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OPINION
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Numerical Simulation of Ultra-Low Permeability Reservoirs: Progress and Challenges

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INTRODUCTION

Over the last two decades, unconventional natural gas resources from tight sandstone and shale reservoirs have garnered substantial interest and have become a focal point for the oil industry and global energy supplies. This is due to their substantial reserves and technological advancements in producing unconventional resources. In comparison to conventional reservoirs, gas production from ultra-low permeability unconventional reservoirs is driven by highly nonlinear flow equations and involves a complex web of coexisting processes as a result of the presence of multi-scale fracture networks and the heterogeneity of porous/fractured and stress-sensitive rocks. As a result, measuring flow in unconventional gas reservoirs continues to be a significant difficulty.

This paper discusses mathematical numerical simulation methodologies for developing ultra-low permeability reservoirs in order to ascertain the capacity of ultra-low permeability reservoirs and the essential parameters affecting development yield. Additionally, the author discusses developments and issues in the simulation of ultra-low-permeability reservoirs and seepage theory. Finally, the merits and cons of evaluating ultra-low permeability reservoirs using physical properties and mathematical simulations are discussed. The study reported in this article is expected to advance the development of ultra-low permeability reservoirs in the future.

RESERVOIR NUMERICAL SIMULATION

Reservoir Numerical simulation is an important technical tool and a basic tool for reservoir management such as oil field development programs, adjustment programming, and dynamic forecasting. In a sense, reservoir numerical simulation is one of the important tools for modern reservoir development (Rao et al., 2021b; Xu et al., 2021; Rao et al., 2022). In recent years, due to the rapid development of computers, reservoir numerical simulation technology has made great progress, especially in terms of calculation methods, program design, and image processing of calculation results. Numerous scholars have enhanced the current conventional reservoir numerical simulation techniques to investigate the nonlinear flow characteristics of fluids in ultra-low permeability reservoirs (Rao et al., 2021a; Zhou et al., 2021). Currently, fluid flow in ultra-low permeability porous media is a nonlinear flow with a minimum starting pressure gradient. Therefore, the classical Darcy's law cannot perfectly represent the flow law in low-permeability reservoirs. The numerical simulation software based on Darcy's flow model has limitations in the application to ultra-low-permeability reservoirs (Sheng et al., 2020). Although the variable permeability numerical simulation method can accurately describe the nonlinear flow law of ultra-low permeability porous media. It cannot yet reflect the continuity and smoothness of the equation of state. This numerical simulation method is still in the research stage (Xu et al., 2022).

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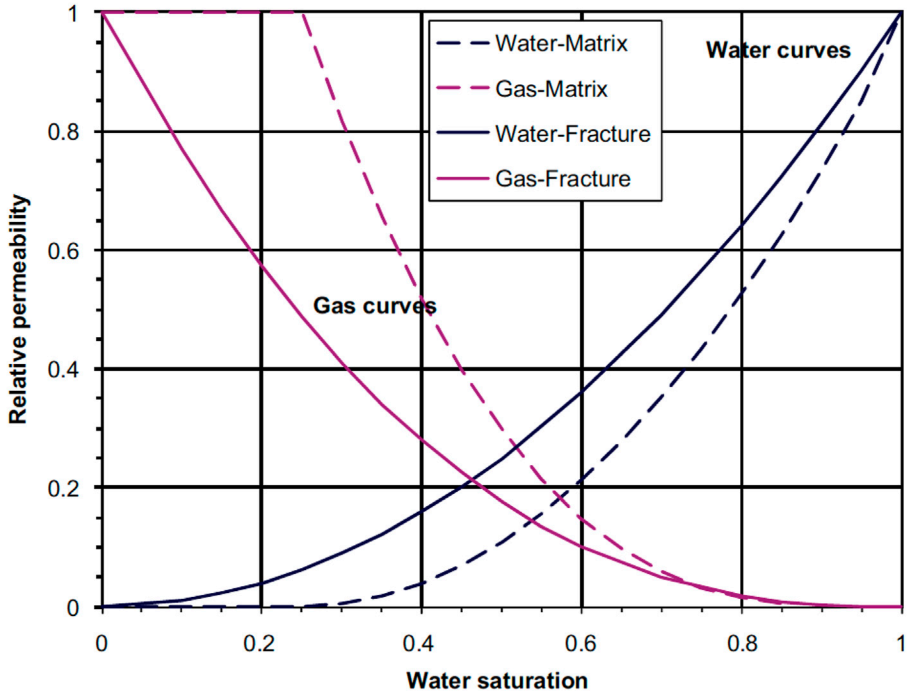

FIGURE 1 | Two sets of relative permeability curves for matrix and fracture systems (Cheng, 2012).

