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THE MODIFICATION OF FLOW RESISTANCE IN A PACKED BED

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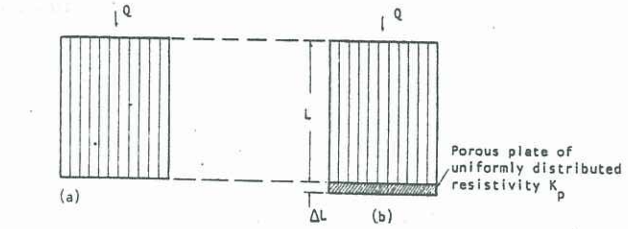
SUMMARY The importance of flow through packed columns in the process industries is well known. The microscopic and macroscopic dispersion of fluid in passing through packings results in reduced efficiency of heat and mass transfer so that any reduction of dispersion is desirable, especially for processes relying on sharp fronts between batches (chromatographic processes). Recently the authors developed a model of flow through porous media consisting in a bundle of capilliaries in parallel, the flow resistances being log-normally distributed. This model successfully correlated dispersion data of packed beds and of porous rocks. The model has now been further developed with the concept of a uniform flow resistance added to each capilliary to render flow in each more uniform and hence lower the overall (macroscopic) dispersion. In the laboratory the high resistance was in the form of sintered particle plates or else composite plastic mesh. The experimental results indicate that even very high added uniform resistances have not the smallest effect on dispersion, an important, though negative, result. The explanation for this is given in the form of an electrical analogy and illustrated with a critical experiment using a packed bed of extreme heterogeneity.

1 INTRODUCTION

The authors previously developed a model of flow through porous media, employing the concept of a bundle of capilliaries, the flow resistances of which were log-normally distributed (Nguyen and Bagster - 1980). The analogy between fluid flow in porous media and electrical current flow has long been known (Muskat - 1931) and Figure 1(a) illustrates the electrical analogue of the capilliary.



Flow resistance in a capillary is K.L

Flow resistance in the capillary is now $(K + K_p \frac{\Delta L}{L})L$

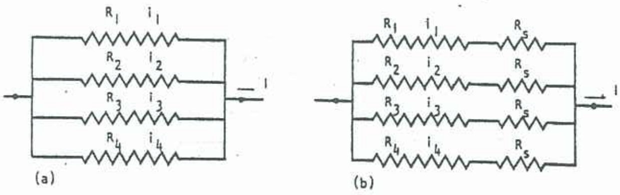


Figure 1 Electrical analogy with Packed Beds

The analogy may then be extended, Figure 1(b). If a constant resistance is placed in series with each conductor the current flows in the various parallel paths will have ratios with each other closer to unity than in the case of Figure 1(a). I.e. there will be an evening up of the elements and the higher the constant resistance R_S the more uniform the currents will become.

Hence experiments were conducted placing a septum of high uniform resistance at the end of a packed bed to observe if macroscopic dispersion could be reduced, accepting of course that microscopic dispersion will not be altered.

Preliminary calculations were made assuming a bundle of capillaries for the porous bed in the manner which has been found successfully to correlate dispersion data for packed beds and porous rocks (Nguyen - 1975). The probability of a capilliary having a permeability between k and k+dk is p(k) dk in which p(k) is the assumed log-normal distribution with standard deviation σ_k:-

$$p(k)\,dk = \frac{1}{\sqrt{2\pi}\,\sigma_k} \exp\left[\frac{-(\ln k - \ln k_{median})^2}{2\sigma_k^2}\right] d\ln k \qquad \ldots(1)$$

With the presence of the resistance plate, each permeability k now becomes*

$$k_{new} = \frac{1}{K + K_p \frac{\Delta L}{L}} \qquad \ldots(2)$$

where flow resistance in a capilliary of length L is KL and that of the resistance plate is $K_p\Delta L$ where ΔL is the thickness of the plate.

$$p(k_{new})\,dk_{new} = p(k)\,dk \qquad \ldots(3)$$

Considering the step input of displacing liquid it may be shown (Nguyen - 1975) that the concentration of displacing lqiuid (volume fraction) will be

$$C(\bar{t}) = \frac{1}{I} \sum_{p=0}^{k=k} \left(1 + \frac{K_p \Delta L}{L} k\right)^{-1} p(k)\Delta k \qquad \ldots(4)$$

where

$$I = \sum_{k=0}^{k=\infty} \left(1 + \frac{K_p \Delta L}{L}\right)^{-1} p(k)\Delta k \qquad \ldots(5)$$

* Footnote: The applicale form of Darcy's Law here is:

$$u = \frac{-\Delta P}{\mu K L} = -\frac{k\Delta P}{\mu L}$$

and
$$\bar{t} = {}^{t}/_{\tau} \qquad \ldots(6)$$

the dimensionless ratio of time to the average residence time.

