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Advances in Proppant Transport and Placement in Unconventional Reservoirs: A Review

Qiang Zhang

Xi’an Shiyou University, Shaanxi 710065, China

Abstract: This comprehensive review delineates the advancements in the pivotal domain of hydraulic fracturing within the realm of unconventional oil and gas reservoir exploitation, specifically focusing on the dynamics of proppant conveyance and positioning. Through a meticulous synthesis of empirical investigations and computational modeling techniques, this discourse aspires to furnish a theoretical framework for the refinement of proppant selection and injection protocols, thereby amplifying the efficacy of oil and gas well stimulation. The research underscores that the intrinsic attributes of proppant, the behavior of fluid flow, and the characteristics of the reservoir are paramount in influencing proppant migration and deposition. The paper also projects prospective advancements in proppant material innovation and simulation methodologies, underscoring the pivotal role of intelligent surveillance in augmenting the precision of fracture stimulation assessments.

Keywords: Proppant; Transport and Placement; Hydraulic Fracturing.

1. Introduction

Hydraulic fracturing emerges as an essential strategy for augmenting the yield of unconventional oil and gas reservoirs, with the core objective of establishing a supportive framework to sustain the permeability of the fracture channels for hydrocarbon flow. The proficient conveyance and strategic positioning of proppant are indispensable for preserving fracture conductivity. Despite significant progress in current research, practical applications still face many challenges, such as uneven distribution of proppant, settling and bridging phenomena, and interactions with reservoir fluids. This review aims to systematically summarize and analyze the current research progress on the transport and placement patterns of proppant, including physical experimental studies and mathematical simulation methods, providing a reference for subsequent research in this direction.

2. Experimental Studies and Simulation Methods

2.1. Physical Experimental Methods

Experimental simulation can intuitively observe the distribution of proppant in fractures, providing a basis for the establishment and verification of theoretical models. Experimental methods mainly include laboratory simulation experiments and field trials. Current research on proppant transport and placement patterns by scholars includes: flat fracture models, rough fracture models, and complex branched fracture models.

The flat fracture model is a basic model for studying proppant transport and placement patterns, simplifying the geometric shape of the fracture, which facilitates experimental operations and theoretical analysis. Experimental studies under this model mainly focus on the distribution pattern of proppant, settling velocity, and the impact of fracture width on proppant distribution. Wang[1] studied the transport and placement mechanism of proppant during hydraulic fracturing through indoor physical simulation experiments. The study found that single grain size proppant can effectively support the near-well area of the fracture. In the pre-fracture stage, increasing proppant grain size, sand ratio, reducing displacement rate, and decreasing fracturing fluid viscosity all contribute to improving the sand balance height. Hou et al. [2] conducted experimental studies on the migration pattern of proppant in fractures after hydraulic fracturing. The results showed that the lowest point height and balance height of proppant are directly related to particle concentration and density, and inversely proportional to transport distance and fracturing fluid viscosity. The research further revealed that, under identical experimental parameters, an increase in the angle of the branch fractures correlates with a decrease in the height of the main and secondary fracture sand dunes. It is posited that the utilization of fracturing fluids with lower viscosity and proppants with reduced density facilitates the optimal distribution of proppant within elongated fractures.

Incorporating the texture of natural fractures, the rough fracture model accounts for the unevenness of fracture surfaces, aligning more closely with the actual conditions encountered in the field. Empirical evidence indicates that the irregularity of the fracture wall substantially impacts the conveyance and positioning of proppant, thereby amplifying the intricacy of experimental and simulation endeavors. Huang Hai et al. [3]embarked on an experimental inquiry into the dynamics of proppant transport and deposition within rough-walled hydraulic fractures. Employing casting techniques to meticulously reproduce the rugged texture of rock fractures, they dissected the influence of fracture inclination, aperture, and the viscosity of fracturing fluids on proppant dispersion, highlighting the multifaceted nature of proppant movement within irregular fractures. Their findings indicated that, in contrast to vertical fractures, inclined fractures can achieve superior proppant deposition rates, albeit with compromised sand dune stability. Moreover, a decrease in fracture aperture and an increase in fracturing fluid viscosity markedly influence the aggregation and conveyance efficacy of proppant. While the study shed light on the intricacies of proppant dynamics in rough-walled hydraulic fractures, it acknowledged certain constraints in model limitations and parameter selection. Notably, the experiment did not account for fluid filtration against the fracture wall, a crucial determinant in fluid dynamics and proppant transport within actual reservoir fracturing scenarios.

