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Analytical Investigation of the Stability and Universal Scaling of the Transition from Spontaneous to Forced Imbibition in Porous Media

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Spontaneous imbibition is an important recovery mechanism in naturally fractured reservoirs as capillary forces control the movement of fluid between matrix and fracture. Imbibition is also important in unconventional reservoirs as the capillary pressure will increase when permeability decreases, impacting fracture fluid imbibition during the fracturing process but also during the soaking period before the initiation of production. However, the classic self-similar solution to spontaneous imbibition is limited in representing physical boundary conditions, as during most physical multiphase flow conditions flow occurs with contributions from both capillary and viscous forces. In this research, we present a theoretical semi-analytic approach to analyze the transient imbibition process where both capillary and viscous forces exist, and compare it with the self-similar solution. Unlike previous analyses that assume purely counter-current or co-current flow, this research proves that for a more general situation, strict self-similarity no longer exists, although a new universal relationship of imbibition rate versus time is obtained.
The transient imbibition boundary conditions we examine are easily achievable in the laboratory and are also comparable to those that will exist in a reservoir. We consider a model where the wetting phase is maintained in contact with the inlet, and hydrocarbon production is allowed on both ends. The hydrocarbon phase is produced from the outlet at a constant imposed rate. Initially, counter-current spontaneous imbibition caused by capillarity at the inlet dominates. As the flood front propagates, co-current flow gradually increases in importance as does the viscous force. The imbibition rate at the inlet will drop to be equal to a prescribed injection flow rate, after which the forced imbibition state is reached and viscous pressure drop totally controls the flow. Traditional Buckley-Leverett theory can then be applied to analyze the subsequent forced imbibition process.
The analytic solution for the transient imbibition process utilizes a fractional flow concept. In the current study, the fractional flow changes with time, as does the ratio of co-current and counter-current fluxes. It will be shown that not all choices of boundary conditions are stable, but that the wetting phase imbibition rate must increase at early time beyond any imposed injection rate to reach a limit of stability. The result of the analysis includes a dimensionless parameter that describes the relative magnitude of capillary and viscous forces at the continuum scale. A universal scaling envelope exists for the limit of stability which may be expressed in terms of this parameter and the dimensionless ratio of imposed fluxes at both ends of the system. Above the envelope, the flow is unstable as capillary pressure will cause the imbibition rate to increase and the dimensionless ratio to decrease. Any point below the envelope is stable and is subject to forced imbibition. The boundary of the envelope is the limit of stability, which describes the overall mechanism of transient imbibition and the relative magnitude of capillary and viscous forces at the continuum scale. This stability limit is different from the result obtained by the assumption of a self-similar solution.

References

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