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[1]Liang Peng,
Master's student, e-mail: 1539552876@qq.com
[1,2]*Hongbin Yang,
Associate Professor, *e-mail: hongbinyang@upc.edu.cn
[1]Zixiang Yi,
Undergraduate student, e-mail: 3297353308@qq.com
[1]Shuhe Zhang,
Master's student, e-mail: 1009383847@qq.com
Xin Chen,
Master student, e-mail: xin_baobei77@163.com
[1]Haobin Shi,
Master's student, e-mail: 2842117353@qq.com
[1]Yubin Zhang,
Master's student, e-mail: 1940390250@qq.com
[3]Wanli Kang,
Professor, e-mail: kangwanli@126.com

[1]Faculty of Petroleum Engineering, China University of Petroleum (East China), Qingdao, PR China
[2]Shandong Key Laboratory of Oil and Gas Field Chemistry, China University of Petroleum (East China), Qingdao, PR China
[3]Xin Jiang Keli New Technology Development Co. Ltd, Karamay, PR China

RESEARCH PROGRESS ON THRESHOLD PRESSURE GRADIENT IN HEAVY OIL RESERVOIRS

Abstract

Polymer flooding is one of the key technologies for enhancing oil recovery. Partially Hydrolyzed Polyacrylamide (HPAM) is widely used due to its excellent viscosity-increasing properties. However, the adsorption and retention behavior of HPAM in reservoir porous media presents a dual effect: on one hand, it improves sweep efficiency by increasing flow resistance; on the other hand, it leads to a loss in effective polymer concentration and viscosity, reducing displacement efficiency and increasing costs. Therefore, a systematic understanding and control of HPAM adsorption behavior are crucial for improving the effectiveness of polymer flooding. This work systematically reviews seven main measurement methods for HPAM adsorption quantity, comparing their applicable conditions and limitations. It summarizes the key factors influencing HPAM adsorption and retention behavior from three aspects: polymer properties, rock mineral characteristics, and reservoir environmental conditions. Furthermore, it outlines chemical anti-adsorption methods, represented by competitive adsorption and nanofilm protection, along with their mechanisms. Finally, future research directions are proposed, focusing on building adsorption prediction models, deepening the understanding of adsorption mechanisms under multi-field coupling conditions, and developing novel functional polymers with anti-adsorption capabilities.

Keywords: partially hydrolyzed polyacrylamide, adsorption retention, factors influencing adsorption, anti-adsorption, enhanced oil recovery.

Introduction

Low-permeability heavy oil reservoirs are challenging to develop due to high crude oil viscosity and poor flow capacity under reservoir conditions. A threshold pressure gradient may exist, meaning heavy oil only begins to flow when the driving pressure gradient exceeds this threshold. During the development of heavy oil reservoirs, the threshold pressure gradient typically influences the process by increasing flow resistance, leading to distinct patterns of remaining oil distribution and ultimate recovery compared to conventional reservoirs [1]. This is one of the main reasons for low productivity and development difficulties in such reservoirs [2]. The low permeability of the reservoir matrix and high fluid flow resistance often result in excessively high injection pressures during water flooding, as well as phenomena such as inadequate water injection in wells [3–5]. The presence of a threshold pressure gradient accelerates the formation of dominant flow channels, reduces the sweep efficiency of water flooding, exacerbates the mobility difference between water and oil, and promotes fingering effects, significantly impacting the pressure and saturation fields [6]. Therefore, accurately determining the threshold pressure gradient is crucial for the rational development of heavy oil reservoirs.

1. Physical Significance of Threshold Pressure Gradient

The threshold pressure gradient is a key parameter in the development of low-permeability oil and gas reservoirs, influenced by both microscopic capillary forces and macroscopic stress sensitivity [7]. As early as 1951, B.A. Florin first proposed the concept of the threshold pressure gradient while studying issues related to dense mudstone and hard clay [8]. Since then, researchers both domestically and internationally have continued to investigate this phenomenon. The threshold pressure gradient refers to the additional pressure gradient required to overcome the resistance caused by adsorbed or hydration films on rock surfaces during fluid flow in low-permeability reservoirs. It plays a critical role in simulating fluid flow, particularly under conditions where fluid begins to move only when pressure accumulation is sufficient and shear stress exceeds the yield stress. Within the framework of classical seepage theory, the threshold pressure gradient depends on fluid properties, surface interactions with the medium, and pore structure. It becomes significant when the thickness of the boundary fluid in rock pores is comparable to the pore radius, resulting in the presence of a threshold pressure gradient during fluid flow through the porous media. The existence of the threshold pressure gradient serves as the theoretical basis for the effective development of low-permeability reservoirs and helps describe low-velocity non-Darcy seepage phenomena.

