Evaluation of Shale Oil Mobility and Enhanced Oil Recovery: Problem Diagnosis and a Theoretical Framework Based on the Fundamental Laws of Porous Media Mechanics

Authors: Qi Yalin, Qi Yalin

Date: 2026-05-06T09:18:54+00:00

Abstract

Shale oil development faces the core contradiction of "large resource volume versus extremely low recovery factor." This paper systematically analyzes the fundamental flaws of six existing categories of hydrocarbon occurrence state evaluation methods: their reliance on indirect empirical thresholds and deviation from the physical laws of fluid migration, which lead to a severe discrepancy between mobility evaluation and production dynamics. It reveals that the deep-seated cause of low recovery is the triple-coupling control of "reservoir constraint—macromolecule retention—small molecule production," which constitutes the rigid constraints for the conversion of geological reserves into recoverable reserves. Returning to the classical theories of seepage mechanics and fluid mechanics, this study clarifies that Darcy' s law and the Hagen-Poiseuille law are the primary governing laws of mobility, while capillary force, adsorption, and effective stress serve as secondary correction mechanisms, establishing a conceptual zoning based on pore-throat radius, effective displacement pressure gradient, and dynamic viscosity. Two basic principles for mobility evaluation are proposed: priority of primary controls equivalent to formation conditions, and the balance between displacement and resistance. This paper provides a systematic theoretical foundation for the efficient development of shale oil and does not provide a directly operational evaluation model.

Full Text

Preamble

Shale Oil Mobility Evaluation and Recovery Enhancement: Problem Diagnosis and a Theoretical Framework Based on the Fundamental Laws of Seepage Mechanics

National Engineering Laboratory for Exploration and Development of Low-Permeability Oil and Gas Fields, Xi'an Exploration and Development Research Institute of PetroChina Changqing Oilfield Company

Abstract

The evaluation of shale oil mobility and the enhancement of recovery factors represent critical challenges in the development of unconventional resources. This paper provides a systematic diagnosis of current technical bottlenecks and proposes a comprehensive theoretical framework grounded in the fundamental laws of seepage mechanics. By analyzing the multi-scale transport mechanisms within shale reservoirs, we address the limitations of traditional evaluation methods and outline strategies for optimizing production through advanced recovery techniques.

1. Introduction

Shale oil has become a pivotal component of global energy supply. However, due to the complex pore structures and extremely low permeability of shale reservoirs, accurately evaluating oil mobility and achieving high recovery rates remain significant hurdles. Current industry practices often rely on empirical models that fail to account for the unique physical and chemical interactions at the nano-scale. This study aims to bridge the gap between theoretical seepage mechanics and practical engineering applications to provide a more robust basis for shale oil development.

2. Problem Diagnosis in Shale Oil Evaluation

The primary challenges in shale oil mobility evaluation stem from the multi-scale heterogeneity of the reservoir and the non-Darcy flow characteristics observed in nanopores.

2.1 Limitations of Traditional Mobility Indicators Conventional parameters such as permeability and viscosity are insufficient to describe the flow behavior in shale. The presence of adsorbed layers and the high threshold pressure gradient mean that a significant portion of the oil remains immobile under standard production conditions. Furthermore, the interaction between the fluid and the organic-rich matrix introduces complexities that are not captured by classical Darcy' s law.

2.2 Challenges in Recovery Factor Prediction Predicting the recovery factor in shale reservoirs is complicated by the rapid decline rates of horizontal wells and the uncertainty surrounding the effectiveness of hydraulic fracturing. Current diagnostic tools often struggle to differentiate between the contribution of matrix flow and fracture networks, leading to inaccurate forecasts of long-term production potential.

3. Theoretical Framework Based on Seepage Mechanics

To address these issues, we propose a theoretical framework that integrates the fundamental laws of seepage mechanics with multi-scale physics.

3.1 Multi-Scale Flow Modeling The framework incorporates a hierarchy of flow regimes, ranging from molecular transport in kerogen nanopores to continuum

摘要

Shale oil development is characterized by a fundamental contradiction between vast resource potential and extremely low recovery factors. This paper systematically analyzes the inherent flaws in the six existing categories of hydrocarbon occurrence state evaluation methods. These methods rely heavily on indirect empirical thresholds and deviate from the physical laws governing fluid migration, leading to a severe discrepancy between mobility assessments and actual production performance.

The study reveals that the underlying cause of low recovery rates in deep reservoirs is governed by a triple-coupling control mechanism: macromolecular retention, small-molecule extraction, and phase-state evolution. These three factors constitute a rigid constraint on the conversion of geological reserves into recoverable reserves.

Returning to the classical theories of seepage mechanics and fluid dynamics, this paper clarifies that Darcy' s Law and the Poiseuille Law serve as the primary governing laws for mobility. In contrast, capillary force, adsorption, and effective stress act as secondary modification mechanisms. Based on these principles, a conceptual zoning framework is established using pore-throat radius, effective displacement pressure, and dynamic viscosity.

Finally, the paper proposes two fundamental principles for mobility evaluation: “Primary Control Priority” and “Formation Condition Equivalence/Resistance Balance.” This work provides a systematic theoretical foundation for the efficient development of shale oil, though it does not offer a direct, operational evaluation model.

关键词

Shale Oil Movability Evaluation and Recovery Enhancement: Fundamental Laws of Seepage Mechanics, Reservoir Constraints, Macromolecule Retention, and Small Molecule Recovery

Abstract

The evaluation of shale oil movability and the enhancement of recovery factors are critical challenges in the development of unconventional resources. This study investigates the fundamental laws of seepage mechanics within the context of shale reservoirs, emphasizing the impact of reservoir constraints on fluid transport. We analyze the phenomenon of macromolecule retention within the complex pore-network systems of shale, which significantly hinders flow efficiency. Conversely, we explore the mechanisms governing small molecule recovery, providing a theoretical framework for optimizing extraction strategies. By integrating multi-scale characterization and fluid dynamics, this research offers new insights into the factors limiting shale oil mobility and proposes pathways for improving ultimate recovery through targeted reservoir management.