Taking a typical value of standard deviation of residence times (or of permeabilities) of $\sigma_k = 0.12$ calculations were made of the resulting standard deviations of residence times σ_M with various constant resistances in series with the capilliary bundle, where R is the ratio of plate resistance to bed resistance. Figure 2 shows a considerable theoretical reduction, for example a halving of standard deviation for an overall doubling of bed resistance.

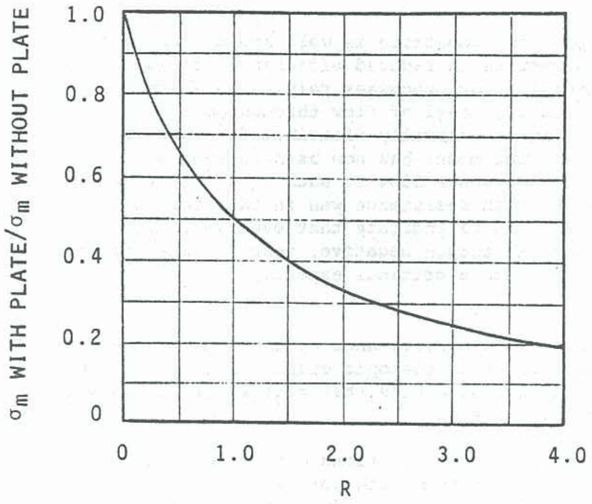


Figure 2 Calculated Effect of Uniform Series Resistance on Dispersion in a Packed Bed.

2 EXPERIMENTAL STUDIES

The apparatus used has been described fully elsewhere (Nguyen - 1975) and consisted of a cylindrical column which could be loaded with different packings, had specially constructed valve at the inlet to enable a step change of input liquid to be passed directly into the packing, an outlet distributor (which here was the resistance septum) and a fraction collector. Table 1 gives details of the two columns used in this study.

Two types of porous plate were used. Type A were made of electrically fused alumina bonded together with aluminous glass fired at high temperature. The product "Alundum", is stated by the manufacturer (Norton Ltd) to have uniform porosity and permeability. The thickness chosen was ¼". The plates were ground to match accurately the flow area of the bed and glued in with Araldite.

Type B were made by superimposing a number of fine (5µm) Nylon filter clotts ("Nytal") on each other. They were glued together at the edges. Unifromity was able to be verified by microscope.

Figure 3 shows the experimental standard deviation σ_0 of the residence time distributions measured from effluent concentration profiles for Column 2 with Resistance Plate A3 as a function of average interstitial velocity U. Also plotted are the σ_0 vs U results for Column 2 without a resistance plate. Resistance Plates A1 and A2 were found similarly to produce no decrease in standard deviation or dispersion.

Experiments were carried out with Column 4 and Resistance Plate B3 and Table 2 shows similar lack of dispersion reduction.

Experiments were then carried out with the 70 mm ID column packed into two separate zones with glass beads of two different sizes, -8+9 mesh and 4 mm. This provides an extreme case of poor packing, Figure 4.

TABLE I

DETAILS OF POROUS MEDIA

1 (a) COLUMNS

Column Number	Length L mm	Diameter mm	Packing	Average Flow Resistance across Column KL	
				$\frac{cm^2 cm\ H_2O}{(cm^3/min)\ (c.p)}$	m^{-1}
2	310	146	-8+ 9 mesh beds	0.164	0.966×10^8
4	310	70	-7+24 mesh beds	0.395	2.33×10^8

1(b) RESISTANCE MEDIA

Plate Number	Thickness ΔL (mm)	Flow Resistance across Plate $K_p\Delta$	
		$\frac{cm^2 cm\ H_2O}{(cm^3/min)\ (c.p)}$	m^{-1}
A1	6.5	0.172	1.01×10^8
A2	6.5	0.325	1.91×10^8
A3	6.5	1.750	10.30×10^8
B1	neglegible	0.309	1.82×10^8
B2	neglegible	0.548	3.13×10^8
B3	neglegible	1.436	8.46×10^8

Figure 5 shows the effluent concentration for this column for the cases - without a resistance plate and with Plates A3 and B3. Even in this very poorly packed situation resistance has made no change to dispersion.

