate system to be evaluated. This approach is efficient since it requires fewer experimental trials than normally required by corresponding single-factor experiments[5]. Fractional factorial experiments further reduce the number of required trials by neglecting selected high-order interactions[5] between variables.

In this study a three-level, three-factor experiment was implemented to evaluate effects of three flow factors upon HECD response. The experiment can be pictorially represented by a cube with the center placed at the origin, or base-point[9], of a Cartesian coordinate system (see Fig. 1). The X, Y, and Z axes represent the three evaluated flow factors, k_1, k_2 and k_3. Each position in the cube defines a combination of the three flows. Each position in the cube can also be related to a point, *i.e.*, an estimated response, on a calculated response surface; this relationship can be established by fitting the factorial data to a polynomial function with multiple linear regression[5]. For the experiments described herein the response surface mathematically

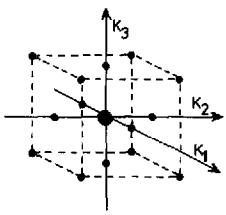

Fig. 1. A three factor, $2^k + 2k + 1$ factorial experimental space. Dots represent the 15 positions at which measurements are required for a central composite factorial experiment.

models the relationship between the three flow factors and the HECD response to 1-chlorooctane.

The number of trials required for a complete factorial experiment is Q^k where k factors are evaluated at Q different values, *i.e.*, Q levels[6]. Thus a complete, or 3^k, factorial design for three factors requires HECD response measurements for at least the 27 flow combinations represented by 27 specified cube positions[6,10]. The data obtained from a 3^k design may then be modeled by a second-order polynomial with parameters for main effects, two-way interactions, three-way interactions and an error term[10].

For this work a fractional factorial experiment was selected instead of a complete factorial experiment. The central composite factorial design used, called a $2^k + 2k + 1$ design, requires only 15 experiments, corresponding to 15 HECD flow combinations represented in Fig. 1[10]. Central composite data were modeled by a second-order polynomial which includes parameters for each main effect, second order two-way interaction effects and an error term[11], and neglects three-way interactions:

$$y = B_0 + B_1X_1 + B_2X_1^2 + B_3X_2 + B_4X_2^2 + B_5X_3 + B_6X_3^2 + B_7X_1X_2 + B_8X_1X_3 + B_9X_2X_3 + e \quad (1)$$

Similar to the 3^k design, y estimates the response surface for factors x_1, x_2 and x_3. The central composite design was preferred for fitting factorial data by multiple regression since fewer trials are required[5,9–13]: the central composite design uses a minimum of $(Q-1)^k + (Q-1)k + 1$ experiments compared to the Q^k experiments required for a complete factorial experiment[10].

Yates' method

Yates' method was also used to evaluate flow-response relations for the HECD. It is also a two-level evaluation which does not consider second-order relationships which may exist between the individual flow factors and the HECD response. Yates' method consists of simple calculations which allow a prompt evaluation of factorial experimental data[6].

RESULTS AND DISCUSSION

Multivariate evaluation of the effects of reaction gas, carrier gas, and conductivity solvent flow-rates on the HECD response by a central composite factorial experiment

Effects of the helium carrier gas, hydrogen reaction gas, and *n*-propanol conductivity solvent flows on HECD sensitivity in the halogen mode were evaluated with a three-level, three-factor, factorial experiment. The three factors were reaction gas flow, k_1, carrier gas flow, k_2, and conductivity solvent flow, k_3. The measured response was the peak area for 1-chlorooctane obtained from packed-column HECD chromatograms, using the halogen mode and 1-μl injections.

The central composite design was used for evaluating the HECD response surface for the three flows. A corresponding second-order polynomial was found by multiple regression and modeled the factorial data. Selection of the central composite design was justified based on limited single-factor flow data in the literature, *i.e.*,

hydrogen flows in the nitrogen mode[2]; hydrogen flow and conductivity solvent flow in the nitrogen mode[4]; and conductivity solvent flow in the sulfur mode[3]. Those studies indicate that HECD response generally increases as hydrogen flow increases and decreases as conductivity solvent flow increases in a second-order fashion without major inflection points. Our experience with the HECD in the halogen mode suggested the same trends. High-order interaction effects were therefore not evaluated, hence reducing the number of required experiments from 27 to 15.