1. Introduction

Shale oil has emerged as a transformative energy resource; however, its commercial viability is often constrained by low primary recovery rates. Unlike conventional reservoirs, shale systems are characterized by ultra-low permeability and a hierarchical pore structure ranging from nanometers to micrometers. Understanding the movability of oil within these confined spaces requires a re-evaluation of classical seepage mechanics. This paper examines how reservoir architecture imposes physical and chemical constraints on fluid movement, leading to the selective retention of heavy components and the preferential production of lighter fractions.

2. Fundamental Laws of Seepage Mechanics in Shale

In shale reservoirs, the traditional Darcy’ s law often fails to accurately describe fluid behavior due to the dominance of surface forces and non-Newtonian flow characteristics. The seepage process is governed by a combination of pressure-driven flow, diffusion, and adsorption-desorption mechanisms.

[Figure 1: see original paper]

The total mass flux can be expressed by considering the threshold pressure gradient (TPG), which must be overcome before flow initiates. As shown in (eq:seepage), the flow velocity v is influenced by the effective permeability k and the fluid viscosity μ:

$$v = -\frac{k}{\mu}(\nabla P - \lambda)$$

where λ represents the threshold pressure gradient. In the nanopores of shale, the interaction between the fluid molecules and the organic matter (kerogen) walls creates a boundary layer that further restricts mobility.

3. Reservoir Constraints and Movability Evaluation

The evaluation of shale oil movability must account for "reservoir constraints," which include pore throat distribution, mineral composition, and wettability. These constraints determine the

Problem Diagnosis Theoretical Framework Based Fundamental Seepage Mechanics Yalin Engineering Laboratory Exploration Development Low-Permeability Fields,Xi' an Shaanxi 710018,China Development Research Institute PetroChina Changqing Oilfield Company,Xi' an Shaanxi 710018,China)

Abstract

Shale development faces contradiction "large resource volume extremely recovery efficiency." paper systematically analyzes fundamental flaws existing

methods

evaluating hydrocarbon occurrence states: reliance indirect empirical thresholds deviation physical fluid migration, resulting serious mismatch between movability evaluation production performance. seated cause recovery efficiency revealed triple coupling control "reservoir constraints macromolecular retention small molecule production," which together rigid constraint conversion geological resources recoverable reserves.

Returning classical theories seepage mechanics fluid mechanics, study identifies Darcy's Hagen Poiseuille dominant governing movability, capillarity, adsorption, effective stress, etc., secondary correction mechanisms. conceptual zonation based throat radius, effective displacement pressure gradient, dynamic viscosity established. fundamental principles movability evaluation proposed: priority primary parameters coupled equivalence reservoir conditions, displacement resistance balance. paper provides systematic theoretical foundation efficient shale development offer directly operational evaluation model. words Shale Movability evaluation; Recovery efficiency; Fundamental seepage mechanics; Reservoir constraints; Macromolecular retention; Small molecule production

1 引言：页岩油可动性评价的现实困境

Evaluation Principles and Directions for Hagen-Poiseuille and Darcy Flows

The evaluation of fluid transport mechanisms, specifically regarding Hagen-Poiseuille flow and Darcy’ s law, requires a rigorous framework to distinguish between microscopic pipe flow and macroscopic porous media permeation. Establishing clear evaluative principles is essential for characterizing flow behavior across different scales and physical environments.

1. Fundamental Principles of Hagen-Poiseuille Flow Evaluation

The Hagen-Poiseuille equation describes the pressure drop in an incompressible, Newtonian fluid undergoing laminar flow through a long cylindrical pipe of constant cross-section. The primary direction for evaluating this model focuses on the validity of the no-slip boundary condition and the maintenance of the laminar regime.

Key evaluative criteria include: - **Geometric Integrity:** Assessing the impact of pipe roughness and cross-sectional uniformity on the theoretical flow rate. - **Viscous Dominance:** Ensuring the Reynolds number (Re) remains well below the critical threshold to justify the neglect of inertial terms. - **Boundary Effects:** Investigating the slip velocity at the walls, particularly in micro-scale or nano-scale channels where traditional continuum assumptions may weaken.

2. Evaluation Framework for Darcy’ s Law

Darcy’ s law serves as the foundational constitutive equation for flow through porous media. Evaluating its applicability involves transitioning from individual pore-scale dynamics to a representative elementary volume (REV).

The strategic directions for evaluating Darcy flow include: - **Permeability Characterization:** Determining the intrinsic permeability of the medium and its dependence on porosity and pore-size distribution. - **Linearity Limits:** Identifying the range of pressure gradients where the linear relationship between flux and pressure drop holds, and marking the transition to non-Darcy flow (e.g., Forchheimer flow) at higher velocities. - **Scale Effects:** Evaluating how the heterogeneity of the porous structure influences the macroscopic flow parameters across different spatial scales.

3. Comparative Analysis and Integration

A critical direction in modern fluid dynamics research is the integration of these two models to describe complex systems, such as the interface between a free fluid zone and a porous zone. Evaluation principles in this context focus on: - **Interface Coupling:** Assessing the accuracy of boundary conditions (such as the Beavers-Joseph condition) at the junction of Hagen-Poiseuille-type conduits and Darcy-type porous matrices. - **Structural Complexity:** Evaluating how tortuosity and connectivity within a network of

2.1 六类方法的共性问题

Its mobility criteria lack support from physical mechanisms. Conventional pyrolysis methods often treat these components as free hydrocarbons based on empirical dynamic viscosity. Techniques such as micro-Raman spectroscopy analyze aromaticity and peak shifts [**?**, **?**] to determine hydrocarbon occurrence states. However, exploration and development practice has shown that the content of free hydrocarbons [**?**, **?**] and the flow patterns revealed through capillary experiments [**?**] must align with the physical foundations of seepage established by fluid laws. Based on this, mobility is proposed; however, models often fail when considering asphaltene mass fractions. Furthermore, dynamic viscosity is frequently measured as a bulk phase value at standard temperature and pressure, rather than under actual formation conditions.

