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Modeling and Simulation of Hydraulic Fracturing in Tight Gas Reservoirs: A Review of Geomechanical and Flow Dynamics Approaches

Mohammed Ahmed M. Al-Janabi[1*], Haider A. Mahmoud[1], Maaly S. Asad[2]
Ahmed Hamid Al-Taie[3,4], Asghar Gandomkar[5]

[1] Ministry of Oil, Baghdad, Iraq
[2] Petroleum Engineering Department, College of Engineering, University of Kerbala, Karbala 56001, Iraq
[3] College of Engineering, University of Baghdad, Baghdad, Iraq.
[4] Gubkin Russian State, University of Oil and Gas (National Research University), Moscow, Russia.
[5] Department of Chemical Engineering, School of Chemical and Petroleum Engineering, Shiraz University, Shiraz 71345, Iran

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ABSTRACT

This paper reviews the developments of modeling hydraulic fracturing in tight gas formations, progressing from elementary analytical models to more advanced and coupled geomechanical-flow simulators. We discuss the significant progress that has been made in understanding fluid flow behavior of ultra-low permeability formations, which has significantly improved methodology for analyzing this complex problem. Findings demonstrate the importance of using Discrete Fracture Network (DFN) and Embedded Discrete Fracture Model (EDFM) for representation of complex fracture geometries and connectivity. However, it remains a great challenge to model the stress-dependent changes in permeability and porosity and the dynamic changes of fracture properties during fracturing, as well as the multi-scale interactions between induced hydraulic fractures and natural ones. This paper provides a novel iterative modeling framework that integrates multi-scale interactions and proposes a roadmap for data-driven modeling coupled with fluid flow to enhance predictive accuracy in TGR stimulation.

1. Introduction

The tight reservoir is considered a viable alternative resource in the field of oil and gas exploration [1-3]. Therefore, successfully using Tight Gas Reservoirs TGRs depends on accurate simulations, which is difficult due to complex rock and fluid behavior [4-6]. Since the advent of horizontal drilling and multi-stage fracturing [7], the field has developed from rudimentary planar fracture models to complex, coupled flow-geomechanics simulations [8-10]. These advanced models are necessary for describing the processes associated with the propagation of fractures as well as reaction with natural fractures in reservoirs[10]. This review addresses the current gaps in understanding fluid flow within stress-sensitive tight gas fractures, categorizing existing techniques into a three-step framework: characterization, geomechanics, and flow dynamics.

2. Methodological Foundations of Modern Simulation

Hydraulic fracturing simulation research relies on numerical models, analytical approaches, and experimental studies. Most work focuses on reservoirs in the Middle East, the United States, and China. A common theme is linking geomechanics with fluid flow, which helps describe fracture networks more accurately and optimize operating settings for improved production.

As illustrated in the simulation framework (Figure 1), the process begins with goal definition and the use of statistical tools to generate realistic network geometries. Next, statistical tools are used to create a realistic picture of the fracture network. This connection allows the simulation to update as pressure changes, giving engineers a reliable tool to improve reservoir design.

2.1. Fracture Network Characterization

Twenty studies in this review employed Discrete Fracture Network DFN or Embedded Discrete Fracture Models EDFM to capture these complex features with high precision. To further enhance realism, multiple studies have incorporated natural fracture interactions, orientation, and heterogeneity. Table 1 synthesizes the primary methods used in the reviewed literature to characterize and model complex fracture networks in TGRs.