Reasonable flow ranges for the HECD system were used as boundaries for the experimental space, *i.e.*, the cube (hydrogen reaction gas low flow = 12.7 ml/min, base point = 30.0 ml/min, and high flow = 51.2 ml/min; helium carrier gas low flow = 12.3 ml/min, base point = 35.8 ml/min, and high flow = 55.8 ml/min; solvent low flow = 0.3 ml/min, base point = 1.4 ml/min, and high flow = 2.7 ml/min). Packed-column carrier gas flow conditions are limited since analyte elution is severely retarded at very low flows, *e.g.*, less than 10 ml/min, but analytes may be lost during the venting procedure at very high flows, *e.g.*, greater than 40 ml/min. Conductivity solvent flow is limited by the useful range of the delivery pump since at low flows, less than 0.2 ml/min, the system becomes erratic, and the upper flow limit is about 4 ml/min. Reaction-gas flow was also restricted since the gas-to-liquid flow ratio in the gas–liquid contactor and separator must be approximately 100:1, according to previous studies[7].

For the three-factor, three-level, second-order, central composite design the system was evaluated at points corresponding to the eight vertices, the centers of the six faces, and the base-point for the experimental cube-space[5]. Replicate measurements were obtained for the base point to establish expected uncertainties. Accordingly, appropriate chromatograms were developed; eight with the flow conditions set as defined by the vertices of the cube, six as defined by the centers of the faces of the cube, and five replicate chromatograms for the base-point. The experimental sequence was not completely randomized due to practical limitations in precisely resetting flows.

The data-analysis computer program (available upon request from the authors) was used to mathematically model the factorial data with the best-fit second-order polynomial using multiple linear regression. The expected values for 1-chlorooctane peak area responses, as modeled by the regression polynomial function, and regression residuals were calculated. Regression parameters for eqn. 1 resulting from modeling factorial data are shown in Table I. Table I also includes confidence intervals based on the Student's *t*-statistic for each of the ten regression parameters. The 90% confidence intervals were calculated from the diagonal elements of the inverted regression matrix and parameter standard deviations as estimated from the corresponding sum of squared residual values[6].

The regression parameters indicate that solvent flow has the largest effect among the three flow factors on the HECD response; the first- and second-order regression parameters for the main-effect of solvent flow on the HECD response are much larger than for any other effect. The hydrogen and helium flow factors yield smaller main-effect parameters than solvent flow, with the first and second main-effect parameters being similar for the two gas flow factors. This indicates that the total gas flow through the HECD is more important for HECD response evaluation than the individual flow-rates of hydrogen or helium within the flow boundaries evaluated in this experiment. The 90% confidence intervals for hydrogen and helium flows indicate that the second-order parameters, as well as the interaction-effect terms, are all relatively small when compared to other parameters.

TABLE I

MULTIPLE REGRESSION PARAMETERS FOR THE 1COA PEAK AREA RESPONSE SURFACE TO HYDROGEN, HELIUM AND SOLVENT FLOW RATES

90% Confidence interval estimates for the individual regression parameters are included[6].

Regression parameter	*Parameter value*	*Estimated 90% confidence interval for parameters*	*Parameter description*		
			Effect type	*Factors*	*Parameter order*
β_0	$2.7 \cdot 10^2$	$1.0 \cdot 10^2$	–	–	Intercept
β_1	5.6	5.1	Main	Hydrogen	First
β_2	$-2.9 \cdot 10^{-2}$	$7.0 \cdot 10^{-2}$		Flow	Second
β_3	7.3	4.3	Main	Helium	First
β_4	$-2.9 \cdot 10^{-2}$	$6.0 \cdot 10^{-2}$		Flow	Second
β_5	$-3.8 \cdot 10^2$	$0.7 \cdot 10^2$	Main	Solvent	First
β_6	97.0	18.0		Flow	Second
β_7	$-4.7 \cdot 10^{-2}$	$4.4 \cdot 10^{-2}$	Interaction	Hydrogen and helium	Second
β_8	−0.76	0.80		Hydrogen and solvent	Second
β_9	1.4	0.7		Helium and solvent	Second

The polynomial model was evaluated for effects of each flow on the HECD response while the remaining two flows were held constant at base-point values. If solvent flow is increased while carrier and reaction gas flows remain constant, then the HECD response is reduced (see Fig. 2). For example, a conductivity solvent flow of 0.2 ml/min yields about ten times the HECD response found with a flow of 2.5 ml/min.