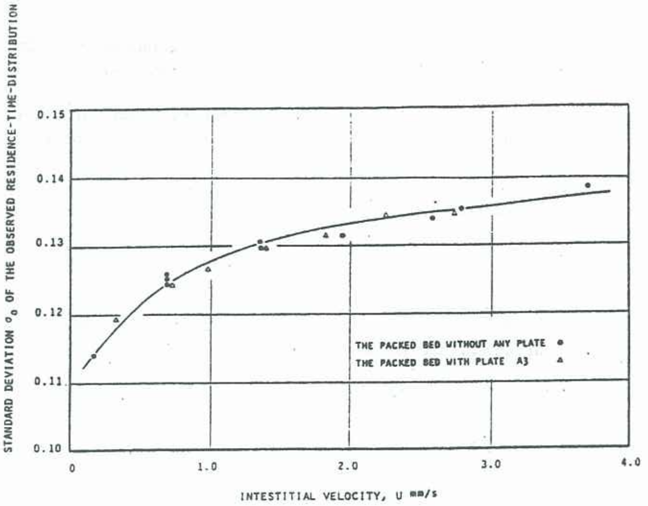


Figure 3 Experimental Dispersion as Function of Flow Rate, Column 2 with and without Resistance Plates.

TABLE II

RESULTS OF AXIAL DISPERSION MEASUREMENT
COLUMN 4, PLATE B3

Flow Rate (ml/min)	Interstitial Velocity (mm/s)	σ_o With Plate	σ_o Without Plate
62.5	0.77	0.129	0.136
95.0	1.17	0.137	0.138
250.0	3.08	0.143	0.143

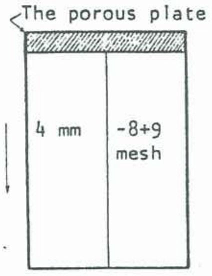


Figure 4 Extremely Heterogeneous Pakced Bed.

3 DISCUSSION

Since even an extremely inhomogeneous bed has no reduction in dispersion even with a resistance more than ten times the average flow resistance of the bed it was suspected that the electrical analogy of Figure 1(b) is inapplicable.

The possibility that cross-flows may be present to the extent that the capilliary model breaks down was considered but actual observation of the flow of the coloured displacing fluid found very little lateral mixing between the two packing zones. This observation is consistent with the finding of Rosenberg (1956).

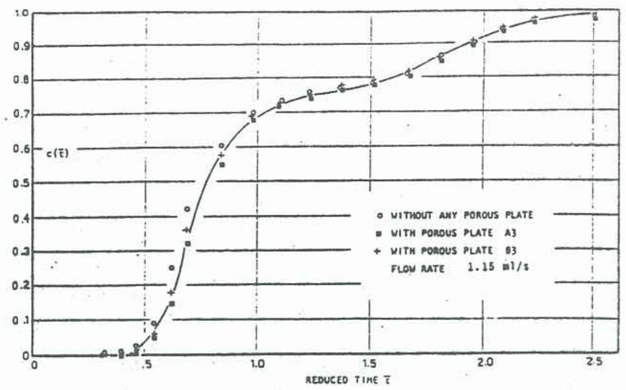


Figure 5 Breakthrough Curves with and without Resistance Plates for Extremely Heterogeneous Placked Bed.

The 70 mm ID column was also packed into two zones as described above but with a thin Perspex sheet between, preventing cross-flow altogether. No change in the dispersion pattern resulted.

Further, electrical calculations were actually made to find the effect of cross-flow in the circuits of Figure 6. Unless the cross resistances R_{ci} are extremely small the evening up effect on current flows remains. (Cross-flow resistances would be of the same order as the axial ones for an isotropic bed.)