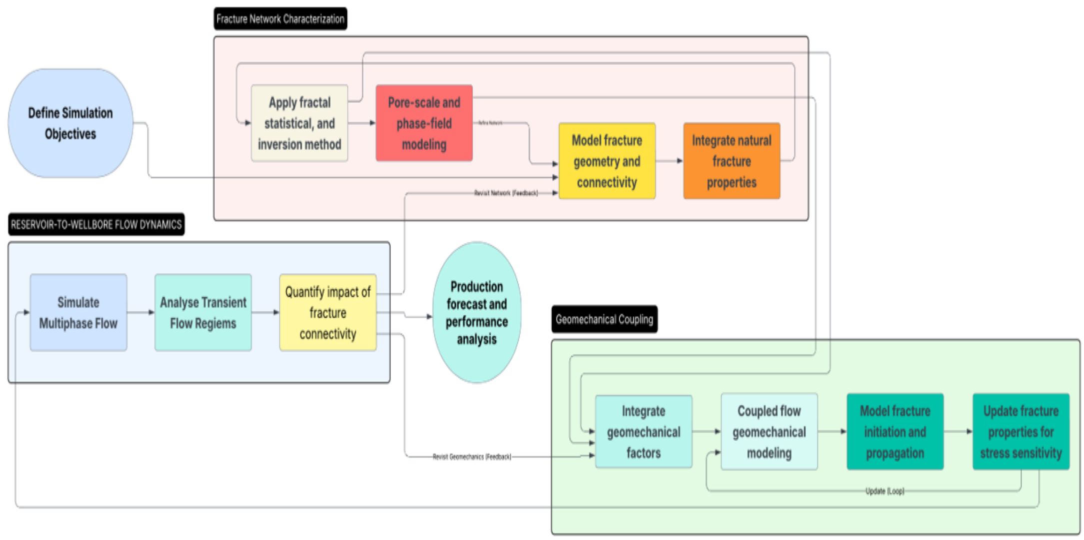

Figure 1. A coupled modeling framework integrating fracture characterization, flow dynamics, and geomechanics.

Table 1. Summary of Fracture Network Characterization Approaches

Characterization Approach	Description	Key Studies
Discrete & Embedded Fracture Models, DFN/EDFM	These models show the complex shapes and connectivity of fractures very accurately. They are used to simulate non-orthogonal fractures and to see how this affects the flow of fluids and geomechanics.	[11-14]
Natural Fracture Interaction & Heterogeneity	These studies create realistic models by incorporating natural fracture properties, such as orientation, density, and interaction modes (crossing, arrest, deflection).	[15-18]
Fractal, Statistical, & Inversion Methods	Mathematical and data-driven approaches utilize fractal and production data to quantify network complexity and permeability.	[19-22]
Pore-Scale & Phase-Field Modeling	These techniques model microscopic fracture growth and pore interaction, providing detailed insights into fracture initiation, branching, and arrest phenomena.	[23-26]

The multi-scale characterization approaches summarized in Table 1 demonstrate a shift toward integrating pore-scale insights into field-scale DFN and EDFM frameworks to capture the geological realism of natural fracture interactions and heterogeneity. This integration provides a more robust foundation for representing the static geometry of the fracture network before incorporating dynamic geomechanical forces.

2.2. Geomechanical Coupling

The integration of geomechanical effects is critical for capturing realistic fracture behavior. Eighteen of the reviewed studies integrated geomechanical factors including in-situ stress, rock mechanical properties, and fracture propagation dynamics. Several models now account for stress sensitivity, which affects fracture conductivity and aperture. For instance, some models incorporate stress-sensitive fracture permeability to better quantify production contributions. Strong geomechanical coupling, often via multiphase Biot's model or explicit modeling using EDFM, allows for accurate prediction of well performance and stress evolution. Other studies have highlighted the importance of geomechanics in understanding fracture initiation near the wellbore and the various interaction modes between fractures. Table 2 categorizes the primary geomechanical factors integrated into simulation models, as identified in the reviewed literature, along with the modeling approaches used and representative studies.

