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Scaled-cPIKANs for Porous Media Flows: Chebyshev-based Physics-informed Kolmogorov-Arnold Networks

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Fluid flow and transport phenomena in heterogeneous porous media have diverse applications in science and engineering fields. These processes are dominated by steep gradients, non-linear interactions, and multi-scale phenomena, rendering the governing equations, aka PDEs, exceedingly complex and computationally demanding to solve. Although decades of research have led to several breakthroughs in numerical techniques, there remains a substantial demand for faster and more scalable methods to solve these complex PDEs. This field of research has intensified significantly with the advent of PDE-solvers driven by neural networks. In particular, advances like Physics-Informed Neural Networks (PINNs) have transformed this domain by introducing mesh-free frameworks that inherently embed multi-scale physical laws into their architecture. This capability is very significant for multi-scale transport phenomena with complicated boundary conditions, as there is no need to use conventional grids, hence paving a pathway to scalability with efficient solutions.

Building on this foundation, this work introduces Scaled-cPIKAN, a novel physics-informed neural network architecture that combines Chebyshev polynomial-based representations with domain scaling techniques. Scaled-cPIKAN integrates the mathematical flexibility of Kolmogorov–Arnold Networks (KANs) with the physics-informed concepts of PINNs, and utilizes Chebyshev polynomials as basis functions to accurately capture high-frequency fluctuations and fine-scale flow features. By scaling the governing PDEs and normalizing the input data, Scaled-cPIKAN enhances the network's ability to model complex dynamics in extended spatial domains, reducing computational overhead and improving accuracy. Key features include efficient handling of sharp gradients, oscillatory behaviors, and the ability to solve problems in large domains without requiring dense collocation points and or deep architectural frameworks (e.g., layers and nodes). To highlight these features, we apply the proposed Scaled-cPIKANs model to solve the advection-diffusion and reaction-diffusion problems. Our results show that, unlike vanilla PINNs and KANs that suffer from oscillations and degradation in accuracy over large domains, the Scaled-cPIKAN approach provides robust convergence rates with high accuracy without excessive computation and data burdens. These improvements stem from the synergistic effect of domain scaling and adaptive Chebyshev polynomial representation, which improve the expressiveness and convergence properties of the network. Thus, Scaled-cPIKAN proves to be an effective model for solving real-world multi-scale transport phenomena in porous media that require significant computational efficiency and accuracy.

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References

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