Shale oil reservoirs are characterized by the dominance of nanopore throats and the co-existence of source and reservoir rocks. The precise characterization of occurrence states (adsorbed vs. free) and component characteristics (distribution of light and heavy components) is the foundation for resource evaluation and the optimization of development schemes. Currently, the industry has developed six mainstream technologies: extraction methods, conventional pyrolysis, stepped pyrolysis, gas chromatography-mass spectrometry (Py-GC), micro-laser Raman spectroscopy, and nuclear magnetic resonance (NMR).

Despite these advancements, shales with similar total quantities can exhibit actual productivity differing by several orders of magnitude. Traditional evaluation results of occurrence states often deviate significantly from production performance. This contradiction reveals deep-seated defects in the existing evaluation system: an over-reliance on indirect, empirical indicators and a failure to follow the physical laws of seepage, specifically the effective displacement pressure gradient of fluids within nanopore throat media.

The fundamental laws of seepage mechanics and the core principles of fluid mechanics discussed in this paper are derived from the most basic physical laws. They are characterized by essential controlling factors, such as displacement pressure and the geometric morphology of the medium, rather than relying on empirical thresholds or statistical fitting relationships. The migration of fluids in porous media follows classical physical laws:

Darcy' s Law, established through sand column experiments, and the Poiseuille equation for macroscopic seepage collectively form the theoretical foundation of seepage mechanics. However, existing evaluation methods rarely apply these physical laws directly to the assessment of mobile fluid behavior. Starting from a diagnostic analysis of the problem, this paper systematically examines the fundamental causes of low recovery rates by returning to the classical principles of seepage mechanics and fluid mechanics. The six categories of methods previously mentioned all evaluate mobility based on the binding strength between hydrocarbons and the rock matrix; the weaker the binding strength, the higher the mobility.

方法

Mobility Criteria and Limitations of Current Methods

Current methodologies for assessing hydrocarbon mobility face several significant technical challenges. A primary issue is that many techniques only measure the total extractable organic matter without distinguishing between different occurrence states. Furthermore, the temperature stages defined in traditional thermal analysis often lack a mechanistic correlation with actual physical mobility. This leads to inaccuracies where light hydrocarbons may volatilize prematurely, while heavier hydrocarbons remain trapped due to incomplete thermal desorption.

Limitations of Stepwise Pyrolysis

The stepwise pyrolysis method suffers from a lack of unified standards regarding temperature thresholds. More critically, these thresholds lack a direct physical connection to essential reservoir parameters such as formation pressure gradients and capillary forces. Consequently, this approach remains semi-quantitative at best; it fails to provide the necessary kinetic parameters required to determine whether a fluid can actually flow under reservoir conditions.

Challenges in Threshold Calibration

While it is common practice to define any value above a specific cutoff as "movable," the calibration of these cutoff values is often problematic. When the cutoff is calibrated using centrifugation experiments, the resulting irreducible water saturation reflects a state of static equilibrium. This equilibrium is typically measured at pressures far below actual production pressure differentials. Therefore, the results obtained via centrifugation do not represent a true mobility threshold in the context of dynamic fluid seepage and flow mechanics.

2.2 深层根源：三大错配与偏离渗流力学基本定律

The root cause lies in the deviation from the equilibrium mechanism between driving and resistive forces during fluid migration, which manifests as three systemic mismatches. First is the pressure scale mismatch: it is generally assumed that the driving force in centrifugal experiments (ΔP_{cen}) is far smaller than the difference between the bottom-hole flowing pressure after hydraulic fracturing and the original formation pressure (ΔP_{field}). However, it must be noted that the latter is not the effective pressure gradient acting directly on the matrix pore throats; the actual pressure drop is primarily concentrated near the fractures and the stimulated reservoir volume (SRV), while the effective pressure gradient within the matrix pore throats is significantly lower. Nevertheless, a massive order-of-magnitude difference remains between the two; centrifugal experimental conditions severely underestimate the displacement energy available in actual production.

Second is the dynamic viscosity mismatch: the bulk dynamic viscosity (μ_{bulk}) obtained through pyrolysis and chromatographic analysis is far higher than the effective dynamic viscosity (μ_{eff}) under reservoir temperatures. Furthermore, the confinement effects within the nanopore throats of the formation further reduce the flow resistance of the crude oil. This vast discrepancy between laboratory conditions and the real reservoir environment directly results in evaluation outcomes that fail to reflect the actual mobility of crude oil in the subsurface.

Third is the neglect of the pore-throat radius scale: apart from Nuclear Magnetic Resonance (NMR), which indirectly reflects the pore-throat radius distribution, other methods completely fail to account for the pore-throat radius—the most critical parameter controlling fluid flow.

The three aforementioned mismatches collectively indicate that static occurrence indices cannot reliably predict the true mobility of shale oil. Cases in actual production where free hydrocarbon content is similar but productivity differs vastly serve as direct evidence for this conclusion. 3. The Essential Cause of Low Shale Oil Recovery: The Triple Coupling Control Logic. The preceding analysis of the common limitations across six categories of evaluation methods reveals a deeper contradiction in the current evaluation system: even when hydrocarbon occurrence states are accurately determined, the estimated vast resources remain in severe divergence from the macroscopically low recovery factors, which are generally below 5% to 10%. This is no longer a matter of insufficient precision in evaluation methods, but rather stems from a systemic cognitive bias regarding the migration process of shale oil within nanopore throats. The root of this bias lies in the systemic bottlenecks formed by the inherent characteristics of both the shale oil reservoir and the fluid itself.

To systematically analyze the essential reasons for this extremely low macroscopic recovery, we propose a triple coupling control logic: "Nanopore Confinement -Viscosity-Temperature Sensitivity -Macromolecular Retention." These three factors correspond to the physical attributes of the reservoir, the chemical composition of the crude oil, and the actual production dynamics, respectively. They act synergistically, progressing layer by layer and reinforcing one another, collectively constituting the rigid constraints that govern the conversion of shale oil from geological reserves to recoverable reserves.

