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Countercurrent imbibition in shale with parallel dense fractures: analytical model and anisotropic relative permeability

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Countercurrent imbibition is the process that the wetting phase spontaneously displace the nonwetting phase in porous media while the nonwetting phase is recovered at the wetting phase inlet[1]. It is a major mechanism of shale oil recovery, where the permeability is so low that co-current imbibition is largely limited[2, 3]. For fractured media, classic dual-porosity model is based on good fracture connectivity and assumes that fractures are evenly distributed into each grid[4, 5]. Although the heterogeneity and anisotropy of porous media are considered in some dual-porosity models, they mainly assume topologically connected fracture network [6, 7].

However, in continental shale reservoir, the distribution and morphology of fractures are very unique. As shown in Fig. 1a , continental shale consists of very densely-packed parallel microfractures. On one fold, fractures are not directly connected, that breaks the assumption of continuous fracture phase in dual-porosity models; on the other fold, the distance between neighboring microfractures are extremely small (100-500 micrometers)[8], so they are hydrodynamically highly correlated by coupling and not independent. Unfortunately, there is still no suitable REV (representative elementary volume) scale model to describe imbibition in such parallel dense fracture system.

In this study, we first numerically simulate the countercurrent imbibition in a dual- unidirectional microfracture system using MRST with fine grids, using typical continental shale parameters. Two distinct stages are identified: an early stage that fractures can be treated as independent, and a late stage that neighboring fractures are strongly correlated by capillarity. In both stages cumulative oil production grows proportional to the t^0.5(shown in Fig. 1), while with different pre-factors. We show that the late stage is the dominant stage in shale oil recovery. After elucidating the mechanisms of fracture-fracture capillary interaction, we successfully derive analytical solution for countercurrent imbibition kinetics at the late stage, and accordingly propose equivalent REV models for both systems. The REV model is validated with fine-grid simulation.

Notably, we find that anisotropic relative permeability is required to depict imbibition in such parallel dense microfracture system at REV scale. This is distinctive from classic approaches for modeling anisotropic media where simply adopting anisotropic absolute permeability is adequate. It brings new challenge in numerical simulation at reservoir scale.

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