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OUTLINE of Thesis: "Numerical Study of Viscous Dissipation in Immiscible Two-Phase Flow through Porous Media"

Viscous dissipation of immiscible two-phase flow in porous Media refers to the loss of mechanical energy due to the viscous forces acting within the fluid phases and at their interfaces as they flow through a porous medium. This phenomenon is significant in various fields such as carbon dioxide capture, utilization and storage (CCUS), petroleum engineering, hydrology, and environmental science. Understanding viscous dissipation in two-phase flow is critical for optimizing energy use and improving the efficiency of processes in porous media. The thesis consists of five chapters to study the viscous dissipation in immiscible two-phase flow through porous media.

Chapter one discusses the significance of studying two-phase flow in porous media for the application in industries, such as CCUS. A widely used fundamental principle two-phase Darcy's law, which describes the flow of a fluid through a porous medium, and its application conditions are introduced. Relative permeability, a dimensionless measure of the effective permeability of each phase in two-phase Darcy's law, and its connection with viscous dissipation is discussed. Pore-scale events (PSEs) (Haines jumps, meniscus reconfiguration, and meniscus merging), which are commonly observed in immiscible two-phase flow through porous media, are also introduced here. The study of connection between viscous dissipation, relative permeability and PSEs extremely constitutes the great significance of this thesis.

Chapter two introduces the simulation scheme of this study. Firstly, to investigate the viscous dissipation rate, this study derived the governing equation for the conservation of mechanical energy and performed direct numerical simulations (DNS) using a weakly compressible scheme that helps to perform parallel computing in high performance GPU. Secondly, by combining the FAVOR method, cell merging method and immersed boundary method, our simulate scheme can incorporate information about the complex boundary object's shape of porous media into calculation. Finally, different from previous research, we evaluated the surface-energy change of the system by using a density-scale continuum surface force (CSF) model. Because this model is solved using the momentum equation and is associated with the time derivative, an accurate instantaneous surface-energy change can be obtained. For two-phase displacement in a circular capillary tube, the simulation results showed that the surface-energy change rate calculated using the density-scale CSF model conforms with the theoretical results. This model was established based on the Young–Laplace equation and applied using the phase-field method. Therefore, the results demonstrate that the phase-field method can accurately track the evolution of the interface and evaluate the surface-energy change rate in porous media. Based on this scheme, the origin of viscous dissipation from mechanical energy (external force, surface energy or kinetic energy) can be analyzed.

Chapter three presents the viscous dissipation rate of PSEs with a very low capillary number (10^{-6}) condition. We discuss the time scale and the growth multiple of the dissipation rate during PSEs. To study those characterization of different PSEs, we designed three cases: case (I), where a Haines jump and meniscus reconfiguration occur individually, case (II), in which both Haines jump and meniscus reconfiguration occur simultaneously, and case (III), meniscus merging occurs. The shorter duration of PSEs, the greater its energy loss. Case (III) has shortest duration and maximum viscous dissipation rate. The simulation results show that maximum viscous dissipation rate during the PSEs can increase by 600 times. The simulation results show that PSEs clearly increase the viscous dissipation rate in the system, leading to significant energy waste in immiscible two-phase flow.

In chapter four, the study uses direct numerical simulations to investigate viscous dissipation of two-phase flow in a heterogeneous 2D micromodel across a range of capillary numbers (Ca) and viscous ratios (M), including both favorable (logM > 0) and unfavorable (logM < 0) displacement scenarios. These simulations can incorporate the characteristics of the three typical two-phase displacement patterns: stable displacement, capillary and viscous fingering. The PSE impact on transport in porous media is quantified by mechanical energy, especially viscous dissipation. The results showed that PSEs markedly reduced two-phase flow mobility in porous media at low Ca, while this effect decreased with increasing Ca and disappeared at near high Ca. Meniscus merging considerably increased the viscous dissipation rate in the system at low, medium, and high Ca values, but it exhibited a markedly lower frequency than Haines jump and meniscus reconfiguration. In favorable condition, the impact of Haines jump and meniscus reconfiguration on system viscous dissipation rate disappeared at medium Ca, whereas in unfavorable condition, it disappeared until high Ca. This resulted from the strengthened interfacial effect caused by the liquid film generated in the front of the viscous fingering.

In chapter five, the main conclusions of each chapter are summarized. The connection between viscous dissipation, relative permeability and PSEs are revealed. The application of the findings in this thesis are also provided for reference.