

CHROM. 6775

DEPENDENCE OF HETP UPON RESIN PARTICLE SIZE AND SOLUTION FLOW-RATE IN HIGH-SPEED ION-EXCHANGE CHROMATOGRAPHY

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SUMMARY

In order to obtain a method for selecting the optimum experimental conditions for achieving difficult separations in high-speed ion-exchange chromatography, the dependence of the height equivalent to a theoretical plate (HETP) on the solution flow-rate and resin particle size was studied.

The HETP has been measured for the nickel-zinc ion exchange (permutation front) at different flow-rates and for several fractions of variable sizes obtained by elutriation from the same variety of a commercially available cationic resin, Dowex 50W-X8 (-400 mesh). For a given particle diameter, d_p , the HETP (H) was found to vary with the solution flow-rate, u , according to the equation

$$H = C \cdot u^\alpha$$

where α depends on the particle size: it decreases as d_p increases, *e.g.*, from 0.9 to 0.4 when d_p varies from 20 to 100 μm , tending to a limiting value which was found to be dependent on the exchange reaction studied. On the other hand, at a constant flow-rate, H was found to vary with d_p according to the equation

$$H = k \cdot d_p^\beta$$

where β depends on the solution flow-rate: it decreases slowly as u increases.

The influence of these parameters on the column efficiency, and of the pressure drop that results from using high flow-rates and very small particles, are discussed.

INTRODUCTION

The application of high-speed liquid chromatography has been very successful. Considerable improvements have been obtained in the field of ion-exchange chromatography by using small and spherical resin particles with a narrow size distribution. One of the best known examples is the separation of amino acids¹⁻³, which very commonly can be achieved in less than 1 h by means of entirely automatic apparatus. Similar results have been obtained in biochemistry (separation of nucleosides, nucleotides, N-bases, etc.^{4,5}), in radiochemistry (very fast separation of short-lived isotopes)⁶⁻⁸ and in pharmacological analysis^{9,10}. All of these separations have been

obtained by using very fast eluent flow-rates (from 10 to 100 times faster than those used in classical ion-exchange chromatography) and particles of ion-exchange resins with diameters ranging from 10 to 50 μm (Ref. 11).

Most of the published studies on ion-exchange chromatography have an applied aspect and most often the efficiency of a separation is improved only by varying several parameters, such as the particle diameter, degree of cross-linking, flow-rate and temperature.

In order to understand better the roles of these parameters, and particularly to know how independent they are, their behaviour on columns of given sizes has been studied as systematically as possible. In the present work, the influence of the size of the particles and the flow-rate of the solution has been studied. The influence of temperature is now being studied and the results will be published soon.

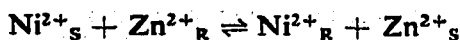
The present results are reported in terms of variations in the height equivalent to a theoretical plate (HETP), which best characterises the efficiency of a chromatographic column. Generally, most workers in this field use the elution technique and choose a given peak for measuring the HETP under various conditions, in order to improve analytical separations. However, ion-exchange chromatography is also a preparative method, and we have accordingly not determined the HETP on elution peaks but on the breakthrough front in the displacement permutation of two ions that have closely similar affinities for the resin. The HETP has the same definition in both instances, but its numerical values may be different as the conditions of the chromatographic process are different in elution and in displacement permutation.

EXPERIMENTAL

Ion-exchange reaction

The reaction of ion permutation studied is that of Zn^{2+} ions, originally fixed in a cation-exchange resin with sulphonate groups (Dowex 50W-X8), with Ni^{2+} ions from an aqueous solution of nickel nitrate which is continuously injected on to the column.

To the exchange equilibrium reaction



corresponds the apparent constant

$$K_{\text{Zn}}^{\text{Ni}} = \frac{[\text{Ni}^{2+}]_{\text{r}} [\text{Zn}^{2+}]_{\text{s}}}{[\text{Ni}^{2+}]_{\text{s}} [\text{Zn}^{2+}]_{\text{r}}}$$

where the quantities in brackets represent the total concentrations of each species in each phase.

