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Resolving the Impact of Biological Processes on Water Transport in Unsaturated Porous Media Through Nuclear Magnetic Resonance Micro-Imaging

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Results To Date

The magnetic resonance microscopy (MRM) work at Montana State University has extended the imaging of a single biofilm in a 1 mm capillary reactor to correlate T2 magnetic relaxation maps displaying biofilm structure with the corresponding velocity patterns in three dimensions in a Staphylococcus epidermidis biofilm fouled square capillary. A square duct geometry is chosen to provide correlation with existing experiments and simulations, as research bioreactors tend to be of square or rectangular cross section for optical or microelectrode access. The spatially resolved velocity data provide details on the impact of biofilm induced advection on mass transport from the bulk fluid to the biofilm and through the capillary bioreactor. These issues are of significant importance in biosensor and bioseparations applications based on microfluidics or “lab on a chip” technology, as well as a model for a flow in fractured geological media. Extension of the published work referenced in the 2003 annual report work has applied concepts from the theory of fluid mixing to quantify the secondary flows induced by the spatially heterogeneous biofilm. The secondary flows are measured to be 20% of the axial velocity and indicate a significant alteration of transport from the bulk fluid to the biomass from diffusive to convective dominated. A paper has been submitted to Biotechnology and Bioengineering (manuscript # 04-454, submitted August 4, 2004) detailing the new experimental results and analysis. The impact of microbial activity, particularly surface attached biofilms, on the transport of fluids in porous systems is relevant to fields as seemingly diverse as geophysics and medicine. Few direct experimental data on the impact of bioactivity on transport dynamics in three-dimensional media are available due to sample opacity. Non-invasive magnetic resonance microscopy (MRM) directly measures length and time scale dependent dynamics in porous media. Our research demonstrates by direct measurement of the propagator, i.e. the displacement conditional probability or van Hove scattering function, the transition from normal to anomalous hydrodynamic dispersion as a function of bioactivity. The microbial activity transforms the porous media from a homogeneous to heterogeneous structure, increasing system complexity as defined in terms of dynamics. Continuous time random walk (CTRW) based fractional advection-diffusion equation (ADE) models which generate anomalous or fractional dynamics are compared to the measured dynamics in both the propagator displacement space and the Fourier reciprocal displacement wavelength space. The data provide insight into the application and development of fractional calculus based models and indicates their direct applicability to biofilm impacted porous media transport. A manuscript has been submitted to Physical Review Letters (manuscript # LV9588, submitted August 27, 2004) reporting these results. Extension to unsaturated porous media is underway.

Deliverables

Papers Submitted J.D. Seymour, J.P. Gage, Sarah L. Codd and R. Gerlach, "Biofilm growth induced normal to anomalous transport transition in porous media." Submitted to Physical Review Letters, August 27, 2004.

E.L. Gjersing, S.L. Codd, J.D. Seymour and P.S. Stewart, "Magnetic resonance microscopy analysis of advective transport in a biofilm reactor." Submitted to Biotechnology and Bioengineering, August 4, 2004.

Invited Seminars by J.D. Seymour "NMR microscopy of the structure and dynamics of microbial biofilms in bioreactors and porous media," EUCHEM Conference on Structure and Mobility in Heterogeneous Systems, Fiskebackskil (Goteborg), Sweden, August 27-29, 2003.

"Magnetic resonance microscopy of scale dependent transport phenomena: porous media, biofilms and microfluidics," Graduate Seminar, Department of Chemical and Petroleum Engineering, University of Kansas, Lawrence, Kansas. April 28, 2004.

"Magnetic resonance microscopy of scale dependent transport phenomena in bioreactors and polymer electrolyte membranes," 1st International Symposium on Micro & Nano-Scale Sensing Techniques for Energy and Bio System. Keio University, Yokohama, Japan, September 14, 2004.

Meeting Presentations J.P. Gage, J.D. Seymour, S.L. Codd and R. Gerlach, "Biofilm Growth Induced Transformation of Porous Media Dynamics", Inland Northwest Research Alliance Environmental & Subsurface Science Symposium, Spokane, Washington, Sept. 20-22, 2004.