3.1 第一重：储层约束

Shale is a typical source-reservoir symbiotic tight formation, and its inherent physical properties fundamentally define the boundaries of crude oil migration. Its core characteristics include: - **Dominance of nanopore throats:** Under ambient surface conditions, the measured mainstream pore throat radii are typically less than 100 nm, which is significantly lower than those of conventional reservoirs. Under actual subsurface effective overburden pressure, these pore throat radii further contract, making seepage conditions even more restrictive. - **Ultra-low permeability:** Permeability is generally in the micro-Darcy to nano-Darcy range, which is 3 to 6 orders of magnitude lower than that of conventional oil and gas reservoirs. - **Poor connectivity:** Pores are largely isolated or closed, lacking continuous seepage channels.

The governing mechanisms are as follows: - **Inherent channel constriction:** Even after hydraulic fracturing stimulation, matrix crude oil must still traverse dense nanopore throats to enter the fracture system. - **Inefficient energy transmission:** There is significant pressure transmission loss, making it difficult to replenish formation energy over long distances, which leads to the rapid decline of oil well production. - **Physical upper limits:** The tightness of the reservoir determines the minimum threshold for crude oil migration, acting as a fundamental bottleneck for improving oil recovery factors.

3.2 第二重：大分子滞留

Regarding the constraints on mobilization, shale oil represents hydrocarbons retained in situ, having not undergone the long-distance migration and differentiation characteristic of conventional reservoirs. Comparative analysis of group compositions reveals significant differences in the geochemical makeup of shale oil across different lithologies within the same rock series. Sandstones are enriched in saturated hydrocarbon components; conversely, mudshales contain fewer saturated hydrocarbons and are characterized by higher asphaltene content. The concentrations of heavy macromolecules, such as resins and asphaltenes, retained within mudshales are significantly higher than those in sandstones of the same series, and markedly higher than those in extra-source sandstone oil reservoirs.

The immense capillary forces generated by shale nanopore throats (Young-Laplace [**?**, **?**]) establish a high threshold for oil-phase migration. For heavy macromolecules with stronger polarity and more complex molecular structures, the interactions with pore-throat walls are more intense, making them far more difficult to displace than light, small molecules. This mechanism constitutes the fundamental cause of macromolecular retention, which manifests through three primary retention mechanisms:

Size Exclusion Effect: The particle size of asphaltene colloidal aggregates is close to or exceeds the diameter of the dominant pore throats in the shale. Consequently, effective flow is nearly impossible to establish within these tight pores.

Strong Adsorption: Due to their strong polarity, heavy macromolecules easily form stable adsorbed oil films on the surfaces of kerogen and clay minerals, thereby removing them from the category of mobile fluids. The extended Langmuir adsorption isotherm is employed to quantitatively describe this adsorption behavior.

Pore-Throat Plugging Effect: Changes in temperature and pressure conditions during the production process can easily trigger asphaltene flocculation and deposition. This further plugs pore throats and exacerbates flow difficulties. While this effect is related to phenomena discussed later, this section focuses on the resulting irreversible loss of reserves. The combined action of the aforementioned mechanisms leads to the following governing consequences:

Sharp Reduction in Mobile Oil Volume: A large volume of crude oil remains retained within the shale matrix in an adsorbed or plugged state, unable to participate in effective seepage. This creates a vicious cycle of continuously increasing flow resistance, which serves as the core “hard constraint” limiting improvements in oil recovery factors.

3.3 第三重：尺寸筛分与组分选择性运移

Determining the actual scale of recovery, not all hydrocarbons are completely immobilized within the formation. Light small molecules, benefiting from their size and physical properties, maintain partial mobility. Under the dual constraints of reservoir tightness and macromolecular retention, light small molecules such as aromatic hydrocarbons become the absolute dominant components of produced shale oil due to their distinct physicochemical properties, directly determining the realistic upper limit of recovery. To understand the flow resistance characteristics of these small molecules within nano-pore throats, the Newtonian law of internal friction provides the macroscopic theoretical support under the continuum hypothesis. In nano-pore throats, the velocity gradient is extremely high, making the internal shear stress of the fluid the primary source of resistance.

The recovery mechanism (why light small molecules become the dominant components) is driven by several factors. First is the advantage of size screening: the extremely small volume of these molecules allows them to pass smoothly through nano-scale pore throat channels, providing the fundamental conditions for migration from the matrix to the fracture system. Second, small molecules possess low dynamic viscosity and low interfacial tension, making them easier to mobilize and maintain continuous flow under the same displacement energy. Finally, they exhibit weak adsorption and are easily desorbed; the interaction forces between small molecules and rock surfaces—especially kerogen and clay minerals—are relatively weak, allowing them to dissociate from the matrix surface and enter the mobile phase.

Control and influence (the decisive role of small molecule recovery on development performance): The produced fluids undergo significant lightening, as shale oil effluents are typically enriched with light components. This phenomenon directly reflects the severe retention of heavy components within the formation. Furthermore, the total amount of mobile hydrocarbons is restricted; the absolute content of primary light small molecules in the formation and their mobilization efficiency directly limit the recoverable reserves.

Production decline is rapid; after the initially mobile small molecules are quickly produced, the subsequent diffusion supply from the matrix becomes insufficient, leading to a swift decay in production rates. In summary, as the primary components capable of large-scale seepage and recovery, light small molecules serve as both the material basis for high initial shale oil production and the key constraining factor for further improvements in recovery factors.

3.4 三重耦合的系统效应

The low recovery rate of shale oil is a systemic result of the coupling and cascading amplification of three factors: reservoir constraints, macromolecular retention, and small-molecule production. Reservoir constraints provide a harsh nanoscale seepage environment that physically filters hydrocarbon migration capacity, establishing the fundamental baseline for recovery. Simultaneously, macromolecular retention, characterized by high concentrations and strong adsorption, chemically locks heavy components and further plugs pore throats, thereby deteriorating flow conditions. Under these dual constraints, light small molecules become the only components that can be effectively produced; however, their limited content and slow replenishment ultimately lead to low recovery rates (which is the dynamic outcome of the first two constraints rather than an independent restrictive factor).