This constant has been measured by frontal analysis with the same experimental conditions as those in ion permutation. We obtained the value $K_{\text{Zn}}^{\text{Ni}} = 1.050 \pm 0.003$.

The broadening of the permutation front between the two species, corresponding to the transformation of the resin from the zinc form into the nickel form, is a function of the number of theoretical plates of the column and also of the difference in the affinity of the resin for the two ions. As this difference is small, as shown by the

value of the exchange constant, the permutation front ranges over a sufficient length of column, and therefore over a sufficient number of plates, to allow the precise determination of the HETP (if the exchange constant is great, the front is narrow and the HETP determination becomes very inaccurate).

Persoz¹² and Conrard and Caude¹³ have described a simulation method, involving the use of a digital computer, that gives the theoretical shape of chromatographic fronts; for ion permutation it becomes a discontinuous process and proportions of the two components of the mixture are calculated, for the two phases, in each plate and after each transfer. The HETP value can then easily be deduced from the superposition of experimental and calculated isoplanes (the molar fraction of the element which is more fixed by the resin as a function of the effluent volume). An example is shown in Fig. 1.

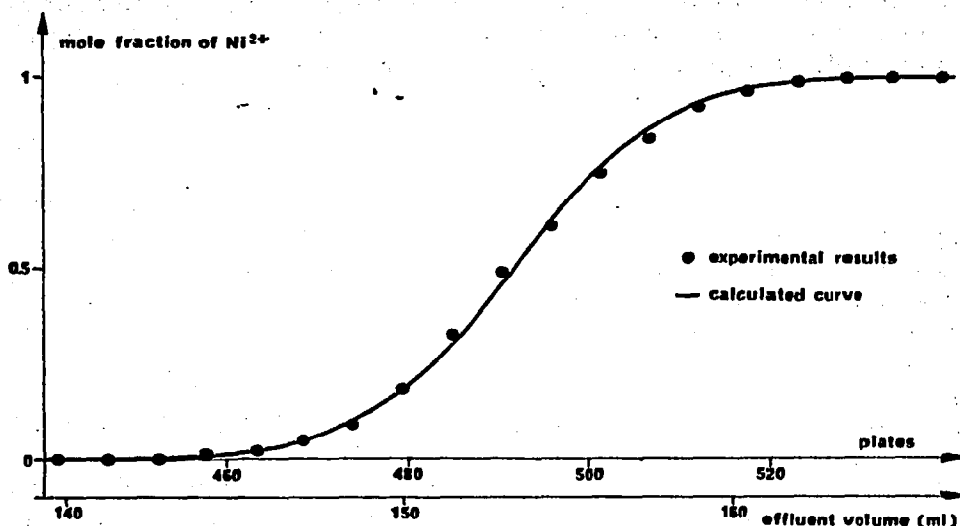


Fig. 1. Determination of HETP value by superposition of experimental and calculated isoplanes. Conditions: resin fraction, 18–24.5 μm ; flow-rate, 450 $\text{ml}\cdot\text{h}^{-1}\cdot\text{cm}^{-2}$; column dimensions, 30 cm \times 7.6 mm I.D.

Resin samples

The study undertaken requires very small resin particles that are as homogeneous as possible. Moreover, if possible, these resins must have the same structure and a same degree of cross-linking. We therefore used the commercial resin Dowex 50W-X8 (–400 mesh), which most probably is homogeneous with respect to the polymerisation reaction and the degree of cross-linking.