HECD response increases as either reaction gas or carrier gas flows are increased. Increasing the carrier gas flow from 10 ml/min to 50 ml/min produces a 120% increase in the HECD response if the other two factors are held constant at base-point values (see Fig. 3). Similarly, hydrogen flow increase over the same flow ranges yields a 45% increase in HECD response (Fig. 4); however, since the helium flow at the base-point is larger than the hydrogen flow at the base-point, different total gas flow-rates are compared. Evaluation of the hydrogen flows from 10 ml/min to 50

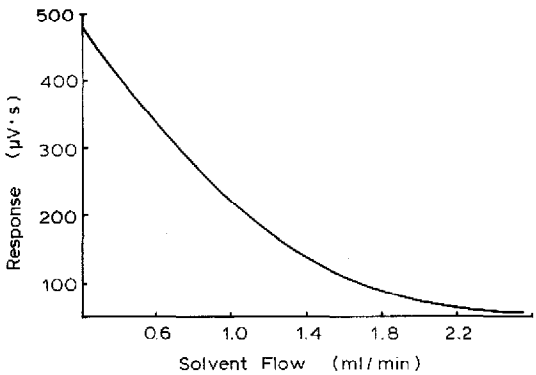

Fig. 2. Effect of HECD solvent flow on 1COA peak area, hydrogen flow = 28.9 ml/min, helium flow = 36.1 ml/min.

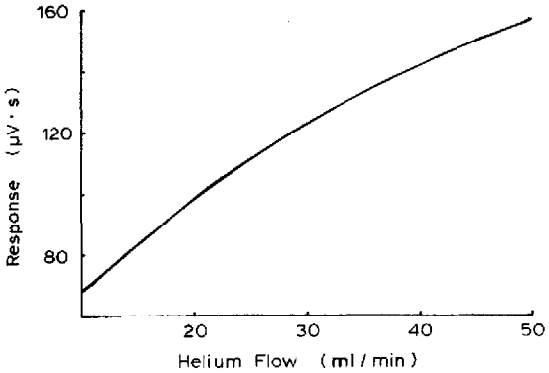

Fig. 3. Effect of HECD helium carrier gas flow on 1COA peak area, hydrogen flow = 28.9 ml/min, solvent flow = 1.4 ml/min.

ml/min, with the helium flow constant at 28.9 ml/min and solvent flow constant at 1.4 ml/min, shows an HECD response increase of 65% (Fig. 5).

Within the 90% confidence intervals for the parameters in eqn. 1 (see Table I), increases of either helium and hydrogen flow causes similar enhancement of HECD response (see Figs. 3 and 5). The increase in the HECD response as total gas flow increases may reflect enhanced mixing dynamics within the gas–liquid contactor and gas–liquid separator. However, a specified total gas flow-rate yields approximately the same HECD response even if the ratio of hydrogen to helium flow changes. This indicates that hydrogen gas is probably only needed in small amounts as a reagent, contrary to conventional assumptions.

Evaluation of the main effects and interaction effects of reaction gas, carrier gas and conductivity solvent flows on the HECD response by Yates' method

To supplement the central composite factorial calculation above, Yates' method for analysis of factorial experiment data was applied to the evaluation of effects of the

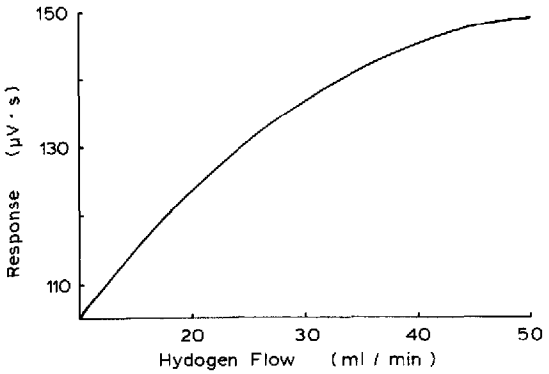

Fig. 4. Effect of HECD hydrogen flow on 1COA peak area, helium flow = 36.1 ml/min, solvent flow = 1.4 ml/min.