Ji et al. investigated the influence of the threshold pressure gradient on pressure propagation behavior around a single well [9]. The presence of the threshold pressure gradient substantially affects pressure distribution within the reservoir. Compared with conventional seepage flow, the threshold pressure gradient intensifies the pressure drop near the wellbore, resulting in a smaller and sharper "pressure depression funnel." Moreover, at any given location within the drainage area, a higher threshold pressure gradient corresponds to a greater pressure gradient.

2. Measurement Methods for Threshold Pressure Gradient

Currently, methods for determining the threshold pressure gradient can be categorized into three major types: laboratory physical experiments, numerical experiments, and well-test interpretation [10–12]. Laboratory physical experiments include steady-state methods, unsteady-state methods, capillary equilibrium methods, bubble methods, among others. In laboratory settings, the threshold pressure gradient is typically measured by determining the relationship between pressure difference and flow rate under stable flow conditions, while in oilfield applications, it is commonly obtained through well-test analysis.

2.1 Laboratory Physical Experimental Methods

(1) Steady-State Method

The steady-state method primarily determines the threshold pressure gradient by directly regressing the linear segment of the seepage curve. For a given core sample, the pressure difference-flow rate method is employed: the flow rate through the core under different pressure differences is measured, with equilibrium pressure plotted on the horizontal axis and displacement velocity on the vertical axis in a Cartesian coordinate system. Using mathematical fitting, if the resulting curve is a straight line passing through the origin, it indicates the absence of a threshold pressure gradient in the core. If the fitted line has an intercept, it confirms the presence of a threshold pressure gradient, and the value of the intercept corresponds to the magnitude of the threshold pressure gradient [13].

(2) Unsteady-State Method

The unsteady-state method defines the threshold pressure gradient as the critical pressure gradient at which fluid transitions from flowing to non-flowing. The experimental procedure is designed as follows: initially, the core sample is saturated with crude oil under high pressure, with one end sealed and connected to a pressure gauge. After the system pressure reaches equilibrium and stabilizes, the other end of the core is depressurized to a specific pressure value. The pressure change at the sealed end is continuously monitored until the system re-stabilizes. This method offers advantages such as operational simplicity, ease of controlling experimental conditions, and short experimental duration.

(3) Capillary Equilibrium Method

The capillary equilibrium method is based on the principle of connected vessels. In this method, capillary tubes are connected to both ends of the core sample, and a height difference is created through gravitational effects. The measured height difference corresponds to the threshold pressure. The purpose of connecting capillaries to both ends of the holder is twofold: first, to sensitively and accurately reflect changes in liquid level, and second, to reduce the total seepage volume and shorten the measurement period. This approach not only confirms the existence of a threshold pressure gradient in low-permeability cores but also allows direct determination of its minimum value. During the measurement, both the capillary tubes and the core are filled with the experimental fluid, with the liquid level at the outlet end maintained lower than that at the inlet end to establish a constant pressure gradient. Driven by this pressure gradient, fluid flows through the core, causing the liquid level at the outlet to rise and that at the inlet to fall. If no threshold pressure gradient exists in the core, the liquid levels at both ends will equalize after sufficient equilibration. If a threshold pressure gradient is present, a height difference will remain, which represents the actual threshold gradient of the core [14, 15]

(4) Bubble Method

The bubble method involves immersing the outlet pipeline of the core sample into water. When liquid displaces the core, an additional pressure is applied to overcome both the resistance within the core and the interfacial tension between fluids, enabling the displacing fluid to enter the pore channels. Once the fluid begins to move, bubbles emerge at the outlet end of the core. The displacement pressure at this moment corresponds to the threshold pressure.

2.2 Numerical Experimental Methods

Mathematical models are used to indirectly determine the minimum threshold pressure gradient by incorporating various influencing factors and establishing mathematical equations. Based on capillary pressure curves or pore-throat distribution curves of core samples, a numerical structure of the porous medium is constructed using the Lattice Boltzmann (LB) model. The LB method is then employed for simulation to generate a corresponding curve. By extending the linear segment of this simulated curve until it intersects the pressure gradient axis, the value at the intersection point represents the dimensionless threshold pressure gradient. A scaling factor between dimensionless and dimensional quantities is derived by comparing simulation results with actual field pressure gradient data, enabling the determination of the threshold pressure gradient for the target formation [16]. Yun proposed an irregular model for the threshold pressure gradient of Bingham fluids in porous media, based on pore properties and capillary pressure effects [17]. Each parameter in this model has a clear physical meaning, and it establishes relationships between the structural parameters of the porous medium, yield stress, capillary pressure parameters, the fractal dimension of the porous medium, and the threshold pressure gradient of Bingham fluids.

