Chapter V

EXPERIMENTAL STUDY OF TRACER DISPERSION
IN MODEL AND NATURAL POROUS MEDIA

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This article is the first in a series of three dealings with the transport of a tracer present in a fluid flowing through a porous medium. The experiments discussed here have been performed (and reported in references 8-10,15,23,27,31,36,38): 1) at ESPCI and at the Schlumberger Doll Research Center by C.Baudet, E.Charlaix, C.Leroy, E.Guyon and J.P.Hulin in cooperation with T.J.Ploza (SDR), C.Deslouis (Laboratoire d'électrochimie de l'Université Paris VI) & C.Zarcone (ENSEEHT-Toulouse). 2) at the Laboratoire d'Ultrasons, by J.C. Bacri, N.Rakotomalala and D.Salin.

This contribution focuses on a classification of the different regimes of dispersion as have been studied experimentally in model (bead packs) and real (heterogeneous porous rocks) porous media. The existence of anomalous (beyond Gaussian) response and of large dispersivities is analyzed.

The following chapters by J. Koplik and by J. Brady and D. Koch emphasize numerical and scaling approaches of the same problem on one hand, and a general theoretical description based on the use of the velocity-velocity correlation function on the other.

I. Introduction

The process of tracer dispersion has numerous practical applications due to its impact on hydrology, chemical or nuclear waste storage, chemical engineering, and petroleum engineering.

From a more fundamental point of view, dispersion measurements are a very sensitive and flexible probe of the detailed structure and geometry of the pore volume. Standard measurements like porosity or permeability give averaged information on the mean pore volume or the average channel size while dispersion studies give additional data on the distribution of flow paths through the medium and on the amount of dead ends, recirculation or inhomogeneities in the pore volume.

1. Gaussian dispersion

In the simplest cases, the variations of the mean tracer concentration C(x,t) can be described by an equation using only macroscopic average variables (Fick's law):

$$\frac{\partial C(x,t)}{\partial t} + (U \cdot \nabla) C(x,t) = D_\parallel \frac{\partial^2}{\partial x^2} C(x,t) + D_\perp \Delta C(x,t) \tag{1}$$

where $U$ represents a local velocity average. The coefficients $D_\parallel$ and $D_\perp$ characterize, respectively, longitudinal and transverse diffusion relative to the mean flow direction. In porous materials, different mechanisms of dispersion are present 1 and lead to $D_\parallel$ and $D_\perp$.

At very low flow rates, molecular diffusion dominates and:

$$D_\parallel = D_\perp = D_m / \alpha \tag{2}$$

$D_m$ is the molecular diffusion; $\alpha (\alpha > 1)$ is the tortuosity of the medium and can be determined independently from conductivity measurements; it characterizes the amount of time necessary for the particles to diffuse into the tortuous branches of the medium.

At higher flow rates, hydrodynamic dispersion $2,3$ appears due to velocity gradients inside individual pores or channels (these are particularly strong in very small channels); the...
The corresponding contribution to the dispersion coefficient varies as $U^2$.

Geometrical dispersion is often dominant in porous media at large enough flow rates: it is associated with the complex trajectory of individual particles in the geometrically disordered material; it gives a contribution to $D_{\parallel}$ proportional to $U$.

Tracer dispersion may also be influenced by hydrodynamic effects; these may be due to boundary layers, stagnation points, dead zones whose effect on the dispersion is discussed theoretically in the chapters by Koch and Brady and by Koplik. The effect of recirculation regions is also discussed by Pumir and Shraiman in this book. Preliminary measurements on glass tubes partly filled with spheres or on parallel plates with notches of square cross-sections have given dispersion constant variations close to $U^{3/2}$ of the type expected for the influence of recirculation zones.

In the insert below, we give a list of theoretical predictions for the contributions of various dispersion mechanisms associated with the complex interplay between molecular diffusion and convective mixing. $Pe$ is the Peclet number of the flow and $l_c$ is a characteristic microscopic length for the medium at the pore scale. In most experiments on 3D systems, we reach (at sufficiently high velocities) flow regimes where $D_{\parallel}$ is, at least even roughly proportional to $Pe$. This allows us to define a typical dispersion length $l_d$ through:

$$D_{\parallel} = U l_d$$  \hspace{1cm} (3)

For a Gaussian dispersion, this "dispersivity" $l_d$ is equal to the Lagrangian correlation length of the velocity field.

<table>
<thead>
<tr>
<th>MOLECULAR DIFFUSION</th>
<th>Significant only at very low flow rates</th>
<th>$D_{\parallel} = \frac{D_m}{\alpha}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOMETRICAL DISPERSION</td>
<td>Associated with random flow velocity variations from one pore to another. Dominant at larger flow rates</td>
<td>$D_{\parallel} = U l_d$</td>
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<tr>
<td>(Bear -Saffman)</td>
<td></td>
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<tr>
<td>TAYLOR DISPERSION</td>
<td>Associated with velocity gradients inside an individual flow channel. Significant in long capillaries or at low flow velocities in porous media</td>
<td>$D_{\parallel} \approx \frac{U^2 a^2}{D_m}$</td>
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<tr>
<td>(hydrodynamic dispersion)</td>
<td></td>
<td>$a = \text{channel size}$</td>
</tr>
<tr>
<td>DEAD ENDS &amp; STAGNANT ZONES</td>
<td>Valid for finite volume stagnant zones exchanging tracer only through molecular diffusion</td>
<td>$D_{\parallel} \approx \frac{U^2 \xi^2}{D_m}$</td>
</tr>
<tr>
<td>BOUNDARY LAYERS</td>
<td>Valid for low velocity zones when the velocity is exactly 0 only in an infinitely small fraction of the pore volume</td>
<td>$D_{\parallel} \propto Pe \log Pe$</td>
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<tr>
<td>STAGNATION POINTS NEAR A SOLID WALL</td>
<td></td>
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<tr>
<td>EQUIPOTENTIAL CHANNELS</td>
<td>Exchange between recirculation zones and main flow may be accelerated by the recirculation flow. Still an open research topic</td>
<td>$D_{\parallel} \propto P_e^\alpha$</td>
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<td></td>
<td></td>
<td>$1 &lt; \alpha \leq 2$</td>
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</tbody>
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2. Anomalous dispersion and finite size effects

Eq. (1) describes a "normal" or "Gaussian" dispersion. It is only valid if the dispersion...