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Fourier-MIONet: Fourier-enhanced multiple-input neural operators for multiphase modeling of geological carbon sequestration

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Geologic Carbon Storage (GCS) is an important technology that aims to reduce the amount of carbon dioxide in the atmosphere. Multiphase flow in porous media is essential to understand CO2 migration and pressure fields in the subsurface associated with GCS. However, numerical simulation for such problems in 4D is computationally challenging and expensive, due to the multiphysics and multiscale nature of the highly nonlinear governing partial differential equations (PDEs). It prevents us from considering multiple subsurface scenarios and conducting real-time optimization. Here, we develop a Fourier-enhanced multiple-input neural operator (Fourier-MIONet) to learn the solution operator of the problem of multiphase flow in porous media. Fourier-MIONet utilizes the recently developed framework of the multiple-input deep neural operators (MIONet) and incorporates the Fourier neural operator (FNO) in the network architecture. Once Fourier-MIONet is trained, it can predict the evolution of saturation and pressure of the multiphase flow under various reservoir conditions, such as permeability and porosity heterogeneity, anisotropy, injection configurations, and multiphase flow properties. Compared to the enhanced FNO (U-FNO), the proposed Fourier-MIONet has 90% fewer unknown parameters, and it can be trained in significantly less time (about 3.5 times faster) with much lower CPU memory (< 15%) and GPU memory (< 35%) requirements, to achieve similar prediction accuracy. In addition to the lower computational cost, Fourier-MIONet can be trained with only 6 snapshots of time to predict the PDE solutions for 30 years. The excellent generalizability of Fourier-MIONet is enabled by its adherence to the physical principle that the solution to a PDE is continuous over time. Moreover, the developed Fourier-MIONet makes it possible to solve the long-time evolution of geological carbon sequestration in a large-scale three-dimensional space accurately and efficiently.