In order to separate the various necessary granulometric fractions, we used a hydraulic classification technique (elutriation) described by Aubouin and Laverlochere¹⁴. Various cylindrical tubes with increasing diameters are arranged in series in such a way that any solution that overflows will be re-injected at the bottom of the following tube. This counter-flow redistribution separates a set of particles into as many fractions as there are tubes: the smaller a particular particle is, the further it is carried along the circuit by the liquid upflow. When applied to the above resin, this

TABLE I
PARTICLE SIZES OF SEPARATED FRACTIONS

Diameter	Fraction				
	I	II	III	IV	V
Extreme values of the diameter (μm)	18-24.5	21-28	28-43	43-63	61-83
Most probable diameter (μm)	21	24	33	51	74

method allowed the separation of five fractions, and 80% of the bead diameters of these fractions, which were measured with a microscope on the resin in suspension in water, varied within the limits given in Table I; the most probable diameter corresponding to the maximum of the distribution curve is also given for each fraction*. Fig. 2 shows an example of a granulometric distribution curve.

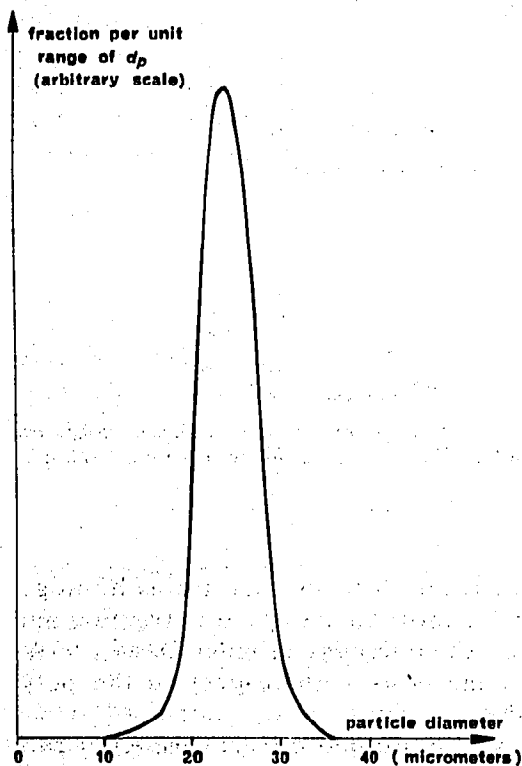


Fig. 2. Particle size distribution curve for 21-28 μm fraction II.

* We find that this way of defining a granulometric fraction is more realistic than the optimistic way in which numerous suppliers state only two diameter values without indicating the percentage of the beads that actually have a diameter between these two limits.

Apparatus

The apparatus has been described in a previous paper¹⁵; it consists of an Orpita pump (DMP Model 1515), an arrangement for damping pulsations which comprises a capillary tube between two Bourdon tube manometers, and a stainless-steel chromatographic column. The effluent is fractionated by means of a fraction collector and analyzed (titrations are carried out by polarography in thiocyanate medium¹⁶).

The method of packing the columns is an important factor in high-speed liquid chromatography. The swelling of ion-exchange resins in water makes a packing technique in liquid medium necessary. We used a dynamic method analogous to that described by Scott and Lee¹⁷, which consists in introducing particles into the column as a suspension in water at a greater rate than the rate of gravity sedimentation.

We checked that this method gave a regular and homogeneous packing along the whole of the column, by showing that the HETP determined for the Zn^{2+} - Ni^{2+} exchange was reproducible and independent of the column length, all other parameters being kept constant; the HETP measured on a 60-cm column was the same as that on a 30-cm column under the same conditions.

RESULTS

Influence of the solution flow-rate

The variation of HETP as a function of solution flow-rate is represented on the log-log diagram in Fig. 3 for the various granulometric fractions studied.