2.3 Well-Test Interpretation Methods

Well-test interpretation methods analyze actual field data to dynamically and in situ determine the threshold pressure gradient [18]. Based on previous research experience, Liu et al. proposed a well-test interpretation approach to address the threshold pressure gradient issue by developing models incorporating control equations, flow velocity equations, and inner/outer boundary conditions distinct from those used in conventional reservoirs [19]. A comparison reveals the key difference between conventional and low-permeability reservoir well-test models: in conventional reservoirs, fluid flow occurs whenever a pressure gradient exists, whereas in low-permeability reservoirs, flow only initiates when the pressure gradient exceeds the threshold pressure gradient. This distinction is reflected in theoretical curves through an upward deflection in the pressure derivative curve.

2.4 Comparative Analysis of the Three Methods

Laboratory simulation methods provide an intuitive and direct approach for studying seepage mechanisms and are currently widely recognized for determining the threshold pressure gradient. However, this approach faces two main challenges: extended experimental durations and the difficulty of maintaining cores in their natural underground state due to stress release. Although the underlying seepage mechanisms remain valid, these factors may introduce significant data errors.

Numerical experimental methods offer advantages such as simplicity, speed, and the ability to explore a wide range of parameters. However, they rely heavily on the pore-throat distribution characteristics of the formation and require comparative experimental data for validation. When combined with laboratory simulation methods, numerical approaches can yield results that align closely with comparative experiments. This makes numerical experimentation a promising auxiliary tool for enhancing laboratory-based physical simulation studies of reservoirs.

Well-test interpretation methods dynamically reflect reservoir behavior, making the threshold pressure gradient determined through this approach highly relevant for practical applications. However, a drawback of this method is that field operations are time-consuming and relatively costly.

3. Factors Influencing Threshold Pressure Gradient in Heavy Oil

Heavy oil only begins to flow when the driving pressure gradient exceeds the threshold pressure gradient. While accurately measuring the threshold pressure gradient is essential, its influencing factors cannot be overlooked. Current research indicates that crude oil viscosity, permeability, and water saturation significantly affect the threshold pressure gradient. Experimental studies have also demonstrated the influence of other factors such as wettability and confining pressure.

3.1 Crude Oil Viscosity

Viscosity is one of the key characteristic parameters of heavy oil. The variable nature of heavy oil viscosity is a primary reason for its classification as a non-Newtonian fluid, and as such, it exhibits specific flow behaviors typical of non-Newtonian fluids. Sun suggested that the viscosity of heavy oil is mainly influenced by the content of non-hydrocarbon components (e.g., resins) and asphaltenes [20]. Asphaltenes, being the most polar components in heavy oil, determine the molecular polarity of heavy oil and affect both liquid-liquid and solid-liquid interfacial tension, thereby influencing the shear stress of heavy oil. During seepage through porous media, the shear stress of heavy oil impacts its threshold pressure gradient. Under porous media conditions, heavy oil exhibits shear-thinning behavior, and the transition point can be used to determine the critical threshold pressure gradient. As the content of resins and asphaltenes increases, the threshold pressure gradient also increases. Cao et al. demonstrated that crude oil viscosity significantly affects the threshold pressure gradient [21]. The threshold pressure gradient is negatively correlated with crude oil viscosity, meaning it decreases as the viscosity increases.

3.2 Permeability

Ke et al. demonstrated that permeability significantly influences the threshold pressure gradient [22]. The threshold pressure gradient is positively correlated with permeability, meaning it decreases as permeability increases. Bai et al. reported similar findings in their research [23]. As permeability increases, the threshold pressure gradient of the core decreases accordingly. This is attributed to the narrow pores and throats in tight reservoirs, which result in significantly higher seepage resistance during fluid flow compared to conventional reservoirs, leading to a larger threshold pressure gradient. When permeability falls below a certain critical value, the threshold pressure gradient decreases sharply.