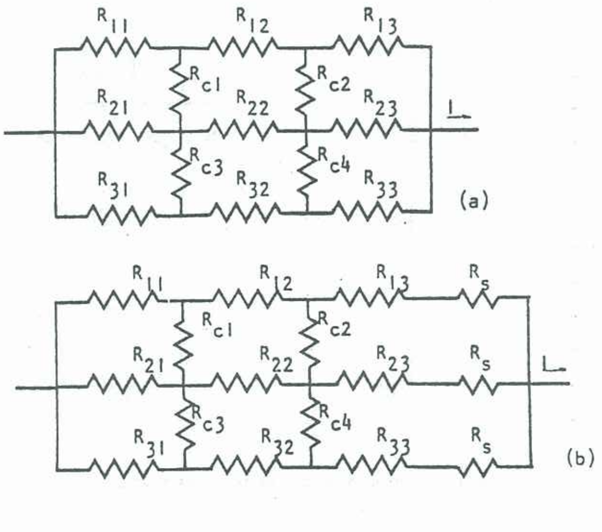


Figure 6 Electrical Analogues with Cross-flow.

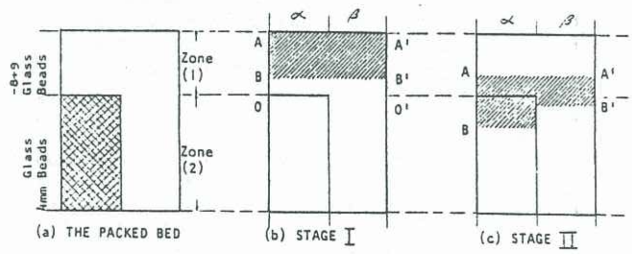


Figure 7 Schematic Diagram of Heterogeneous Bed with Slug of Marker Liquid.

It was then decided to make visual observations on actual flows in a column set up (without resistance plate) as shown schematically in Figure 7. Here Zone (1) should have an effect like that of a porous plate. Zone (2) represents the packed bed. Hence flow behaviour could be observed in bed and "plate" regions.

A slug of blue solution AA'B'B was introduced to displace clean water from the bed. In stage 1 the front BB' was observed moving evenly down the column. However at stage 2 as front BB' entered Zone (2) it started to separate on each side α and β of the packed bed. Front AA' continued to move evenly down Zone (1). This observation shows that there does not seem to be a connection between the velocity fronts in Zones (1) and (2). Apparently any axial dispersion due to the flow separation α and β mentioned can only be effected within Zone (2) where permeabilities on each side are unequal.

Further evidence in support can be found in work by Stanek and Szekely (1972) who carried out a theoretical computation of streamlines in liquid flows in a two-dimensional packed bed, with a pattern similar to the scheme of Figure 7. In the computation the fluid is introduced unformly over the top of the packing. The results show that the fluid is redistributed rapidly according to the hydraulic resistances offered by individual sections of the bed "within a relatively narrow region near the inlet".

Thus axial dispersion is not affected by a uniform resistance across a bed. Dispersion is only affected within the packed bed itself. The electrical analogue of placing a resistance across a packed bed is therefore given in Figure 8. Uniform resistance R_3 raises the overall voltage for a given total current but does not alter the ratio i_1/i_2.

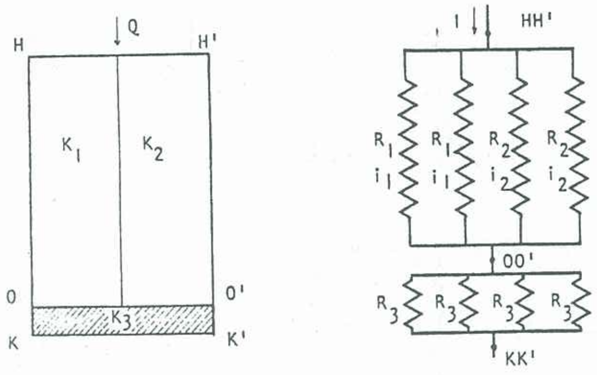


Figure 8 Deduced Analogy of Packed Bed with Uniform Resistance.

It is interesting to note that a similar situation arises in the flow of granular media down a bunker (Bagster and Tsetong - 1977) where flow in the converging hopper can be highly non-uniform whereas in the upper, constant cross-section bin portion flow is found to be quite constant across the bin.

4 CONCLUSION

Heterogeneous dispersion as measured by the standard deviation of the residence times of displacing fluid cannot be reduced by the device of adding a uniform high resistance across a packed bed even where packing heterogenities are extreme.

Reduction of dispersion must therefore be attempted by attention to inlet distribution and withdrawal or more uniform packing of the bed.

5 REFERENCES

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