It can be seen that, for a resin of given dimensions, the variation of the HETP with flow-rate can be represented by the relationship

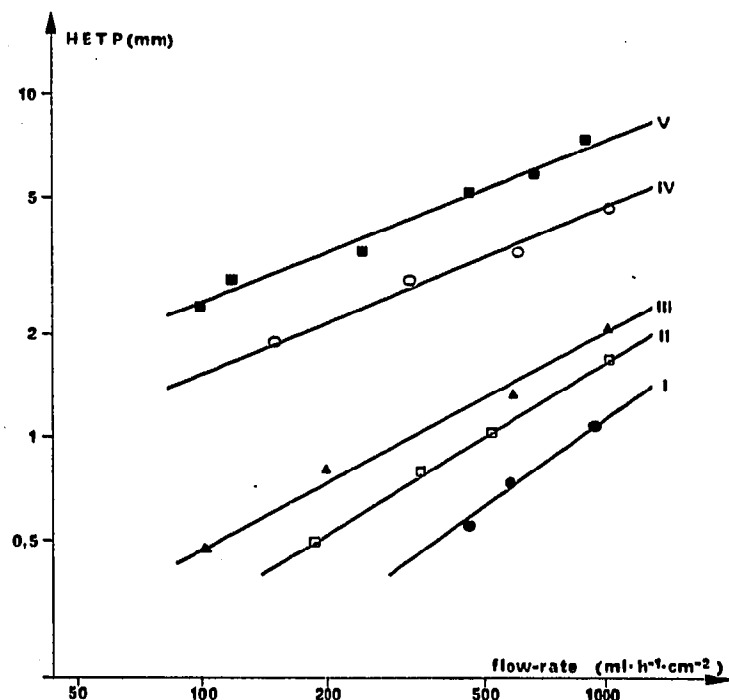
$$H = C \cdot u^\alpha \quad (1)$$

where H is the HETP, u the flow-rate and C and α are constants.

However, the experimental lines obtained on logarithmic coordinates are not parallel, indicating that α depends on the particle diameter, d_p . The variation of α with d_p is shown in Fig. 4. In the case considered, α decreases from about 0.7 for the smallest particles to 0.45 for the largest particles, the variation becoming smaller as the diameter increases. The increase in HETP, and therefore the efficiency loss of the column, becomes more sensitive as the particles used become smaller.

These results can be compared with those obtained in other high-speed liquid chromatographic methods. Thus, eqn. 1 is identical with that proposed by Snyder¹⁸, which has been checked on numerous examples in both adsorption and partition chromatography^{19,20}. In most instances, α varies between 0.3 and 0.6, and is often close to 0.4; according to Kirkland¹⁹, it should be virtually independent of the particle diameter, but it must be pointed out that all systematic studies are carried out on particles with a diameter greater than $30 \mu\text{m}$, which corresponds to a part of our curve where variations are slight. Moreover, Beachell and De Stefano^{21,22} have shown that α increases when the column diameter increases.

This increase in α for the smallest particles can be assumed to be due to difficulties in ensuring homogeneous packing and to the existence of "preferential paths" inside the exchanger, which would have a greater effect on the efficiency as the flow-rate increases. This is a limiting factor to decreasing the size of exchanger particles below a certain value in high-speed ion-exchange chromatography.



fraction	I	II	III	IV	V
d_p (μm)	18-24.5	21-28	28-43	43-63	61-83

Fig. 3. Effect of solution flow-rate on HETP.

Influence of the exchange reaction. The limiting value of α is dependent on the exchange reaction studied: in Fig. 5, HETP values have been plotted against the flow-rate of the solution for a given particle size ($75 \mu\text{m}$) for the Ni^{2+} - Zn^{2+} , K^+ - Li^+ and K^+ - Na^+ pairs. The lines obtained are not parallel; α depends on the particular reaction of ion permutation.

The results are in good agreement with those of Morris *et al.*²³, who showed that, for the separation of lanthanides by elution on an ion-exchange resin, the variation of HETP with the eluent flow-rate could be expressed by a relationship identical with eqn. 1, where $\alpha = 0.145$ for $205 < u < 13,500 \text{ ml} \cdot \text{h}^{-1} \cdot \text{cm}^{-2}$.