3.3 Water Saturation

For low-permeability cores, the oil phase remains relatively continuous under irreducible water conditions. After water flooding for a period, water saturation increases, and some oil is displaced. The oil phase in the core becomes disconnected by the water phase, existing as oil droplets or columns within the pores. As a result, additional resistance is generated when oil begins to flow. Higher water saturation leads to more dispersed oil droplets, increasing this additional resistance. Therefore, the threshold pressure gradient in low-permeability cores increases with rising water saturation. In contrast, for medium-permeability cores, increasing water saturation causes the water phase to gradually become continuous, forming dominant flow channels. Due to the relatively larger pore radii, the additional resistance caused by oil droplet mobilization has less impact. Thus, the threshold pressure gradient decreases with increasing water saturation [24, 25].

Zou et al. studied the two-phase threshold pressure gradient in cores and found that, depending on the strength of capillary effects, the two-phase threshold pressure gradient first increases and then decreases with increasing average water saturation [26].

3.4 Other Factors

Zhang et al. verified that the threshold pressure gradient of core samples decreases as the relative wettability index increases [27]. The stronger the hydrophilicity of the core, the lower the threshold pressure gradient. Additionally, the threshold pressure gradient exhibits a strong linear correlation with the thickness of the boundary layer liquid: as the boundary layer thickness increases, the threshold pressure gradient gradually rises.

Wang et al. suggested that enhanced oil-wettability of rock samples strengthens the molecular interactions at the oil-solid interface, ultimately leading to an increase in the thickness of the crude oil boundary layer and a higher threshold pressure gradient [28]. In other words, greater oil-wettability of the rock sample corresponds to an increase in the threshold pressure gradient.

Tian et al. investigated the effects of confining pressure and clay properties on the threshold pressure gradient [29]. They found that the threshold pressure gradient increases with rising net confining pressure, though the rate of increase gradually diminishes. The presence of microfractures reduces the threshold pressure gradient. An increase in the volume fraction of expansive clay worsens seepage efficiency. Additionally, an increase in water saturation causes the threshold pressure gradient to first rise and then decline.

Xu et al. studied the influence of irreducible water on the threshold pressure gradient [30]. Experimental results showed that the measured threshold pressure gradient in rock samples containing irreducible water is higher than in those without irreducible water.

Xiong et al. investigated the influence of dominant throat radius and movable fluid saturation on the threshold pressure gradient [31]. They found that the threshold pressure gradient gradually decreases as the dominant throat radius increases. Similarly, a higher movable fluid saturation corresponds to a lower threshold pressure gradient. This is because lower movable fluid saturation leads to a thicker interfacial layer, significantly reducing the effective seepage space in low-permeability reservoirs and resulting in a higher threshold pressure.

Conclusion

This study summarizes the measurement methods for the threshold pressure gradient, including laboratory physical experiments, numerical simulations, and well-test interpretation. It compares the advantages and disadvantages of these different approaches to reduce measurement errors and improve accuracy. A systematic summary of the influencing factors on the threshold pressure gradient-such as crude oil viscosity, permeability, and water saturation-is provided. The research findings offer theoretical support and a foundation for experiments on the threshold pressure gradient in heavy oil.

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[1]Лян Пэн,
магистрант, e-mail: 1539552876@qq.com
[1,2]*Хунбин Ян,
доцент, *e-mail: hongbinyang@upc.edu.cn
[1]Цзисян И,
бакалавриат студенті, e-mail: 3297353308@qq.com
[1]Шухэ Чжан,
магистрант, e-mail: 1009383847@qq.com
[1]Синь Чен,
магистрант, e-mail: xin_baobei77@163.com
[1]Хаобин Ши,
магистрант, e-mail: 2842117353@qq.com
[1]Юйбинь Чжан,
магистрант, e-mail: 1940390250@qq.com
[3]Ваньли Кан,
профессор, e-mail: kangwanli@126.com

[1]Мұнай инженериясы факультеті, Қытай мұнай университеті (Шығыс Қытай), Циндао қ., ҚХР
[2]Шаньдун провинциясының мұнай және газ кен орындарының химиясы жөніндегі негізгі зертханасы, Қытай мұнай университеті (Шығыс Қытай), Циндао қ., ҚХР
[3]Xin Jiang Keli New Technology Development Co. Ltd, Қарамай қ., ҚХР