The intricately branched fracture model captures the intricacies of fracture networks within actual petroleum and natural gas reservoirs, encompassing the dynamic interplay between primary and secondary fractures. Investigations into such models are instrumental in deciphering the distribution and transport mechanisms of proppant within intricate fracture networks. Kong et al. [4] delved into the migration dynamics of proppant within complex fracture geometries. Through simulated experiments, they assessed the influence of injection velocity and proppant particle dimensions on proppant migration across single and multi-branch fractures. The research revealed that augmenting the injection velocity intensifies the vortex at the forefront of the sand dune, thereby bolstering the proppant's transport capacity. However, at elevated injection velocities, proppant struggled to adequately penetrate the fractures in proximity to the wellbore, susceptible to premature closure under in-situ stress, thereby diminishing the fracture's overall conductivity. Conversely, enlarging the proppant particle size accelerates sedimentation rates, diminishing the vortex's efficacy in transporting proppant particles and consequently shortening the proppant deposition range. The study proposes that fracture design should incorporate fracturing fluids of varying viscosities and proppants of diverse densities, tailored to specific reservoir conditions and stimulation objectives.

Field trials, executed within the confines of oil and gas wells, offer a direct observation and analysis of proppant transport and placement efficacy through actual hydraulic fracturing operations. These trials yield more pragmatic data, albeit at a higher cost and operational complexity.

2.2. Numerical Simulation Technology

Simulation technology serves as a prognosticator for the behavior of proppant under diverse conditions, offering a theoretical foundation for experimental design and field deployment. Computational Fluid Dynamics (CFD) emerges as a robust instrument for emulating fluid dynamics and proppant transport within subterranean reservoirs. The Discrete Element Method (DEM) adeptly captures the intricate interactions among particles and between particles and the wellbore walls, facilitating the simulation of bidirectional solid-liquid interactions. The Finite Element Method (FEM) is leveraged to model fracture propagation and the distribution of proppant, providing an in-depth comprehension of proppant transport dynamics within fracture networks.

Chen et al.'s investigation [5] probed the transport phenomena of proppant within the transverse fractures of horizontal wells through numerical simulation. The study formulated mathematical constructs that encompass rock elastic deformation, the continuity of fracturing fluids, flow behavior, and proppant continuity, which were resolved employing the Finite Element Method. The findings indicated that proppant fragmentation, embedding, and migration adversely impact fracture conductivity, while proppant concentration and the roughness of the fracture wall positively modulate the settling velocity, potentially constraining its horizontal transport and influencing the effective proppant fracture span. The study acknowledged the omission of complex variables inherent in actual fracturing operations; future research is poised to refine the model by amalgamating field data, thereby enhancing the fidelity and applicability of simulations.

Cheng and Qin's study [6] discussed the migration and settlement behavior of backflow proppant after hydraulic fracturing of tight sandstone. The study developed a fitting technology based on multi-task learning networks, effectively integrating multi-dimensional interference factors, and achieved mapping logic fitting from engineering parameters to transport patterns through continuous correction of multi-layer networks. The model showed good input-output relationship fitting ability, providing strong support for the study of proppant transport and settlement patterns. However, the study was limited by the scale of experimental equipment, with a short simulated distance of proppant migration, failing to fully simulate the actual migration pattern of proppant in fractures.

Liang et al.'s research [7], which was tailored to the intricacies of deep shale reservoirs, developed a two-phase flow model for proppant and fracturing fluid dynamics and engineered a comprehensive fracture model. The congruence between experimental outcomes and simulation data substantiated the model's precision, elucidating the tri-phase accumulation dynamics of proppant within fractures. However, the study encountered limitations in scaling up the fracture dimensions in the simulation apparatus, which deviated from field-scale realities, introducing constraints in the experimental analysis of proppant transport and placement mechanisms

3. Outlook on Current Research Progress

In the exploitation of unconventional oil and gas resources, the performance criteria for proppant are escalating in stringency, prompting the industry to innovate towards low-density, high-strength, high-conductivity, and multifunctional proppant materials. These materials are engineered to cater to the variegated demands of different oil and gas wells, encompassing low-density proppant, high-conductivity proppant, and functional proppant, thereby enhancing oil and gas well productivity and operational efficiency while curtailing costs and environmental footprint. Advanced simulation technologies, such as Euler-Euler, Euler-Lagrange, and Lagrange-Lagrange models, when integrated with empirical data, enrich our comprehension of proppant transport within fracture networks, which is pivotal for optimizing hydraulic fracturing designs and augmenting the productivity of unconventional oil and gas wells. Intelligent monitoring technologies, including the utilization of tracer proppant and in-situ proppant, offer innovative methodologies for monitoring the position and geometry of subsurface fractures post-hydraulic fracturing, enhancing the precision of fracture stimulation assessments and mitigating environmental impacts. The advancements in these technologies are instrumental in facilitating the efficient development of oil and gas resources.

4. Summary

The mechanical and chemical attributes of proppant substantially influence its conveyance and deposition within subterranean fractures. Selecting an apt proppant is pivotal for augmenting the productivity of oil and gas wells. Fluid dynamics properties and reservoir characteristics are paramount factors impacting the migration and placement of proppant. Experimental analyses and numerical simulations offer synergistic methodologies for deciphering the patterns of proppant transport and deposition. The innovation of advanced proppant materials and the deployment of high-precision simulation technologies present novel avenues for enhancing the efficacy of proppant transport and placement, thereby curtailing operational expenditures.

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