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The role of temporal and spatial fluctuations for scalar transport at the interface between a free turbulent flow and a porous medium

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Exchange processes at the interface between a porous medium and a turbulent flow field are relevant in a wide range of natural and industrial systems: Prominent examples for technical applications range from food drying up to processes within fuel cells. In the environment, the exchange of mass within the hyporheic zone is vital for the health of aquatic ecosystems, whereas the evaporation from soils must be considered for sustainable land use. Despite the apparent heterogeneity of these fields, scalar transport across the interface is driven by a common set of mechanisms, which can be distinguished in the double-averaging framework (e.g. [1,2,3]): Whereas transport due to molecular diffusion requires gradients in the scalar concentration field, turbulent scalar transport results from correlated fluctuations of the flow and scalar field *in time*. In contrast, dispersive scalar transport is caused by correlated fluctuations of the mean flow and scalar field *in space*.

The objective of our research is to contribute to a more comprehensive mechanistic understanding of scalar transport in the interface region. We (i) identify the regions of influence of individual scalar transport processes and (ii) analyze the interaction between the fundamentally different processes within the double-averaging framework.

For the numerical investigation with our in-house code MGLET [4,5], the porous medium is represented by a static random pack of spheres with uniform diameter. While the advection-diffusion equation is solved for a passive scalar with a Schmidt number of $Sc = 1$, the flow field is obtained from solving the incompressible Navier-Stokes equations. By means of a single-domain Direct Numerical Simulation (DNS), all temporal and spatial scales are resolved both in the free flow region and in the pore space of the porous medium, which avoids any model assumptions. For a representative case, the flow field is validated against experimental data [6]. In total, we consider eight different simulation cases with shear Reynolds numbers in the range of $Re_\tau = 150$–500 and permeability Reynolds numbers of $Re_K = 0.4$–2.5.

Instantaneous fields (please, find figure attached) provide an intuitive impression of the processes, which is supported and quantified by the double-averaged statistics of the results: Whereas turbulent scalar transport dominates in the free flow region, dispersive scalar transport takes the leading role in the topmost sediment layers below the interface, before molecular diffusion becomes most relevant in deeper regions. The results confirm that the relative importance of different processes is determined by Re_K [7]. Observing that turbulent and dispersive scalar transport hardly co-exist in any regions, we evaluate budget equations for temporal and spatial fluctuations in the scalar concentration field to explain the interaction between the two processes.

The obtained insight is meaningful for the development of hyporheic scalar transport models, as the described interaction prohibits addressing the problem as a mere superposition of two transport processes. Also, ecological implications can be derived, as the presence or absence of strong spatial mean concentration gradients influences the biocenosis in a habitat.

Participation

In-Person

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