

Experimental Investigation of the Miscible Process and Mechanism of Crude Oil-CO₂-Brine System Under High Temperature and Pressure

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The phase behavior of geological fluids in deep and ultra-deep hydrocarbon-bearing basins crucially impacts the interaction dynamics of complex fluids, fluid-rock contact relationships, and fluid-rock interactions, influencing hydrocarbon reservoir development and quality. Presently, there is a paucity of research directly investigating the miscibility processes and mechanisms of crude oil, CO₂, and brine under high-temperature and high-pressure conditions analogous to actual burial environments. This scarcity of studies has impeded our comprehension of the storage states of deep and ultra-deep hydrocarbons, as well as the interactions between fluids and rock formations. This study employs an in situ visual thermal simulation system and molecular dynamics numerical simulations to systematically investigate the miscibility of various crude oils-CO₂-brine systems under conditions ranging from 25°C to 480°C and 5 MPa to 106 MPa. The research delves into the miscibility processes and mechanisms of the crude oil-CO₂-brine three-phase system across a broad spectrum of temperature and pressure conditions, from low-temperature low-pressure to high-temperature high-pressure regimes. The results indicate that, by integrating physical and numerical simulations, the miscibility process between crude oil, CO₂, and brine can be classified into eight distinct stages. These stages result from the combined effects of intermolecular interaction energies and hydrogen bonding variations within the system. The miscibility behavior of different crude oil-CO₂-brine systems is influenced by a complex interplay of factors. Specifically, in systems where the crude oil properties and brine salinity are held constant, an increase in CO₂ concentration raises the temperature and pressure required for complete miscibility between crude oil and CO₂, while lowering the temperature and pressure thresholds for three-phase miscibility with brine. In systems with identical CO₂ concentrations and brine salinity, light crude oil exhibits complete miscibility with CO₂ and brine at lower temperatures and pressures compared to medium crude oil. These findings are pivotal for understanding phase behaviors and microscopic miscibility mechanisms of geological fluids from shallow low-temperature low-pressure (LTLP) systems to ultra-deep high-temperature high-pressure (HTHP) systems.