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Fast Prediction of Immiscible Two-Phase Displacements in Heterogeneous Porous Media with Convolutional Neural Network

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Abstract. A convolutional neural network is developed for rapidly predicting multiphase flow in heterogeneous porous media. Some direct numerical methods can acquire accurate results of multiphase flow in porous media. However, once the geometry of the porous media changes, it takes much computational time to perform a new simulation. Here, a deep neural network model in the field of semantic segmentation is developed. It takes the two-dimensional microstructure of heterogeneous porous media as inputs and is able to predict corresponding multiphase flow fields (pressure and saturation fields). Compared to the direct lattice Boltzmann simulations, the inference time on new geometry of porous media can be reduced by several orders of magnitude. Our results show that the machine learning method is a good prediction tool in a wide range of porosity and heterogeneity. Besides, to better understand the inherent process, a visible explanation is presented on what our neural networks have learned.

AMS subject classifications: 76S05, 76T99, 68T99

Key words: Porous media, multiphase flow, convolutional neural network, porosity, sorting.

1 Introduction

Multiphase flow in porous media widely exists in industrial applications such as geological carbon capture and storage, oil recovery and treatment of contaminated groundwater and soil, etc [1–4]. Studying and understanding the process of immiscible displacements in porous media are important. Due to different underlying heterogeneous pore geometry, wettability, fluid properties and flow conditions, there are several typical displacements patterns such as capillary fingering, viscous fingering and stable displacement [5]. In different pattern, there are different features on the saturation, the finger length, and

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the size of the trapped clusters. For the capillary fingering, the invading fingers grow in all directions and the defending fluid may be trapped by the invading fluid. For the viscous fingering, the fingers grow like a tree and no defending fluid would be trapped. For stable displacement, the invading front is almost flat and moving forward stably.

Early works on multiphase flow in porous media are mostly experimental works and numerical simulations. The experimental studies focused on internal fluid distribution inside realistic rocks. With the help of advanced computer-aided imaging system (such as X-ray computed microtomography) [6–8], the pore-scale two-phase displacement in real sample porous rock can be obtained in real-time. Holtzman et al. [9] defined the disorder coefficient λ to represent the heterogeneity of synthetic porous media. They investigated the impact of λ on two-phase displacements by experiments. In the study of Hu et al. [10], the competing effect of disorder and wettability on the fluid displacements in porous media was investigated through microfluidic experiments and pore-scale simulations.

Numerical simulations methods, e.g., the lattice Boltzmann method (LBM) can achieve detailed flow fields (e.g., pressure, velocity and saturation field) in porous media [11–15]. These studies mainly paid attention to impacts of flow conditions and fluid properties on immiscible displacements. Few studies focused on the effects of the pore-scale disorder of porous media. Although the LBM results are accurate, the LBM simulations are computationally intensive. Once the porous medium changes, it would take much time to carry out a new simulation.

Among these years, deep learning methods [16] have been proposed as a new solution to classic physics problems [17, 18]. Their prediction accuracy, generalization ability, and especially computational efficiency are very impressive compared with experimental methods and numerical simulations. Wu et al. [19] proposed a convolutional neural network embedded with physics information to predict the permeability from the images of porous media. Since permeability is indeed a function of the pore geometry, using neural networks to learn the implicit mapping from the pore geometry to permeability is successful. The usage of a convolutional encoder-decoder network for image-to-image regression task has been explored by Zhu et al. [20]. Taking the log-permeability field of porous media as inputs, the model is able to give an approximation on the single-phase flow in heterogeneous porous media. The spatial information was taken into account since its inputs and outputs are two-dimensional sliced tensors in a real physical scene. Mo et al. [21] extended the above neural network to predict the two-phase flow in heterogeneous porous media. In his work, in addition to the original regression task for the pressure fields, there is another pixel-wise classification task for the saturation fields. Moreover, Jin et al. [22] proposed variational U-net network to predict the CO_2 saturation and pressure fields under the variation of random well locations in porous media. Similarly, Wang et al. [23] constructed a network to approximate the mapping from the permeability fields to the velocity fields. Zhu et al. [24] embedded the governing equations into the loss function, and trained the neural network without labelled data to get the pressure and flux fields in a random field. It is more efficient and physical. Actually, not only deep neural networks methodology, but also fully Bayesian surrogate model