CHALLENGES OF ULTRA-LOW PERMEABILITY RESERVOIRS

Considering ultra-low permeability reservoirs are unconventional (**Figure 1**), many of the procedures developed for conventional reservoirs must be adapted but are not strictly relevant, and new ways are being sought to improve them (Ding et al., 2014). These include, but are not limited to, transient capillary equilibrium, the measurement of the physical parameters of ultra-low permeability reservoirs (i.e., rock and fluid properties such as water saturation, capillary pressure, and permeability), non-Darcy flow, and production prediction tools (Arogundade and Sohrabi, 2012).

SIMULATING ULTRA-LOW PERMEABILITY RESERVOIRS

Darcy's law has long been considered the cornerstone of reservoir flow mechanics. Ultra-low permeability reservoirs differ from conventional reservoirs in the following ways (Jiang et al., 2012). First, the physical properties of the reservoir are exceptionally poor. Second, the oil recovery rate and oil recovery are very low. Due to the compact rock structure of these low-permeability reservoirs, fluid flow in the reservoir is impeded. As a result, the fluid flow does not follow Darcy's law (Yang et al., 2007; Mahani et al., 2018; Bartels et al., 2019). Due to complex flow behavior, strong fluid-rock interactions, and multi-scale heterogeneity, traditional Darcy's method-based models may not be applicable in general to describe flow phenomena in unconventional gas reservoirs. Blasingame (2008) pointed out that high velocities may be important in shale gas production because gas flows mainly in fractures towards the wellhead. Gas velocities may be particularly high in areas close to wells.

In comparison to conventional reservoirs, the key to success in Ultra-low Permeability reservoirs is to concentrate on the well's size rather than the field's size. To accurately analyze well performance, it is necessary to model hydraulic fracturing and estimate reservoir flow. We will use numerical examples to illustrate well production simulations in the vicinity of a single fracture or within an SRV. Desorption of gases has been shown to be crucial in determining the production capacity of shale gas deposits. This is because organic surfaces in shales have a high capacity for adsorption of gas. Methane molecules are mostly adsorbed on carbon-rich components, i.e., horizons, which are often defined as total organic carbon in Ultra-low Permeability reservoirs. As the sustained gas production pressure in the reservoir falls, more adsorbed gas is liberated from the solid into the free gas phase. Facilitates production and flow (Ding et al., 2014).

The relative permeability of ultra-low permeability reservoirs is usually influenced by the water injected during hydraulic fracturing. The relative permeability changes when capillary forces are considered (Helset et al., 1998; Sohooli, 2012). At a lower injection rate, it can simulate the seepage flow of injected water under reservoir conditions and reflect the determination of relative permeability more accurately (Moghaddam and Foroozesh, 2017). Changing the temperature has an effect on the thick oil and water phase percolation curves. When the viscosity of the oil phase decreases, the relative permeability of both oil and water increases, and the increase of injection flow rate leads to higher relative repair permeability of oil layer and lower relative permeability of water layer, and the Corey equation is modified by experimental data, and the accuracy of the equation is verified by theoretical study, and the modified equation is more consistent with the relative permeability curves of thick oil and water than the Corey equation (Torabi et al., 2016).

PROSPECTS AND CHALLENGES

In comparison to conventional reservoirs, ultra-low permeability reservoir exploration is in its infancy. As a result, there are still numerous obstacles to overcome. There are no standard operating procedures for several of the measurement techniques used to determine the physical parameters of ultra-low permeability reservoirs, such as permeability, water saturation, and so on. Furthermore, these strategies are used in conventional reservoirs.

Commercial simulation software now includes modules specialized for simulating ultra-low permeability reservoirs, significantly increasing the accuracy of modeling ultra-low permeability reservoirs. Although tremendous progress has been made in modelling ultra-low permeability reservoirs, major obstacles remain. It is implausible to assume negative capillary pressures in numerical models of ultra-low permeability reservoirs, in particular with respect to transient capillary pressures.

Techniques for predicting ultra-low permeability reservoirs require the application of decline curve analysis, another difficult topic. This is because the methodologies used to predict the future production profiles of conventional reservoirs have been shown to be ineffective for ultra-low permeability reservoirs, and new techniques are being developed and tested to reliably predict the future production profiles of these reservoirs. Given that we now have several years of production data from ultra-low permeability reservoirs to use in predicting future longer-term production, the current results are encouraging, but the oil and gas industry may need to wait a few more years to determine the accuracy and reliability of these newly developed and subsequent production prediction models.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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