Nature of the resin. For a given separation, the HETP depends on the nature of the resin. Fig. 6 represents the variation of HETP with the solution flow-rate for the Zn^{2+} - Ni^{2+} exchange, obtained with a 21-28 μm fraction of Dowex 50W-X8 resin and an 8-18 μm fraction of Hi-Rez Durrum sulphonate type resin. It can be seen that whereas the former resin has a greater efficiency for low flow-rates, it is the contrary for high flow-rates. The HETP with a Durrum resin is also much less sensitive to an increase in flow-rate than it would be for a fraction of equivalent diameter in Dowex 50W-X8. The HETP for an ion exchanger is therefore dependent not only on

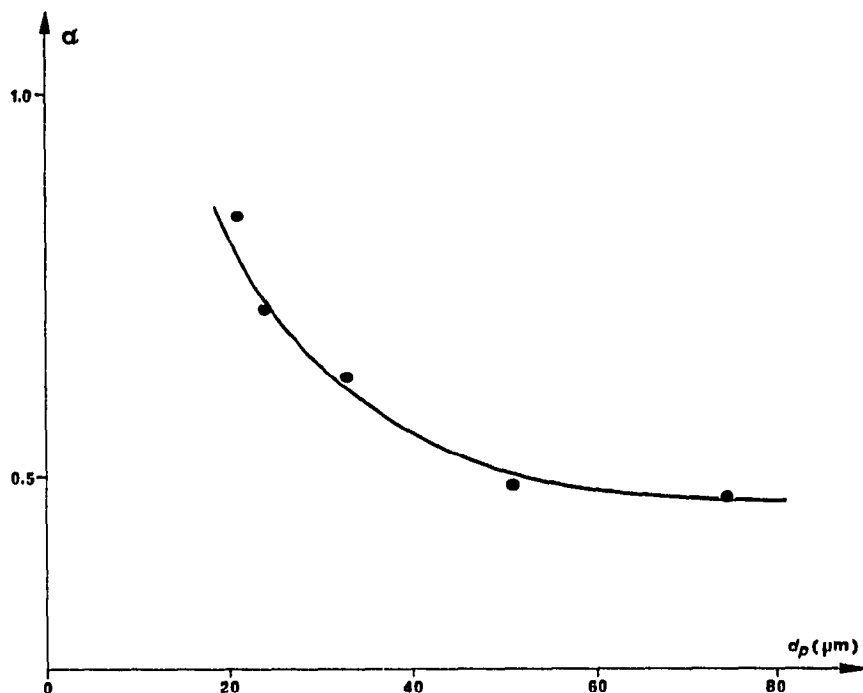


Fig. 4. Dependence of α on d_p (α values calculated from Fig. 3).