Table 2. Summary of Geomechanical Coupling Aspects in Hydraulic Fracturing Models

Geomechanical Aspect	Description & Modeling Approach	Key Studies
Coupled Flow-Geomechanics & Stress Evolution	Models that fully integrate fluid flow with rock deformation to simulate how pressure changes affect the in-situ stress field, and how that stress evolution in turn influences reservoir and fracture properties. Often implemented using Biot's theory or strongly coupled Finite Element Methods (FEM).	[27-30]
Stress Sensitivity & Dynamic Properties	Models that explicitly account for changes in fracture properties (e.g., conductivity, aperture, permeability) as the effective stress on the fracture network changes during production. This is critical for accurate long-term production forecasting.	[31-34]
Fracture Propagation & Interaction Dynamics	Simulations that model the dynamic growth of hydraulic fractures and their interaction with natural fractures (crossing, arresting, or deflecting). The outcomes are governed by the in-situ stress state, rock mechanical properties, and fluid injection parameters.	[26, 35-37]
Fracture Initiation & Near-Wellbore Effects	Geomechanical analysis targeted near-wellbore stress concentrations to predict fracture initiation and growth, a prerequisite for validating stimulation efficacy.	[36, 38, 39]

Table 2 shows that adding geomechanics to models is complex, as it covers the full production timeline and multi-scale processes like fracture creation [36, 38, 39] to the dynamic propagation and interaction of fractures within the reservoir itself [26, 35-37]. Furthermore, the analysis extends beyond the initial fracturing event to consider the long-term impact of stress sensitivity on fracture properties during the production phase [31-34]. Coupled flow-geomechanics integrates these aspects and governs the reservoir's stress evolution [27-30]. Once the fracture network is created, the next critical modeling step is to simulate fluid transport from the reservoir to the wellbore.

2.3. Modeling Reservoir-to-Wellbore Flow Dynamics

Twenty reviewed studies focus on this, distinguishing between rapid fracture flow and slow matrix diffusion while highlighting the importance of fracture connectivity. Advanced models now move beyond simple assumptions to incorporate complex transient behaviors and multi-physics phenomena, as summarized in Table 3.

Table 3. Summary of Reservoir-to-Wellbore Flow Dynamics Modeling

Flow Dynamics Aspect	Description & Modeling Approach	Key Studies
Flow Mechanisms & Transport Physics	Models distinguish between fluid transport mechanisms, separating rapid fracture advection from slow matrix diffusion while incorporating advanced physics like sorption and multiphase flow.	[40-43]
Transient Flow Regimes & Pressure Behavior	Analytical and semi-analytical models identify transient flow periods, such as linear and bilinear flow, which are essential for interpreting well tests and estimating reservoir properties.	[31, 32, 34, 44, 45]
Fracture Network Properties & Connectivity	Simulations quantify how fracture geometry impacts production, identifying connectivity as the dominant factor controlling flow efficiency and ultimate recovery.	[46-49]

These patterns are essential for analyzing production. Next, we examine the strengths and weaknesses of these models.

3. Critical Analysis of Modeling Approaches

Although the reviewed literature demonstrates an overall consensus on the principles in terms of the role of fracture geometry to the overall fracture network and the role of geomechanics, there exist some differences at the level of application. Amidst this level of consensus, the literature demonstrates some variances at the level of the specific models used, scale of analysis, and level of treatment of dynamic parameters such as stress sensitivity. For this analysis, the reviewed literature will be compared on some of the key parameters identified, summarized within Table 4.

Table 4. Agreement and Divergence Across Key Modeling Criteria

Comparison Criterion	Studies in Agreement	Studies in Divergence
Model Accuracy	There is consensus that models incorporating fracture complexity and validated against field data achieve good prediction accuracy for both flow and production [50, 51]	Handling of multiphase flow, transient effects, and scale-dependency (pore vs. field) [24, 52, 53].
Fracture Network Characterization	High importance of geometry, density, and connectivity (using DFN/Fractal tools) [46, 54, 55].	Level of simplification (planar vs. non-orthogonal) and inclusion of full network topology [20, 32].
Geomechanical Coupling	Mandatory for capturing realistic propagation and stress sensitivity [27, 28, 30]	Intensity of coupling (sequential vs. fully coupled) and trade-offs for computational speed [56, 57].
Reservoir-to-Wellbore Flow Dynamics	Connectivity and SRV are the primary drivers of recovery efficiency [58-60].	Treatment of two-phase flow, capillary pressure effects, and near-wellbore dynamics [61-63].
Practical Applicability	Data-driven calibration is essential for optimized field design [64-66].	A gap exists between theoretical/academic models, which prioritize specific mechanisms without immediate field application, and simplified models for practical deployment [24, 67, 68]. There is still a challenge in capturing proppant transport and conductivity evolution [69, 70].