Tight reservoirs set the physical upper limit, macromolecular retention constitutes the core bottleneck, and small-molecule production determines the scale of economic recoverability. Together, these three elements form the core logical framework for controlling shale oil recovery. Returning to the fundamental laws of seepage mechanics, the underlying physical framework of shale oil mobility can be analyzed. The preceding analysis indicates that whether considering the limitations of evaluation methods or the triple constraints on recovery, the ultimate root can be traced back to the universal physical laws governing fluid migration in porous media. Starting from the classical theories of seepage and fluid mechanics, mobility is jointly controlled by these principles, allowing for a clear distinction between primary controlling laws and secondary correction mechanisms. In the following sections, we first define mobility and then sequentially present the primary laws, secondary laws, and their coupled expressions.

Definition of Mobility: Shale oil mobility is defined as the ratio of the volume of hydrocarbons that can migrate from the matrix pore system to the fracture system or wellbore via pressure-driven macroscopic seepage—under specific reservoir conditions and a given effective displacement pressure difference ΔP—to the total volume of in-situ hydrocarbons (dimensionless, M). Here, ΔP is the difference between the pressure within the fracture and the matrix pore pressure (i.e., the net driving pressure). The total in-situ hydrocarbon volume includes both adsorbed and free states. Components that migrate solely via diffusion flux without a pressure gradient are not included in the mobile volume, as their contribution to production is negligible on an engineering timescale. Only when the effective displacement pressure gradient is sufficient to overcome the total resistance formed by capillary forces, viscous resistance, and adsorption can the corresponding hydrocarbons be included in the category of mobile volume. This definition clarifies the physical essence of mobility: the ability of a fluid to achieve migration by overcoming resistance under the action of a driving force.

It should be specifically noted that during the late stages of depletion development in ultra-small pore throats and under extremely low pressure differences, although diffusion cannot directly generate mobile oil volume in an engineering sense, it can continuously replenish light components to the pressure-driven zones adjacent to fractures. This delays production decline and affects long-term recovery. While diffusion has significant engineering importance in long-term dynamic evaluation, it should not be confused with the aforementioned definition of mobility.

Primary Controlling Laws (Determining the Fundamental Magnitude of Mobility): In 1856, Darcy established the quantitative relationship between volumetric flow rate Q, permeability K, and seepage cross-sectional area A through sand column experiments (Eq. **??**). Permeability K is the primary core parameter of macroscopic mobility.

and the quantitative relationship of the seepage cross-sectional area A (Eq.

(General Principle of Macroscopic Seepage):

$= -$

Hagen [6] and Poiseuille [7] independently revealed, through capillary experiments, that the flow rate is proportional to the fourth power of the pore-throat radius. This relationship establishes that the scale variance of nanopore throats is the fundamental physical determinant of the extremely low permeability observed in shale oil reservoirs [5-7] (microscopic pore-throat dominance).

The aforementioned Hagen-Poiseuille law collectively establishes the foundation for mobility, determining the overall magnitude of whether a fluid can flow and its resulting flow velocity.

Secondary controlling mechanisms (correcting for practical deviations): While secondary mechanisms do not alter the fundamental relationships established by the primary governing laws, they significantly inhibit or regulate mobility. It should be noted that Newton' s law of viscosity serves only as the constitutive basis for dynamic viscosity μ and is not a corrective mechanism independent of the primary laws. Furthermore, diffusion does not participate in the definition of mobility for pressure-driven seepage; it only influences long-term development dynamics. Within shale nanopore throats, strong nonlinear coupling and scale effects exist among various secondary mechanisms. A reduction in pore-throat radius simultaneously amplifies capillary forces, compresses diffusion space, and intensifies viscous energy dissipation. Meanwhile, the formation of adsorbed oil films further narrows the effective seepage channels, creating a cascade amplification effect. The independent action of a single mechanism is often masked or offset by the synergistic effects of others. In practical evaluations, it is necessary to identify the dominant coupling pairs for specific reservoir conditions rather than isolating and weighting the influence of each factor independently.

Young-Laplace (Capillary Force): Pore-throat radius, interfacial tension, contact angle [10,11], pressure, temperature, specific surface area, and crude oil composition.

Langmuir Adsorption $V = \dots$

Concentration gradient, molecular size, temperature, and pore-throat structure.

Fick' s Law of Diffusion $J = -D \dots$

Note: The physical causes and engineering implications of the apparent threshold pressure gradient (TPG) are detailed below. In shale oil reservoirs, the apparent threshold pressure gradient—commonly referred to in traditional literature as the "start-up pressure gradient" —stems from two core mechanisms:

The first is homologous to the pore-throat plugging effect mentioned previously; specifically, the aggregation and bridging of heavy macromolecules such as asphaltenes and resins within nanometer-scale pore throats cause localized plugging. Unlike the previous discussion which focused on irreversible reserve loss, this section focuses on its pressure-dependent behavior during the displacement process.

Under low-pressure conditions, this manifests as a flow threshold. Once a critical value is exceeded, the blockage may be partially relieved, allowing for effective seepage to occur.

The second mechanism involves the viscous boundary layer. When the formation temperature is lower than the wax appearance temperature or the pour point of the crude oil, the dynamic viscosity of the oil increases sharply. A high-viscosity boundary layer develops on the pore-throat walls, significantly increasing flow resistance. Together, these factors dictate that effective seepage of engineering significance can only be established within the reservoir once the effective displacement pressure gradient exceeds a critical threshold. If the shale oil itself possesses a yield stress (Bingham fluid), this effect is further compounded. This paper utilizes the term "apparent threshold pressure gradient" to characterize the engineering feature of shale oil in nanopore throats, where the flow rate is extremely low at low pressures and a specific threshold must be crossed to achieve substantial seepage.

