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Pore-Scale Study of the Non-Linear Mixing of Fluids with Viscous Fingering in Anisotropic Porous Media

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Abstract. Mixing processes of miscible viscous fluids in anisotropic porous media are studied through a lattice Boltzmann method in this paper. The results show that fluid mixing can be enhanced by the disorder and interfaces induced by viscous fingers. Meanwhile, the permeability anisotropy affects the developments of viscous fingers and the subsequent mixing behaviors significantly. Specifically, as the streamwise (longitudinal) permeability is larger than the spanwise (transverse) one, the mixing process is faster and stronger than that in the contrary case. Furthermore, the anisotropy can lead to different behaviors of the dissipation rates in streamwise and spanwise directions. Generally, the dissipation rate is dominated by the transverse concentration gradients when the longitudinal permeability is higher than the transverse one; on the contrary, as the transverse permeability is higher than the longitudinal one, the contributions to the dissipation rate from longitudinal and transverse concentration gradients are both significant.

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Key words: Mixing, pore-scale, anisotropy media, scalar dissipation rate, lattice Boltzmann method.

1 Introduction

Understanding mixing processes in porous media is of great importance to a number of practical applications, such as oil and gas recovery, carbon-dioxide sequestration, micro electro-mechanical systems, and fuel cells. Previous studies [1–6] indicate that two competing mechanisms, i.e., velocity fluctuations and local diffusion, influence the mixing behavior in porous media significantly. On the one hand, velocity fluctuations create opportunities for mixing by generating disorder and large interfaces between fluids. On the

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other hand, local diffusion smoothes out the disorder and turns these opportunities into effective mixing.

It is well understood that hydrodynamic instabilities caused by large disparities of physical properties of the fluids can strongly influence the velocity field, and therefore such instabilities will affect the mixing of fluids inevitably. Viscosity fingering, which is generated when a more viscous fluid is displaced by a less viscous miscible fluid, has also received particular attentions as a typical instability. Particularly, viscous fingering phenomenon of miscible fluids in porous media have been investigated experimentally and numerically in the past decades. For instance, Zimmerman and Homsy [7, 8] studied the effects of viscosity contrast and dispersion on viscous fingering in homogeneous problems, Ben-Jacob *et al*. [9, 10] reported an experimental study on the effects of the anisotropy of porous media, and a number of studies on the viscous fingering process in different heterogeneous porous media [11–13].

Although there exists a considerable amount of work on miscible mixing [1–6] and viscous fingering [7–13], these two physical phenomena were studied independently in most of the previous studies, and very few studies have been done to investigate the interaction between viscous fingering and fluid mixing. To our best knowledge, the recent works by Jha *et al*. [14, 15] provided the first quantitative studies of the relationship between the two physical processes. They showed that the miscible viscous fingering can act as an agent to enhance mixing, and developed a mathematical model to predict the behavior of the scalar dissipation rate at the late stage of the mixing process. However, their works are limited to viscous fingering and mixing in isotropic porous media. In anisotropic porous media, since flow paths in different directions can have considerable different properties, viscous fingering and mixing processes and their interactions may be quite different from those in an isotropic medium. It should also be noted that all of the previous studies on miscible viscous fingering and mixing in porous media are based on the representative elementary volume (REV) scale, where a number of assumptions have been employed in the employed theory and/or models containing some empirical or semi-empirical correlations.

In order to fill these gaps, in this paper we will provide a pore-scale study of the interactions between viscous fingering and mixing in anisotropic porous media numerically, focusing on the effects of permeability anisotropy on mixing of miscible fluids. The numerical method employed is a lattice Boltzmann method (LBM) which is designed based on kinetic theory. The method has the advantages in simulating pore-scale fluid flows due to its particle nature. We also noted that a variety of pore-scale simulations of flow in porous media using LBM have been reported in the past two decades [16–20]. Particularly, LBM has been employed in the study of viscous fingering phenomenon of immiscible fluids at the pore scale, with emphasis on the effects of capillary force, viscosity ratio, and surface wettability [21–26], but pore-scale LBM studies of viscous fingering phenomena of miscible fluids in porous media are quite rare.

The rest of this paper is organized as follows. In Section 2, the pore-scale governing equations and the LBM as well as a numerical validation are presented, and numerical