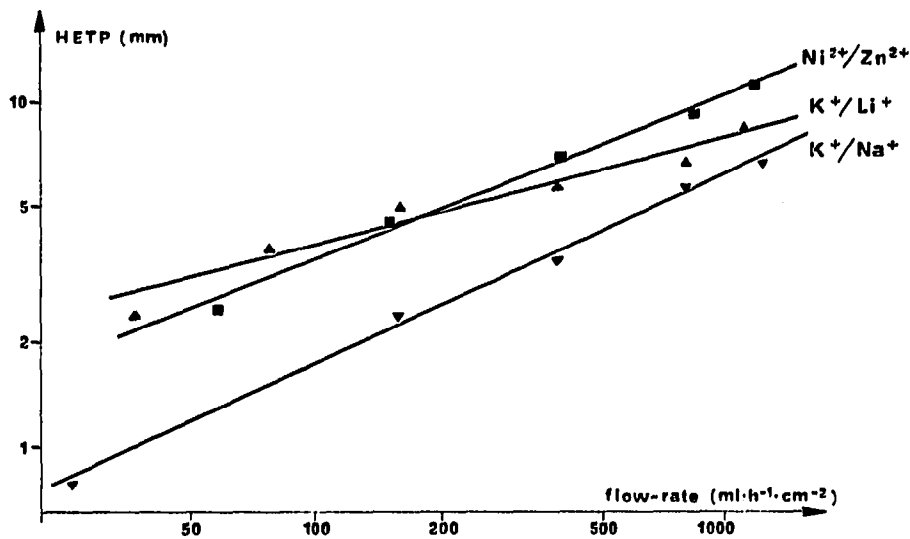


Fig. 5. Dependence of α on the nature of the ion-exchange reactions: HETP vs. u curves for various ion permutations.

the particle size but also on the resin structure (gel or macroporous structure and degree of cross-linking). Hi-Rez resin was assumed to be macroporous, but this was not checked.

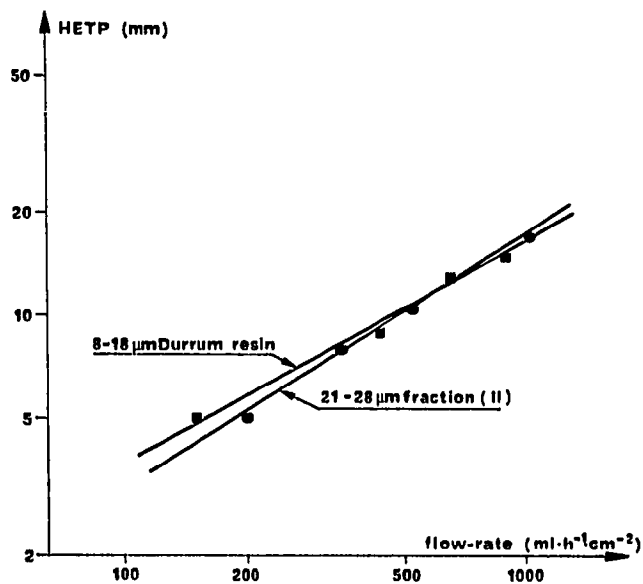


Fig. 6. Dependence of α on the nature of the ion exchanger.

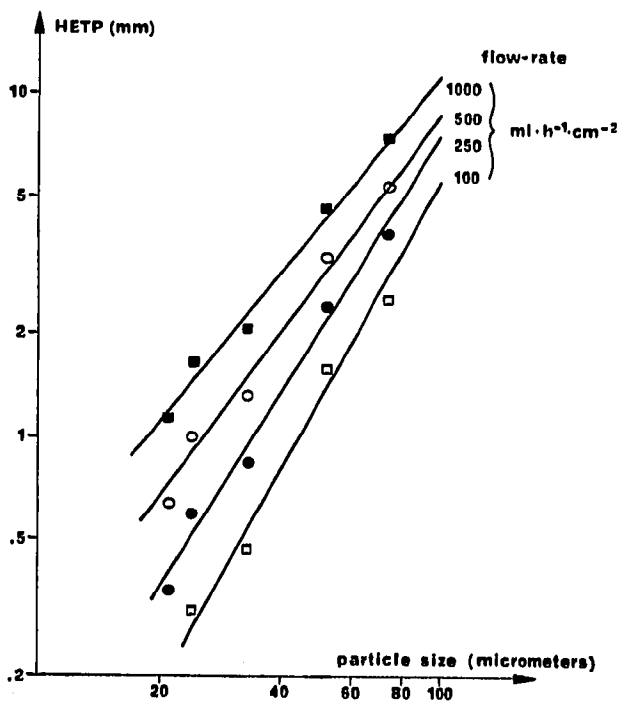


Fig. 7. Effect of particle size on HETP.

Influence of the particle size

In Fig. 7, the variation of HETP is represented on log-log coordinates as a function of particle size for various solution flow-rates for the Zn^{2+} - Ni^{2+} exchange mentioned above.