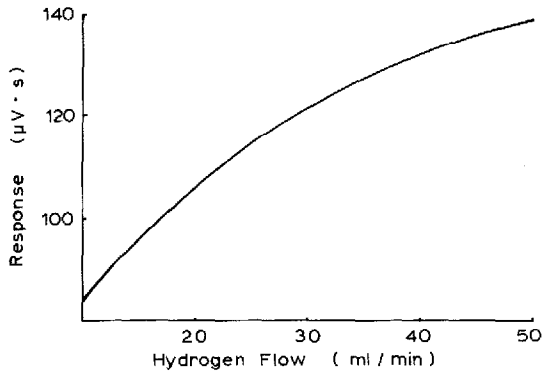

Fig. 5. Effect of HECD hydrogen flow on 1COA peak area, helium flow = 28.9 ml/min, solvent flow = 1.4 ml/min.

three flow factors on HECD response[6]. Yates' method utilizes simple calculations to quickly estimate the main and interaction effects, however, the method is restricted to two-level experiments. Thus, only the eight chromatograms, corresponding to the eight vertices of the experimental cube in Fig. 1 were used. Resulting estimates of Yates' effects suggest trends similar to those suggested by the multiple regression analyses described above.

For calculations according to Yates' method, only three effects are significantly different from zero at the 90% confidence level based upon the Student's *t*-statistic: the main effects of solvent and helium flows and the interaction effect between solvent and helium flows[6]. The estimate of the main effect of solvent flow on the HECD response is much larger than the main effect for hydrogen or helium flows, consistent with the dependence found via the multiple regression evaluation above. However, results of Yates' method indicate that the interaction effect between helium and solvent flows is much more significant than estimated by the multiple regression evaluation. This second-order relationship between solvent flow and the HECD response is also evident from the multiple regression parameters discussed above and from previous work[3].

Flow conditions for optimum HECD response for GC separations

Flow conditions were selected, based upon results described above, to provide a maximum HECD response to organochlorine for the HECD under practical operating conditions. (Flows for maximum HECD response were hydrogen = 50 ml/min, helium = 50 ml/min and solvent = 0.2 ml/min; practical optimum flows were hydrogen = 50 ml/min, helium = 20 ml/min and solvent = 0.5 ml/min) However, criteria other than HECD response also must be considered for optimal GC measurements; signal-to-noise evaluations and resolving power are also important. For example, a solvent flow of 0.5 ml/min provides an enhanced HECD response over higher flows but does not introduce significant pump-related noise into the system. Similarly, a solvent flow of 0.2 ml/min is too low, as it increases HECD response but includes substantially increased noise, thus jeopardizing measurements of analytes and degrading the limit of detection.

Experimental results described above suggest that the HECD response mainly changes with total gas flow. However, carrier gas flow also affects resolution and

retention times in addition to the HECD sensitivity. Thus, carrier gas flow may also be optimized for resolution, and reaction gas flow may be increased to raise the total gas flow if the HECD response needs to be further enhanced. An optimum helium carrier gas flow of 20 ml/min was thereby selected for subsequent packed-column separations. Under those conditions hydrogen reaction gas flow of 50 ml/min provides the most sensitive HECD response according to the experimental results described above.

HECD responses were calculated, based upon the response surface, as single factors were changed while the other flow factors remain constant at the selected optimum flow-rates. The effect of solvent, helium and hydrogen flows on the HECD response near the optimization point are consistent with the discussion above but shows greater dependences than shown in Figs. 2–5 above.

Evaluation of flow factors for capillary separations using hydrogen carrier gas and hydrogen make-up gas eliminated the need for addition of reaction-gas. The major dependence of the HECD upon the main factors of total gas flow and solvent flow, discussed above, therefore allowed for easy adaptation to capillary GC. Because high resolution was provided at very low capillary carrier gas flows, *e.g.*, 1 ml/min, hydrogen as make-up gas was varied to provide maximum HECD response without degrading eluate resolution; this was approximately 60 ml/min. Similarly, HECD solvent flow was selected to provide sufficiently low noise, *e.g.*, at approximately 0.5 ml *n*-propanol/min.

These statistical optimizations for maximized sensitivities allow for efficient assessments of appropriate HECD flows via few experiments. Other parameters such as signal-to-noise ratios or resolution might also be considered in other evalutions which use criteria other than enhanced responses. The optimum flows reported here are consistent with typical flows recommended for the HECD based upon extensive empirical efforts[2–4,7,8]. However the results herein also contradict some conventional assumptions: (a) only small amounts of hydrogen are required for effective reductions of organochlorine to HCl, and (b) total gas flow is typically much more important than the ratio of hydrogen-to-carrier gas flows.

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