This comparison makes it clear that while there is great agreement on the basic ideas, there is divergence in modeling. As shown in Table 4, this is exactly because of certain trade-offs between realism and cost. This is important for understanding implications in the next section.

3.1. Model Accuracy and Validation

Achieving model accuracy is vital for reservoir simulation. Experts agree that the best predictions come from models that combine detailed fracture networks with strict validation. For instance, fifteen studies proved their high accuracy by testing their results against real field data or standard analytical solutions.

Despite the above considerations, the differences in the choices of practice mean that the outcome will also be different. Prioritizing speed means that the complexity of the model needs to be simplified. Hence, the accuracy of the results will also be affected. Moreover, the reliability of the analysis will differ depending on whether the analysis is carried out on the pore level or the reservoir level. This is as indicated in Table 5 above.

Table 5. Comparative Analysis of Model Accuracy and Validation

Studies in Agreement	Studies in Divergence	Potential Explanations for Divergence
There is a consensus that models improve in reliability and accuracy when they incorporate complex fracture networks and are validated against field data [40] or analytical solutions [27, 50, 71]. This is demonstrated in coupled flow-geomechanics approaches and discrete fracture network simulations [27, 72, 73].	Models differ significantly in: 1. Simplifying Assumptions- Neglecting stress sensitivity or assuming uniform fracture properties[74-76]. 2. Handling of Flow Complexity- Varying treatment of multiphase flow or transient effects [77-79]. 3. Scale of Analysis- Ranging from pore-scale to full reservoir-scale [80, 81].	Divergences stem from fundamental differences in: 1. Modeling Approaches - (e.g., analytical, numerical, data-driven) [75, 77, 79, 82]. 2. Assumptions - Necessary simplifications made about fracture properties [74-77, 79, 82]. 3. Scale of Analysis - The intended focus of the study, whether on micro-scale physics or field-scale application[77, 79].

Table 5 illustrates that for complex models, the norm is reliability, whereas simplification is more often a conscious strategy than a weakness. Such decisions are pre-determined by the question being asked, problem scale, and computational resources. This trade-off between accuracy and feasibility does not remain abstract; it manifests when examining how different studies approach the basic task of characterizing the geometry of the fracture network itself.

3.2 Divergence in Core Methodologies

While the industry agrees on the core stages of simulation, characterization, geomechanics, and flow dynamics, significant technical gaps exist in their execution.

Aside from overall model performance, large technical gaps appear in the three essential components or stages of modeling hydraulic fracturing processes, including characterization, geomechanics, and flow dynamics. These differences are mostly fueled by the "Accuracy vs. Efficiency" trade-off problem, where accurate models (coupled DFN model with multiphase flow) are of great academic value but still computationally challenging for optimization on the field scale [20, 32]. On the other hand, simplified models (uncoupled 2D planar fractures) are computationally efficient in real time but cannot represent stress-dependent permeability [56, 57]. Flow models can be of varying levels of complexity, including advanced physics such as two-phase flow and capillary pressure, as well as the basic principle of single-phase flow [61, 62]. These points of agreement and difference are incorporated in Table 4.

3.3. Strengths and Weaknesses of Integrated Modeling Frameworks

Contemporary simulation models, including DFN and EDFM, integrate various methodologies to provide a greatly improved level of accuracy. As seen in Table 6, these combined methodologies demonstrate a distinct advantage, although they are also faced with certain remaining challenges[27, 50, 83, 84].