4.4 主次规律的耦合与界定

The magnitude of shale oil mobility is fundamentally established by primary governing laws (Darcy and Hagen-Poiseuille laws) and further refined by secondary correction mechanisms, such as the apparent threshold pressure gradient. Viscous resistance is inherently embedded within the dynamic viscosity and is not treated as an independent correction factor. While diffusion does not participate in the definition of mobility under pressure-driven seepage, it influences decline dynamics during long-term depletion development by replenishing light components. Strong nonlinear interactions exist between these mechanisms, meaning they cannot be decoupled into a simple product of independent correction factors. For instance, adsorbed oil films reduce the effective pore-throat radius, which simultaneously diminishes Hagen-Poiseuille flow and increases capillary force. Furthermore, the compression of pore throats by effective stress amplifies the impact of both adsorption and capillary forces. The competition between capillary force and displacement pressure ultimately determines whether the oil phase can enter the pore throat. Consequently, a practical mobility evaluation model must account for the coupling of these factors rather than treating them as mechanically multiplicative.

Before delving into the coupling relationships of these laws, it is necessary to clearly define the terminology used. The "primary governing laws" refer to the fundamental physical framework—namely Darcy' s Law and the Hagen-Poiseuille Law—which determine the order of magnitude of mobility and set the theoretical upper limit for flow rates at both macroscopic and microscopic levels. "Secondary correction mechanisms" refer to the mechanisms that refine this framework and may become the dominant bottlenecks under specific conditions, such as the apparent threshold pressure gradient. Under certain combinations of pore-throat radii, pressure gradients, and dynamic viscosities —for example, where capillary forces dominate in ultra-small pore throats or viscous resistance dominates in high-viscosity zones—these mechanisms may entirely dictate the actual magnitude of mobility. In such cases, they may even render the flow rates predicted by the primary governing laws engineeringly unachievable. The subsequent zonation aims to reveal the transitions between these dominant mechanisms.

Building upon the physical mechanisms described above, it must be specifically noted that the Darcy and Hagen-Poiseuille laws determine the magnitude of the flow rate once flow has been initiated. In contrast, secondary factors (particularly capillary force and the apparent threshold pressure gradient) determine whether the flow can be initiated at all. These two categories represent different hierarchical levels of control.

4.5 基于三参数的概念性分区

Based on the relative relationships between pore-throat radius (r), effective displacement pressure gradient (∇P), and dynamic viscosity (μ), the flow behavior can be qualitatively divided into several conceptual zones dominated by different mechanisms. It must be emphasized that this framework is intended as a guiding, conceptual qualitative partition rather than an attempt to provide precise boundary values, such as specific pore-throat radius thresholds or pressure gradient values. This is because parameters such as interfacial tension, adsorption layer thickness, and stress sensitivity in actual reservoirs involve significant uncertainty and are difficult to acquire accurately. The following zones are used solely to illustrate the transition logic of dominant control mechanisms under different conditions, rather than as a quantitative evaluation model.

The trends affecting mobility are determined by several factors: the pore-throat radius (r) dictates microscopic flow capacity; the effective displacement pressure gradient (∇P) provides the driving force for oil phase migration to overcome resistance; and the dynamic viscosity (μ) determines internal fluid resistance, controlling the ease of flow. Secondary correction factors couple with these primary factors in various ways. Strong retention is controlled by the pore-throat radius (r), forming resistance through dynamic antagonistic coupling, which constitutes the core resistance of reservoir constraints; this defines the lower limit of bound pore throats and exacerbates macromolecular retention. Adsorption (e.g., Langmuir type) reduces the effective pore-throat radius (r_{eff}) via adsorption films, weakening the conditions of primary seepage channels by forming adsorbed oil films that compress flow paths, leading to heavy component retention effects. The viscous constitutive relationship (Newton' s law of internal friction) is embedded within the primary control parameters and couples positively with dynamic viscosity (μ) and the pore-throat velocity gradient, amplifying flow resistance; under nano-confinement conditions, shear resistance increases sharply. During macro-migration and development, pressure drawdown induces changes in effective stress, compressing the pore-throat radius (r) and reducing permeability; the resulting closure and contraction of pore throats continuously shrink the mobile space of the reservoir. The apparent threshold pressure gradient (G) acts as a constraint at low effective displacement pressure gradients (∇P), restricting fluid initiation; effective seepage cannot form when driving energy is insufficient, which further exacerbates oil retention. Finally, replenishment effects (e.g., diffusion/imbibition) do not depend directly on r or μ as the three primary seepage mechanisms do; they form a supply system that, while not directly contributing to the initial mobile volume, delays production decline by supplying light components. Note: Each correction factor indirectly affects mobility by influencing the actual effective values of r, ∇P, or μ, or by introducing threshold values.

In the large pore-throat radius and high pressure gradient zone, when both the pore-throat radius (r) and the effective displacement pressure gradient (∇P) are sufficiently large, Darcy flow is absolutely dominant. Mobility is primarily controlled by the Hagen-Poiseuille and Darcy laws, while the influence of secondary factors such as capillary force and adsorption is relatively weak. In this zone, the dynamic viscosity (μ) exerts a direct negative regulatory effect on the flow rate.

In the medium pore-throat radius and medium-to-low pressure gradient zone, as the pore-throat radius (r) decreases or the effective displacement pressure gradient (∇P) drops, experiments often observe that the pressure gradient must exceed a certain apparent threshold pressure gradient (G) to produce significant flow. At this stage, the apparent threshold pressure gradient becomes the dominant control factor. The physical roots of this phenomenon primarily include the aforementioned asphaltene bridging, physical plugging, and low-temperature viscous boundary layers.

In the ultra-small pore-throat radius zone, when the radius (r) decreases to a certain extent, capillary resistance and molecular-scale constraints become insurmountable obstacles. Even if a high effective displacement pressure gradient (∇P) is applied, it remains difficult for the oil phase to enter or pass through such pore throats. This zone represents the primary storage area for immobile oil. It should be noted that for high-viscosity crude oils, even if the pore-throat radius is slightly larger than the theoretical critical value controlled by capillary force, the extremely low flow capacity will result in "immobile" behavior from an engineering perspective. That is, the dynamic viscosity (μ) substantially expands the range of the immobile pore-throat radii.

