PGSE NMR Measurement of Hydrodynamic Dispersion: Nonequilibrium statistical mechanics, structure and permeability

Joseph D. Seymour[a], *Sarah L. Codd*[b] *Tyler R. Brosten*[c] *and Robert S. Maier*[c]

[a]Department of Chemical & Biological Engineering, Montana State University, Bozeman MT
[b]Department of Mechanical & Industrial Engineering, Montana State University, Bozeman MT
[c]Engineer Research & Development Center, U.S. Department of Defense, Vicksburg MS

The measurement of time scale dependent hydrodynamic dispersion provides a direct test of non-equilibrium statistical mechanics models of porous media transport. The connection between structure and dispersion for porous media from consolidated granular systems to high porosity foams is demonstrated using displacement time scale dependent measurement of dispersion by pulsed gradient spin echo (PGSE) nuclear magnetic resonance (NMR). The generalized short-time expansion of hydrodynamic dispersion is derived in accordance with well-known cases of shear flow in ducts and pipes. For viscous flow in porous media, the expansion facilitates measurement of permeability by PGSE-NMR measurement of time dependent molecular displacement dynamics. Porous media characterized by a homogeneous permeability coefficient K, fluid volume fraction ϕ. and negligible surface relaxivity, the effective dispersion coefficient $D(t) = \langle|\mathbf{R}|^2\rangle/6t$ of molecular displacements due to flow and diffusion $\mathbf{R}$ for a saturating fluid of molecular diffusivity D_m in viscous dominated (low Re) flow is shown to be:

$$D(t) = D_o(t) + \frac{1}{6}\langle \mathbf{u}' \cdot \mathbf{u}' \rangle t - \frac{\langle \mathbf{u} \rangle \cdot \langle \mathbf{u} \rangle}{18} D_m \phi K^{-1} t^2 + O\left(t^{5/2}\right)$$

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Here $\mathbf{u}'$ is the fluctuating advective velocity $\mathbf{u}' = \mathbf{u} - \langle \mathbf{u} \rangle$, and $D_o(t)$ is the time dependent diffusion coefficient in the absence of advection. The short-time expansion agrees with PGSE NMR measurement of $D(t)$ in a sphere pack and random-walk particle tracking transport simulation data using lattice Boltzmann methods.