For the sake of time efficiency, some models tend to make simplifications, thus finding it difficult to incorporate dynamic attributes like sensitivity to stress. This implies that scientists encounter a compromise between time efficiency and accuracy[32, 33, 57, 65, 85-87].

Table 6. Strengths and Weaknesses of Integrated Modeling Approaches

Strengths	Weaknesses
Effectively combines semi-analytical, numerical, and data-driven techniques for hybrid forecasting[50].	Frequent reliance on planar or uniform fracture assumptions, failing to represent real-world complexity [87].
Coupled geomechanics (DFN/EDFM) provides high-resolution simulation of propagation and fluid transport [27, 83, 84].	Dynamic stress-sensitivity and property evolution are often neglected to avoid computational lag[32, 33, 57, 86].
Multi-scale frameworks	Critical trade-off between high-fidelity accuracy and

successfully link pore-level interactions to reservoir-scale flow behavior[14, 88].	field-scale computational efficiency/scalability [65, 85].

Table 6 shows a paradox in that although techniques such as EDFM are capable of modeling complex geometries, there is a trade-off between realism and cost that imposes a limit on prediction. Closing this gap between model effectiveness and reality represents the key challenge for science.

3.4. Synthesis of Contributions and Future Frontiers

This review categorizes the critical trade-offs between physical realism and computational feasibility in TGR modeling, as summarized in Table 7.

Table 7. Synthesis of Key Contributions and Research Advancements

Area of Contribution	**Technical Focus / Mechanism**	**Key Insights & Novelty**	**Practical Impact on Petroleum Engineering**
Advancements in Tight Reservoir Physics	Dynamic geomechanical stress response and non-linear pore pressure-permeability relationship.	Clarifies that "tightness" is a dynamic response to stress; identifies that ignoring time-dependent property changes leads to significant overestimation of production decline.	Provides a quantitative baseline for long-term recovery prediction in ultra-low permeability formations.
Knowledge of Hydraulic Fracturing Connectivity	Transition from geometry-centric to connectivity-centric modeling using DFN and EDFM frameworks.	Demonstrates that fracture network connectivity, rather than individual fracture conductivity, is the dominant control on Stimulated Reservoir Volume (SRV) efficiency.	Establishes a strategic priority for engineers during history matching and the optimization of multi-stage stimulation designs.
The Next Frontier: Physics-Informed Data-Driven Approaches	Use of data-driven surrogates to emulate complex geomechanical solvers (FEM/XFEM).	Identifies the "computational bottleneck" as the primary barrier and proposes physics-informed machine learning as the solution to maintain accuracy without prohibitive run-times.	Enables the practical, field-scale application of fully coupled geomechanical-flow simulators for real-time decision-making.

It highlights that the future of simulation for hydraulic fracturing exists not only in increased numerical accuracy, but also in the intelligent fusion of multi-scale physics and adaptive, data-driven methodologies to address the shortcomings in stress-sensitive modeling.

4. Gaps and Future Research Directions

Analyzing existing models reveals both their current capabilities and the boundaries of our understanding. Despite progress, complex challenges remain. This section outlines key gaps and proposes research directions to enhance the predictive accuracy of hydraulic fracturing simulations. These gaps, summarized in Table 8, concern the dynamic, time-dependent, and multi-scale aspects of fracture behavior that are not yet fully captured by mainstream models. Table 8 details the primary limitations in current hydraulic fracturing simulation and outlines targeted research directions to address them.