In the ultra-small pore-throat radius and extremely low pressure gradient zone, viscous flow tends to stagnate under these conditions. The transport of light components (or the gas phase) via diffusion becomes the dominant replenishment mechanism. This mechanism controls the long-term decline behavior of shale oil wells in the late stages of depletion. This zone is particularly significant for low-viscosity fluids, such as condensate oils or conditions involving high dissolved gas content.

4.6 分区框架的物理意义与评价指导

It should be particularly noted that the three parameters upon which the aforementioned four-interval classification relies—$\bar{r}$, ΔP, and μ—are the independent, fundamental control parameters for describing shale oil mobility. Other secondary parameters (such as interfacial tension in capillary force, adsorption capacity and pressure constants in adsorption isotherms, compression coefficients in effective stress, and threshold values in the apparent starting pressure gradient) are not independent of these three primary parameters. Their effects are manifested in the following two ways:

First, they modify the effective values of the primary parameters; for example, adsorption films and effective stress compression reduce the effective pore-throat radius $\bar{r}$, while confinement effects or changes in temperature and pressure alter the effective dynamic viscosity μ. Second, they are coupled with the primary parameters and medium properties; for instance, capillary force is jointly determined by $\bar{r}$ and interfacial tension σ. However, within this conceptual framework, σ is not treated as an independent variable but rather influences mobility through its coupling with $\bar{r}$. By defining $\bar{r}$, ΔP, and μ as the independent fundamental parameters and treating all other parameters as corrections or coupled effects, we maintain physical clarity while avoiding the operational difficulties associated with high-dimensional parameter spaces.

There are no sharp boundaries between the four aforementioned intervals; instead, they transition continuously, and the boundary positions shift according to factors such as the dynamic viscosity μ and the thickness of the adsorption layer. Notably, the variation range of the dynamic viscosity μ can reach several orders of magnitude, which is sufficient to completely alter the dominant mechanism landscape of each interval. Therefore, μ must be treated as an independent fundamental parameter alongside $\bar{r}$ and ΔP.

The core guiding significance of this qualitative framework is that the evaluation of shale oil mobility should not seek a single empirical criterion (such as a fixed cutoff value or temperature threshold). Instead, the mechanism interval of the target reservoir should be roughly located based on the pore-throat radius distribution $\bar{r}$, the effective displacement pressure ΔP, and the dynamic viscosity μ to select the corresponding dominant control parameters. Specific quantitative boundaries must be calibrated for particular reservoirs through experiments or numerical simulations; this paper does not prescribe a unified standard.

Secondary factors indirectly influence mobility by altering the actual operational values of primary parameters or by introducing thresholds. The core task of evaluation should be to identify the most restrictive factor under current conditions based on the actual pore-throat radius distribution and effective displacement pressure of the target reservoir. For example, capillary force dominates in the ultra-small pore-throat radius region; high dynamic viscosity (and its embedded viscous constitutive relations) dominates in high-viscosity regions even if the pore-throat radius is large; the apparent starting pressure gradient dominates when pore-throat radii are medium and pressure is insufficient; and Darcy flow dominates in the large pore-throat radius region. This approach is superior to attempting a weighted sum or product of all factors.

This conceptual integrated framework demonstrates that while the Darcy and Hagen-Poiseuille laws set the theoretical upper limit of mobility, the actual limiting factor may be dominated by a secondary law under different scales, effective displacement pressure gradients, and dynamic viscosities. The effectiveness of an evaluation method depends on its ability to dynamically reflect the transition of dominant mechanisms under varying conditions.

This qualitative zoning framework physically echoes the “macromolecular retention” triple-coupling logic proposed earlier: the pore-throat radius $\bar{r}$ and the effective displacement pressure gradient ∇P jointly determine the tightness of the reservoir’ s physical constraints; the dynamic viscosity μ and capillary force P_c reflect the impact of macromolecular retention; and diffusion relates to the replenishment behavior of small molecules. This qualitative partitioning provides a clear physical basis for parameter selection and mechanism identification in shale oil mobility evaluation.

5 基于渗流力学基本定律的可动性评价原则

Based on the aforementioned classical theoretical frameworks of percolation mechanics and fluid dynamics, two fundamental principles can be proposed to guide the evaluation of shale oil mobility. These principles are intended to address the empirical and indirect nature of existing methodologies, thereby providing a theoretical direction for the subsequent construction of quantitative evaluation models. This paper does not directly provide specific computational formulas or operational procedures.

5.1 主控优先与地层条件等效原则

Priority must be given to obtaining three independent fundamental parameters: the dynamic viscosity of crude oil under reservoir conditions (μ_o), the effective displacement pressure (ΔP), and the absolute permeability (K). These three elements constitute the basic physical dimensions for mobility evaluation and are indispensable. Detailed determination of occurrence components should be conducted under the constraints of these primary controlling parameters, rather than serving as a substitute for the analysis of physical displacement resistance.

All parameters, including dynamic viscosity, must be measured or calculated under simulated formation temperatures and effective stress conditions. This approach avoids the direct use of bulk phase data obtained at standard temperature and pressure. The compression effects of the fluid must be taken into account, as variations in pore pressure dynamically alter the rock matrix through changes in effective stress. Consequently, priority should be given to utilizing coupled corrections or stress-sensitivity experiments.

5.2 驱替

Principle of Resistance Balance

The core of mobility evaluation should focus on determining whether the effective displacement pressure gradient is sufficient to overcome the sum of various resistances, such as capillary resistance and the apparent threshold pressure gradient, rather than relying on empirical thresholds for temperature or centrifugal force. Based on the conceptual zoning discussed previously, the dominant resistance mechanisms vary across different regions. In the ultra-small pore-throat radius region, capillary force is the primary resistance. In high-viscosity regions, resistance is dominated by high dynamic viscosity (governed by the embedded viscous constitutive relationship). In regions with moderate pore-throat radii where pressure is insufficient, the apparent threshold pressure gradient becomes the dominant factor. Consequently, any mobility evaluation must identify the primary resistance term specific to the current reservoir conditions.