АУЫР МҰНАЙ КОЛЛЕКТОРЛАРЫНДАҒЫ ҚЫСЫМНЫҢ ШЕКТІ ГРАДИЕНТІ ЖӨНІНДЕГІ ЗЕРТТЕУЛЕРДІҢ ПРОГРЕСІ

Аңдатпа

Ауыр мұнай құрамындағы шайырлар мен асфальттер сияқты жоғары молекулалық қосындылар оның бірегей құрылымдық қасиеттерін, яғни сызықты емес сүзілу сипаттамаларын айқындайды. Қысым градиентінің табалдырық мәні (threshold pressure gradient) – Дарси емес ағынды зерттеудегі маңызды параметр. Бұл мақалада ауыр мұнай коллекторларындағы қысым градиентінің табалдырық мәнін зерттеу саласындағы жетістіктерге жан-жақты шолу жасалған. Онда қысым градиентінің табалдырық мәнін анықтаудың негізгі әдістері – зертханалық физикалық эксперименттер, сандық модельдеу және ұңғымаларды сынау нәтижелерін талдау – қарастырылып, әр тәсілдің артықшылықтары мен шектеулері салыстырылған. Сонымен қатар, шикі мұнайдың тұтқырлығы, өткізгіштігі және суға қанығуы сияқты негізгі әсер етуші факторлар талданады. Зерттеу нәтижелері қысым градиентінің табалдырық мәні, әдетте, шикі мұнайдың тұтқырлығы артқан сайын өсетінін, төмен өткізгіштігі бар керндерде суға қанығу артқан сайын көбейетінін, ал өткізгіштік артқан сайын азаятындығын көрсетеді. Бұл зерттеу әсер етуші факторлар мен өлшеу әдістеріне қатысты жүйелі қорытындылар ұсына отырып, өлшеу қателіктерін барынша азайтуға және ауыр мұнай коллекторларындағы айдау мен өндіру процестерін оңтайландыруға теориялық негіз береді.

Тірек сөздер: ауыр мұнай, Дарси емес ағыс, қысым градиентінің табалдырық мәні, сынау әдістері, әсер етуші факторлар.

[1]Лян Пэн,
магистрант, e-mail: 1539552876@qq.com
[1,2]*Хунбин Ян,
доцент,*e-mail: hongbinyang@upc.edu.cn
[1]Цзисян И,
бакалавр, e-mail: 3297353308@qq.com
[1]Шухэ Чжан,
магистрант, e-mail: 1009383847@qq.com
[1]Синь Чен,
магистрант, e-mail: xin_baobei77@163.com
[1]Хаобин Ши,
магистрант, e-mail: 2842117353@qq.com
[1]Юйбинь Чжан,
магистрант, e-mail: 1940390250@qq.com
[3]Ваньли Кан,
профессор, e-mail: kangwanli@126.com

[1]Факультет нефтяной инженерии, Китайский нефтяной университет (Восточный Китай), г. Циндао, КНР
[2]Ключевая лаборатория химии нефтяных и газовых месторождений провинции Шаньдун, Китайский нефтяной университет (Восточный Китай), г. Циндао, КНР
[3]Xin Jiang Keli New Technology Development Co. Ltd, г. Карамай, КНР

ПРОГРЕСС ИССЛЕДОВАНИЙ ПО ПОРОГОВОМУ ГРАДИЕНТУ ДАВЛЕНИЯ В КОЛЛЕКТОРАХ ТЯЖЕЛОЙ НЕФТИ

Аннотация

Высокомолекулярные смеси, такие как смолы и асфальтены в тяжелой нефти, определяют ее уникальные структурные свойства, проявляющиеся в характеристиках нелинейного просачивания. Пороговый градиент давления является критическим параметром при изучении недарсиевского течения. В данной статье представлен всесторонний обзор прогресса исследований погрешности градиента давления в коллекторах тяжелой нефти. В ней обобщены основные методы определения порогового градиента давления, включая лабораторные физические эксперименты, численное моделирование и интерпретацию результатов испытаний скважин, а также сравниваются преимущества и ограничения каждого подхода. Кроме того, в ней анализируются ключевые факторы влияния, такие как вязкость сырой нефти, проницаемость и водонасыщенность. Результаты показывают, что пороговый градиент давления, как правило, увеличивается с ростом вязкости сырой нефти, увеличивается с ростом водонасыщенности в низкопроницаемых кернах, но уменьшается с ростом проницаемости. В данном исследовании представлены систематические выводы относительно этих факторов влияния и методов измерения, направленные на минимизацию погрешностей измерений и предоставление теоретической основы для оптимизации процессов закачки и добычи в коллекторах тяжелой нефти.

Ключевые слова: тяжелая нефть, недарсиевский поток, пороговый градиент давления, методы испытаний, влияющие факторы.

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