Table 8. High-Priority Gaps and Future Research Directions in Modeling

Gap Area	Description of Current Limitation	Proposed Future Research Directions	Justification for Priority	Research Priority
Dynamic Fracture Property Modeling	Current models inadequately capture dynamic changes in fracture properties, such as conductivity loss and aperture variation under stress during production.	Develop fully coupled, time-dependent models integrating geomechanics and multiphase flow to simulate dynamic fracture property evolution, validated with field data.	Dynamic fracture behavior critically affects production forecasting accuracy and refracturing design but remains computationally challenging and underrepresented in models[27, 29, 33].	High
Complex Fracture Network Inversion	Existing inversion methods for fracture network morphology and flow capacity are limited, often assuming simplified geometries and lacking the integration of multi-source data.	Create integrated inversion frameworks that combine fracture growth algorithms, microseismic data, production history, and advanced optimization to reconstruct realistic complex fracture networks.	Accurate fracture network characterization is essential for production analysis and evaluation, but current methods suffer from ambiguity and low accuracy[89-92].	High
Multi-Scale Flow Coupling	Many models treat matrix and fracture flow separately or use oversimplified dual-porosity approaches, insufficiently capturing multi-scale and multi-mechanism flow processes (diffusion, sorption, etc.).	Develop multi-scale, multi-physics models that couple pore-scale flow, fracture network flow, and geomechanics, incorporating multiphase transport and capillary pressure effects, with experimental validation.	Tight reservoirs exhibit complex flow mechanisms across scales; neglecting these leads to inaccurate predictions of production and recovery[42, 93, 94].	High
Hydraulic-Natural Fracture Interaction	The prediction of hydraulic fracture interaction with natural fractures remains uncertain due to variability in natural fracture properties, in-situ stress, and other conditions.	Advance 3D numerical and experimental studies that incorporate fracture friction, heterogeneity, and realistic stress states to better predict interaction modes (crossing, arrest, deflection).	Interaction modes strongly influence fracture network complexity and production but are not yet fully understood or accurately modeled[37, 95, 96].	High

As appears in Table 8, the basic issue that creates this bottleneck in the industry today is the transition from static, simplified models to dynamic models on multiple scales, because of the cost of full-physics coupling. The solution to this problem in multiphysics dynamics, such as in multiflows, to give an example, definitely does not lie in an increased grid size, because one needs to merge transport on the molecular scale with geomechanics on the pertinent field scale. This was highlighted in our critical analysis among the issues to address on the path to predictive models.

Through the integration of fracture inversion and the development of dynamic properties, engineers can move from a "reactive" mode of history matching to a "proactive" approach to reservoir management. This integration highlights the fundamental outcome of this review, namely the recognition that the future of TGR stimulation lies in the integration of high-fidelity numerical solvers and adaptive machine learning models. These findings form the technical basis of the conclusions that follow.

5. Conclusion

1. The field has evolved from planar models to integrated frameworks, with 33% of reviewed studies now prioritizing DFN/EDFM for complex geometry.
2. Geomechanical coupling is essential for accuracy, though 30% of studies still utilize simplified assumptions to maintain computational efficiency.
3. Connectivity is identified as the primary control on recovery, yet significant gaps remain in modeling dynamic property evolution under stress.
4. Future research must prioritize multi-scale flow coupling and 3D hydraulic-natural fracture interaction modeling.

Abbreviations

DFN	Discrete Fracture Network
EDFM	Embedded Discrete Fracture Model
FEM	Finite Element Method
SRV	Stimulated Reservoir Volume
TGR	Tight Gas Reservoir
XFEM	Extended Finite Element Method

Symbols

K	Permeability
$Ø$	Porosity
σ	In-situ stress
P	Reservoir pressure
ω	Fracture aperture
C_f:	Fracture conductivity
α	Biot’s coefficient (from Biot's
μ	Fluid viscosity
t	Time (for transient flow analysis)

Conflict of interest

The authors declare no conflicts of interest concerning this research.

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Author Contribution

M.A.M. Al-Janabi, H.A. Mahmoud, and A. Gandomkar proposed the research problem.

M.A.M. Al-Janabi, A.H. Al-Taie, and M. Asad developed the theoretical framework.

M.A.M. Al-Janabi, A.H. Al-Taie, and A. Gandomkar verified the analytical methods.

All authors participated in the discussion of the results and contributed to writing the manuscript.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

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