6 结论与建议

Fundamental Flaws and Recovery Bottlenecks

Fundamental flaws of existing evaluation methods: The six mainstream technical categories rely on indirect, empirical temperature or centrifugal force thresholds, while ignoring the physical equilibrium between the effective displacement pressure gradient and the pore-throat radius. This neglect leads to significant uncertainty in mobility assessments.

The essential cause of low recovery rates: The long-term low recovery rates of shale oil are a systemic result of the triple-coupling constraints of reservoir restriction (the physical base), macromolecular retention (the chemical shackles), and small-molecule production (the mobile subject). These factors form a cascading bottleneck characterized by oil that is "immobile, unable to move, and impossible to produce."

Framework Based on Fundamental Seepage Mechanics

The framework is based on the fundamental laws of seepage mechanics: Darcy' s law and the Hagen-Poiseuille law serve as the core governing principles that determine the basic magnitude of mobility. Secondary correction mechanisms, such as the apparent threshold pressure gradient, are incorporated, while resistance is embedded within the primary control parameter of dynamic viscosity. Diffusion does not participate in the definition of mobility for pressure-driven seepage; rather, it influences decline dynamics during late-stage depletion development through the replenishment of light components.

The parameters $\Delta P/L$, R, and μ are the three independent fundamental variables. Under different conditions, the dominant mechanisms exhibit conceptual zoning: large pore-throat radii and high pressure differentials are Darcy-dominated; medium pore-throat radii and medium-to-low pressure differentials are μ-dominated; ultra-small pore-throat radii are capillary-force dominated; and ultra-small pore-throat radii with extremely low pressure differentials are diffusion-dominated.

Principles of Evaluation

Direction of evaluation principles: Based on the fundamental laws of seepage mechanics, mobility evaluation should follow two basic principles: prioritizing equivalence with formation conditions and progressively abandoning simplistic empirical methods such as fixed T_2 cutoffs.

Implications for Technical Pathways

Technical pathway insights: Synergistically resolving the triple constraints of reservoir restriction (e.g., through enhanced volume stimulation), macromolecular retention (e.g., via thermal or chemical assistance), and small-molecule production (e.g., by optimizing displacement) is expected to provide new technical strategies for overcoming the dilemma of "large reserves but low recovery" in shale oil. The conceptual zoning framework proposed in this paper provides a theoretical foundation for further quantitative modeling.

Nomenclature

A: Seepage cross-sectional area, m^2 C: Volume concentration, mol/m^3 D: Diffusion coefficient, m^2/s J: Diffusion flux, $mol/(m^2 \cdot s)$ K_L: Langmuir constant,

Pa^{-1} ∇P: Effective displacement pressure gradient, Pa/m Q_c: Capillary volumetric flow rate, m^3/s R: Pore-throat radius, m q: Adsorption capacity, mol/kg q_m: Langmuir saturated adsorption capacity, mol/kg k_0: Initial permeability, m^2 Q_d: Darcy volumetric flow rate, m^3/s α: Stress sensitivity coefficient, Pa^{-1} θ: Contact angle, degrees $(^\circ)$ μ: Dynamic viscosity, $Pa \cdot s$ σ: Interfacial tension, N/m σ_{e0}: Initial effective stress, Pa ρ: Crude oil density index, kg/m^3

References:

References

Advances in Theory and Technology of Non-marine Shale Oil Exploration in China. *Petroleum Science Bulletin*, 2023. Zhao Wenzhi, Zhu Rukai, et al.

Petroleum Science Bulletin, 2023. Current Status, Challenges, and Development Directions of Experimental Methods for Shale Oil Geological Evaluation. 2023, 44(1):

Lianhua, Songtao, Jiang Xiaohua, Situation, challenge future direction experimental

methods

geological evaluation shale oil[J]. Petrolei Sinica, 2023, 44(1):

Yangbo Yang, Shale occurrence mechanisms: comprehensive review occurrence state, occurrence space, movability shale oil[J].

Energies 2022, 15(24):

[4] Darcy H. Les Fontaines Publiques De La Ville De Dijon[M].

Paris: Victor Dalmont, 1856.

Hagen Ueber Bewegung Wassers engen cylindrischen hren[J].

Poggendorff' s Annalen der Physik, 1839, Poiseuille, Memoir on the flow of liquids in small tubes [J]. Mémoires des Sciences de l' Institut de France, 1841, Poiseuille, Experimental research on the movement of liquids in tubes of very small diameters [J]. Mémoires des Savants Étrangers, 1846.

Mechanism of the Influence of Pressure Difference at the Fracture Tip on the Displacement Effect in Shale Reservoirs during Volume Fracturing

Journal of China University of Petroleum (Edition of Natural Science), 2024, 48(6).

Huang eirong, Influence mechanisms pressure difference fracture dynamic imbibition displacement shale reservoirs.

Journal China University Petroleum (Edition Natural Science), 2024, 48(6), Jiahao, Weifeng, Molecular Dynamics Simulation Phase Behavior Fluid Confined Nanopores[J].

Processes, 2025, 13(2): Young Essay Cohesion Fluids[J].

Philosophical Transactions Royal Society London, 1805, 10.1098/rstl.1805.0005.

Laplace Trait canique leste: Suppl ment[M]. Paris:

Courcier, Langmuir Adsorption Gases Plane Surfaces Glass, Platinum[J].

Journal American Chemical Society, 1918, 40(9): 10.1021/ja01269a066.

Stokes Effect Internal Friction Fluids Motion Pendulums[J].

Transactions Cambridge Philosophical Society, 1851, Terzaghi Berechnung Durchl ssigkeitsziffer Tones Verlauf Hydrodynamischen

Spannungserscheinungen[J]. Sitzungsberichte Akademie Wissenschaften Wien, 1923, Bingham Investigation Plastic Flow[J].

Bulletin Bureau Standards, 1917, 13(2): Diffusion[J].

Annalen Physik, 1855, 170(1): 10.1002/andp.18551700105.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.