For a given flow-rate, these variations can be expressed by an equation of the following type:

$$H = k \cdot d_p^\beta \quad (2)$$

where β depends on the flow-rate. In Fig. 8, which shows the variation of β with u , it can be seen that β decreases as the flow-rate increases and approaches a limiting value close to 1.4. This result is also in good agreement with those obtained by Snyder¹⁸, Kirkland¹⁹ and Beachell and De Stefano²¹ in liquid chromatography.

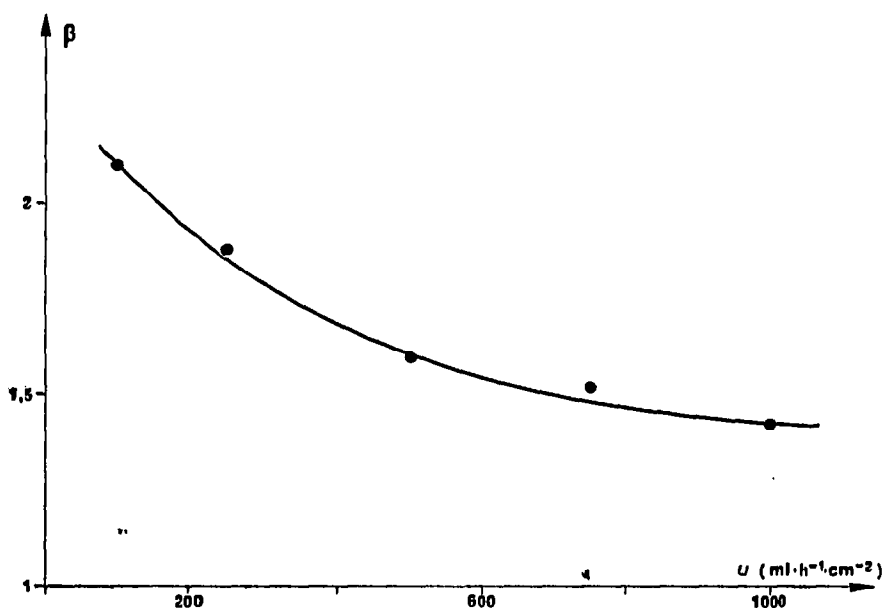


Fig. 8. Dependence of β on solution flow-rate (β values calculated from Fig. 7).

These authors have shown that at high speed, the C term in eqn. 1 could be expressed in the form

$$C = C_0 \cdot d_p^{1.4}$$

and, by considering eqns. 1 and 2, for constant u , $\beta = 1.4$. Once again, it can be seen that for our resin this is a limiting value that can be considered to be reached as soon as the flow-rate becomes greater than 1000 ml·h⁻¹·cm⁻².

CONCLUSIONS

The HETP in ion-exchange chromatography and in displacement permutation

cannot be written as simply as

$$H = C' \cdot u^\alpha \cdot d_p^\beta$$

except as an approximation; α is dependent on the particle size and β on the flow-rate. For particles with a diameter greater than about $50 \mu\text{m}$ and for very high flow-rates (above $1000 \text{ ml} \cdot \text{h}^{-1} \cdot \text{cm}^{-2}$), α and β approach limiting values of 0.4 and 1.4, respectively. The increase in α when d_p decreases means that very small-sized resins are not necessarily desirable, especially as the pressure drop through the column increases as d_p^2 (Refs. 15 and 24).

These results will permit a better understanding of chromatographic phenomena and the appropriate selection of the optimum conditions for various separations by ion exchange for particular experimental conditions. It will then be possible to use a method analogous to Snyder's method²⁵ in liquid chromatography.

ACKNOWLEDGEMENTS

We would like to thank the Division du Génie Isotopique du Commissariat à l'Énergie Atomique, which supported this study, and also Miss M. C. Schmiedt, whose assistance with the experimental work is greatly appreciated.

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