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Perspective

An *in-situ* low-carbon enhanced oil recovery approach applied in high viscous oil reservoir

Xiang Zhou[1,2], Jianhao Liu[1], Yulong Zhao[1,2]*, Fanhua Zeng[3], Qi Jiang[1,4]*, Liehui Zhang[1,2]

[1]*Petroleum Engineering School, Southwest Petroleum University, Chengdu 610500, P. R. China*

[2]*State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu 610500, P. R. China*

[3]*Energy Systems Engineering, University of Regina, Regina, SK, S4S 0A2, Canada*

[4]*Schulich School of Engineering, University of Calgary, Calgary, AB, T2N 1N4, Canada*

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Abstract:

High heat loss, substantial energy consumption, considerable CO_2 emission and low thermal utilization efficiency are main challenges in the thermal-based production methods applied in high viscous oil reservoir. To address these limitations while achieving both high oil recovery and reduced carbon footprint, this perspective systematically investigates an enhanced high viscous oil recovery method that integrates *in-situ* pyrolysis with downhole electric heater. Laboratory experiments and field applications demonstrate that this novel technology offers multiple advantages over conventional thermal-based methods, such as higher thermal utilization efficiency, lower carbon emissions and reduced energy consumption. In this novel technology, with high temperature in the reservoir, inducing pyrolysis and cracking reactions in high viscous oil, significantly reducing oil viscosity and enhancing oil recovery factor. Thereby, this novel method presents a viable, low-carbon, and efficient pathway for future development of high viscous oil resources.

1. Introduction

As conventional oil reserves declining significantly, scholarly focus has progressively shifted toward the high viscous oil recovery. The characteristically high viscosity of heavy oil severely impedes production by limiting fluid mobility, making viscosity reduction essential (Chen et al., 2025). In the high oil recovery approaches, thermal-based recovery methods are widely recommended to reduce oil viscosity, including steam-assisted gravity drainage (SAGD), steam huff-n-puff, steam flooding, *in-situ* upgrading, etc. (Dong et al., 2019). Uniting the dual objectives of high recovery and low emissions, a novel *in-situ* upgrading coupled with downhole electric heater has been developed. This process is considered as the most cutting-edge technology, primarily attribute to extremely high viscosity reduction, high oil upgrading ratio, low to net carbon emission, and friendly to the environment, etc.

Effective implementation of *in-situ* upgrading technology depends on efficient heat transfer into the reservoir formation. While energy can be derived from fossil fuels (such as oil, natural gas, coal) or renewable resources (such as wind, solar), renewables are particularly advantageous owing to their reduced carbon footprint and cost efficiency (Yang et al., 2024). A notable example is the successful deployment of solar-powered steam generation for heavy viscous oil production at the Xinjiang Oilfield in September 2025, underscoring the viability of renewable energy in oil field. In this configuration, surface-generated electricity from renewables is transmitted to downhole heaters, which convert it into thermal energy within the high viscous oil zone. The downhole electric heater transmits energy directly into the reservoir, avoiding heat loss

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*Corresponding author.
E-mail address: shawnzhou326@126.com (X. Zhou); 202221000933@stu.swpu.edu.cn (J. Liu); swpuzhao@swpu.edu.cn (Y. Zhao); fanhua.zeng@uregina.ca (F. Zeng); qijiang@shaw.ca (Q. Jiang); zhangliehui@163.vip.com (L. Zhang).

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in wellbores and pipelines compared with the conventional thermal-based methods. The combined *in-situ* upgrading coupled with downhole electric heater process reaches temperature up to as high as 300-400 °C or higher, facilitating hydrolysis and molecular decomposition of high viscous oil, which markedly enhances fluid mobility and recovery. Moreover, at these temperatures, long-chain hydrocarbons undergo cracking into shorter chains, effectively upgrading the oil into relative lighter hydrocarbons (Zhao et al., 2024). A portion of these products is further transformed via gasification into solvent gases including CO_2, CH_4, C_2H_6, and C_3H_8, which act as *in-situ* viscosity-reducing agents upon dissolving into the crude oil (Ifticene et al., 2024).

This work introduces an integrated technological framework combining *in-situ* upgrading with downhole electric heater. This new approach extremely decreases the oil viscosity by decomposing the high viscous oil into light oil, and thus oil recovery factor can be significantly enhanced. The findings can be guidance for enhancing oil recovery in high viscous oil reservoir. By tracking the dual constraints of energy intensity and carbon footprint, this novel approach establishes a sustainable and economically feasibility pathway for the high viscous oil development.

2. Mechanism

A new approach is developed as reservoir thermal stimulation via electric heating delivers electrical energy to a downhole heater, which converts it into thermal energy within the formation (Guo et al., 2019). Significant viscosity reduction can be obtained and induces the molecule cracking of long-chain into short-chain molecule fractions, thereby altering the physical and chemical properties of oil in heated region and increasing oil mobility, thus enhancing oil recovery factor remarkably.

Electric energy is transferred into thermal energy by the downhole electric heater, developing a high-temperate chamber around the heater. Thermal energy dissipates radially through conduction and convection, creating a temperature gradient that governs reaction regimes: chemical cracking predominates near the heater, while physical processes dominate near the boundary of the high-temperature chamber (<150 °C) (Zhang et al., 2025). By regulating power input, temperatures adjacent to the heater are maintained around 300-400 °C, surpassing the pyrolysis threshold of high viscous oil (Zhou et al., 2025). This induces molecular scission of long-chain hydrocarbons, generating light oil fractions and gas species. The resulting viscosity reduction and chemical upgrading remarkedly improve oil mobility, enabling rapid drainage to the producer and oil saturation decline in the high temperature chamber. Because of gravity differentiation between gas phase and liquid phase, part of the generated gas phase migrates in the high temperature chamber. The gas phase accumulates at top and boundary of the chamber, forming an insulated zone which has both disadvantage and an advantage (Yang et al., 2025). For the advantages, the accumulated gas dissolves into oil phase at the oil interface, reducing oil viscosity and increasing oil mobility, the dissolved oil flows along the oil interface to the producer. Thus, more oil assembles around the producer and higher oil recovery factor is obtained. Also, this layer hinders the upper part expansion of the high temperature chamber by reducing heat transfer to the upper interface, reducing overburden heat loss. For the disadvantages, the gas layer intends an isolation to thermal convection and conduction, results in an obstacle to the thermal reaction radius.

A radial thermal gradient extends from the heater to the periphery of the high-temperature chamber, declining to ambient reservoir conditions. Along the high temperature chamber boundary, aqueous and volatile phases evaporate as temperatures surpass their evaporation temperature under prevailing pressure. In water-rich zones, steam generation activates solvent-assisted SAGD mechanisms (Dong et al., 2019). The resulting vaporized solvents co-transport with steam toward the oil interface, dissolving into the crude to reduce viscosity. Furthermore, the generated CO_2 mixing with the steam lowers the partial pressure of steam, reducing its saturation temperature and condensation tendency, thereby helping maintain the chamber pressure. Condensation of the generated steam and solvents (light hydrocarbons) occurs at interface of the steam chamber (Yang et al., 2024). The concentration of the solvent peaks at the boundary of the chamber and exhibits a declining gradient toward the drainage interface, indicating diffusion into the high viscous oil phase.

The application of catalysts is considered essential for enhancing pyrolysis efficiency in high viscous oil, various catalysts are considered to employ into the reservoirs. Catalytic systems lower the optimal temperature for maximum reaction rate (Yang et al., 2022), and higher reaction rate can be achieved. Through reduction of reaction activation and modification of reaction mechanisms, catalysts substantially improve *in-situ* pyrolysis performance and reduce processing time (Gu et al., 2024). Additionally, they serve to inhibit coke formation, preventing potential wellbore impairment due to carbonaceous deposits and coke generation (Pham et al., 2025). With downhole electric heater, more benefits can be gained than the conventional thermal-based recovery methods, provides superior performance through uniform wellbore heating and controlled growth of the thermal chamber.

This approach effectively suppresses water coning in high viscous oil reservoirs with bottom-water zone by maintaining gradual thermal propagation and reduced reservoir-producer pressure gradients, thus, oil recovery factor can be boosted. Specifically, the interlayer in the oil reservoir is an obstacle in the conventional thermal-based recovery methods, mainly due to it hinders the steam chamber expansion, the oil beyond the interlayer cannot be heated (Wu et al., 2022). While, with the downhole electric heater, the location of electric cable can be settled, so that the heating area can be controlled and the oil beyond the interlayer can be produced, leading to high oil recovery factor can be obtained.

3. Influence factors

The performance of this novel technology is governed by three primary factor categories: formation characteristics, engineering and operational parameters, and chemical/catalyst systems. For the effect of formation property, the thermal conductivity critically determines the spatial extent of the reactive zone by regulating the dimensions of the high-temperature chamber. Enhanced thermal conductivity facilitates chamber expansion, increasing the zone of upgraded oil and thereby enhancing oil production performance. The heterogeneity of the formation, leading to generated gas figuring in the high temperature chamber and uneven efficiency of the drainage in different permeability formation zones. The thickness of the formation is another influence factor for the novel approach. Because pay zone thickness significantly affects thermal management, with thin formations exhibiting substantial heat loss to adjacent strata upon chamber development. Furthermore, oil composition of the targeted reservoir directly impacts process effectiveness: elevated asphaltene and resin concentrations enhance coking propensity, while sulfur and metal contents elevate catalyst deactivation risks.

Within the engineering and process domain, heater power is vital factor for this novel method. This parameter controls thermal input dynamics, with experimental evidence confirming a positive correction between heating rate and pyrolysis reaction rate. The temperature in the chamber relates to the type of light components can be generated, and if an excessive temperature is implemented, the coke will be generated in the heat zone, leading to blockage for the heat transfer and reduces oil decomposition efficiency. Therefore, the heater power should be selected according to the oil property and formation property for a certain high viscous oil reservoir.

For the chemical and catalyst aspect, the introduction of specific catalysts promotes the pyrolysis of side chains in both saturated and unsaturated compounds, leading to the cracking of C-C, C-S bonds and generation of small molecules (Alpak and Karanikas, 2020). Previous studies have demonstrated the application of diverse catalytic systems in reservoir settings, encompassing water-soluble catalyst, oil-soluble catalyst, solid acid catalyst, dispersed catalyst, and bifunctional catalyst (Wei et al., 2025). Optimal catalyst selection depends on integrated considerations of crude oil composition, formation properties, and operational parameters including temperature, water saturation, and permeability. A suitable catalyst is benefit to the oil production, so that the catalyst should be optimized for each reservoir. Notably, in the absence of introduced catalysts, indigenous minerals can serve as effective natural catalysts for *in-situ* solvent generation (An et al., 2024), with several mineral types demonstrating catalytic enhancement.

4. Field application

Since the 1970s, pilot tests of the electric-based method have been carried out in the oilfields, the technical feasibility of applying electric heating for oil recovery in high viscous oil reservoirs, leading to continued technological refinement. The commercial-scale application of renewable resources (e.g., wind, solar) to generate electricity and heat the high viscous oil reservoir using downhole electric heater is still not reported. Most of the existing pilot tests predominantly employ conventional electricity generation from oil, natural gas, coal and so on. The technology remains in limited pilot testing, with significant development needed before broad commercialization. The successful implementation of the electric heating technology for high viscous oil reservoir are usually reported as effective implementations utilize electromagnetic, resistive, or electrode heating to convert surface-supplied electricity into reservoir thermal energy. Production performance from the successful field tests of the electric heating process indicates that, with high temperature (as high as 300 °C) gained in the reservoir (Alpak and Karanikas, 2020), the pyrolysis process occurred and the significant viscosity reduction of the produced oil is investigated, also the fractions of the light hydrocarbons in the produced oil increased remarkably, proving the *in-situ* upgrading mechanism of the process. Till now, the cost for high viscous oil recovery is investigated as low as around 7dollar/bbl, even the cost is calculated as 22.5 dollar/bbl for the whole life process (You et al., 2025). That is much lower than the conventional thermal-based methods, and will gain much benefits in the high viscous oil production using this method.

5. Challenges and prospects

Although *in-situ* upgrading coupled with downhole electric heater demonstrates significant potential, its commercial deployment confronts multiple technical barriers. These include: (1) the precise control of the outside temperature of downhole heater and reaction process, when the temperature is too high around the wellbore, high viscous oil may be prone to coking, reducing heating efficiency of the electric heater or even causing damage of heater or liner tube. (2) Acidic gases such as H_2S can be generated in this novel process, increasing the risk of the produced gas separation, elevating surface treatment costs, and hydrogen embrittlement damage of the pipelines. (3) Most of the studies on *in-situ* upgrading coupled with downhole electric heater are reported using numerical simulation and laboratory scale experiment methods. The upscale of the laboratory results to filed scale is lack nowadays, results in less guidance for the filed application. (4) The application of catalyst in the laboratory gained much better production performance than the reaction without catalyst. However, how to employ the catalyst into the reservoir, and increase the reaction zone need further studies. Most of the catalysts applied in the *in-situ* upgrading process are reacted near the wellbore, the application far away from the wellbore should be investigated. (5) The heating power of the downhole electric heater is another challenge to increase the area of *in-situ* upgrading, higher heating power gained a larger heating area, leading to higher oil recovery factor, but will face the risk of coke generation and block the formation. (6) New technologies should be developed to ensure safe-long-term running of high heating power downhole electric heater, and application coupled with other thermal-based recovery methods, such as SAGD, steam flooding, steam huff-n-puff, toe to heal air injection, etc., the coupled methods will gain significant oil production with both upgrading and thermal recovery mechanisms.

With benefits of high thermal utilization efficiency, low-carbon, low energy consumption, the *in-situ* upgrading coupled with downhole electric heater holds clear prospects for sustainable development: (1) It can be used with the other thermal-based EOR process mentioned before, the *in-situ* generated gas phase in the upgrading process provides solvent mixture, with the co-injection steam, a solvent assisted steam-based method is developed. (2) The downhole electric heater can be treated as an underground steam generator, which can extremely increase the steam quality and extend the adaptation depth of the reservoir for steam-based recovery methods, leading to steam-based recovery methods can be successfully applied in the medium to deep high viscous oil reservoirs. (3) The *in-situ* upgrading coupled with downhole electric heater can be applied in complex high viscous oil reservoir, such as reservoir with bottom water zone. The water invading from the bottom water zone in the conventional thermal-based recovery method will be released, and higher recovery factor can be obtained. (4) Coupled with other solvent-based methods, such as cyclic solvent injection, solvent vapour extraction process, the downhole electric heater can supply higher temperature for oil viscosity reduction, the generated solvent in the *in-situ* upgrading technology can improve concentration of the injected solvents in the reservoir. Therefore, oil viscosity can be extremely reduced and higher oil recovery can be gained.

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Conflict of interest

The authors declare no competing interest.

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