energies

MDPI

Review

Technology Progress in High-Frequency Electromagnetic In Situ Thermal Recovery of Heavy Oil and Its Prospects in Low-Carbon Situations

Yang Yang [1], Wenchao Liu [1,2,*], Jifei Yu [1], Chen Liu [2], Yanfeng Cao [1], Mingkai Sun [2], Menglong Li [1], Zicheng Meng [2] and Xinjiang Yan [1]

[1] State Key Laboratory of Offshore Oil and Gas Exploitation, Beijing 100028, China; yangyang42@cnooc.com.cn (Y.Y.); yujf2@cnooc.com.cn (J.Y.); caoyf@cnooc.com.cn (Y.C.); liml26@cnooc.com.cn (M.L.); yanxj3@cnooc.com.cn (X.Y.)

[2] School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China; m202110025@xs.ustb.edu.cn (C.L.); m202310031@xs.ustb.edu.cn (M.S.); mengzicheng2023@163.com (Z.M.)

* Correspondence: wcliu_2008@126.com or b1701026@ustb.edu.cn

Abstract: Heavy oil resources are abundant globally, holding immense development potential. However, conventional thermal recovery methods such as steam injection are plagued by high heat loss, substantial carbon emissions, and significant water consumption, making them incompatible with carbon reduction goals and the sustainable socioeconomic development demands. A new method of high-frequency electromagnetic in situ heating, which targets polar molecules, can convert electromagnetic energy into heat so as to achieve rapid volumetric heating of the reservoir. This method has the potential to overcome the drawbacks of traditional techniques. Nevertheless, it faces significant drawbacks such as limited heating range and inadequate energy supply during later production stages, which necessitates auxiliary enhancement measures. Various enhancement measures have been reported, including nitrogen injection, hydrocarbon solvent injection, or the use of nano-metal oxide injections. These methods are hindered by issues such as pure nitrogen being easy to breakthrough, high costs, and metal pollution. Through extensive literature review, this article charts the evolution of high-frequency electromagnetic in situ heating technology for heavy oil and the current understanding of the coupled heat and mass transfer mechanisms underlying this technology. Moreover, based on a profound analysis of the technology's progression trends, this work introduces a new direction: CO_2-N_2 co-injection as an enhancement strategy for high-frequency electromagnetic in situ heavy oil recovery. There is promising potential for the development of new technologies in the future that combine high efficiency, low carbon emissions, environmental friendliness, economic viability, and energy conservation. Furthermore, some research prospects in low-carbon situations and challenges for the new technology in future are presented in detail. All in all, the contribution of the paper lies in the summarizing of some main drawbacks of current enhanced electromagnetic in situ thermal recovery methods, and presents a novel research direction of using CO_2-N_2 co-injection as an enhancement strategy based on its current research status in low-carbon situations.

Keywords: heavy oil; electromagnetic in situ thermal recovery; low carbon emission; multi-physics coupling mechanism; CO_2-N_2 co-injection

check for updates

Citation: Yang, Y.; Liu, W.; Yu, J.; Liu, C.; Cao, Y.; Sun, M.; Li, M.; Meng, Z.; Yan, X. Technology Progress in High-Frequency Electromagnetic In Situ Thermal Recovery of Heavy Oil and Its Prospects in Low-Carbon Situations. *Energies* **2024**, *17*, 4715. https://doi.org/10.3390/en17184715

Academic Editor: Dameng Liu

Received: 9 August 2024
Revised: 7 September 2024
Accepted: 20 September 2024
Published: 22 September 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Heavy oil reservoirs are widely distributed across countries such as China, the United States, and Canada. China's heavy oil resource volume reaches up to 1.98 billion tons, representing enormous development potential. These resources in China are primarily located in Liaohe oilfield, Shengli oilfield and Xinjiang oilfield, and the Bohai Bay offshore area [1–5]. Heavy oil is characterized by high contents of colloid and resin, leading to

high fluid viscosity and exhibiting Bingham non-Newtonian fluid properties, which pose significant challenges for extraction. Amidst the increasing global demand for oil and gas and declining production from conventional sources, the exploitation of difficult-to-produce heavy oil reservoirs has become a key focus for sustaining oil output. Traditionally, thermal recovery methods have been employed to enhance the mobility of heavy oil in situ [1–5], including steam flooding, steam stimulation, Steam Assisted Gravity Drainage (SAGD), and solvent injection (such as hydrocarbons, CO_2, N_2, etc.) to augment steam processes. However, these techniques entail substantial water consumption, high carbon emissions, significant heat loss in the wellbore, and relatively low economic efficiency. High-frequency electromagnetic (EM) in situ heating (operating in the frequency range of 300 kHz to 300 GHz) [6–10] stands as a novel "waterless" recovery approach, boasting advantages like high thermal energy utilization (over 92% of the electromagnetic energy can be transmitted to the heavy oil reservoir), rapid volumetric heating, controllable heating targets, lower development costs with in situ conversion, environmental friendliness, and suitability for deep, thin, and heterogeneous reservoirs. Additionally, the surface radiofrequency (RF) equipment occupies minimal space and can be powered by renewable energy sources like solar or wind, making it adaptable for offshore and remote onshore heavy oil exploitation (see Figure 1a). Therefore, there will be no carbon emissions for electricity productivity, and the question of how to utilize on-site wind and solar energy for providing sufficient electricity production is a big challenge. Consequently, conducting research on the scientific theories and engineering methods related to this new technology of electromagnetic in situ thermal recovery for heavy oil holds crucial significance for tackling the engineering challenges faced in current heavy oil extraction practices in China, offering both theoretical insights and practical applications. Here, the main objective of the paper is to introduce the development history of high-frequency electromagnetic in situ heating technology, the challenges in engineering applications of this technology and its enhancement measures, the research progress by physical experiment method and mathematical modeling method, and the research prospects and challenges of this technology in low-carbon situations.

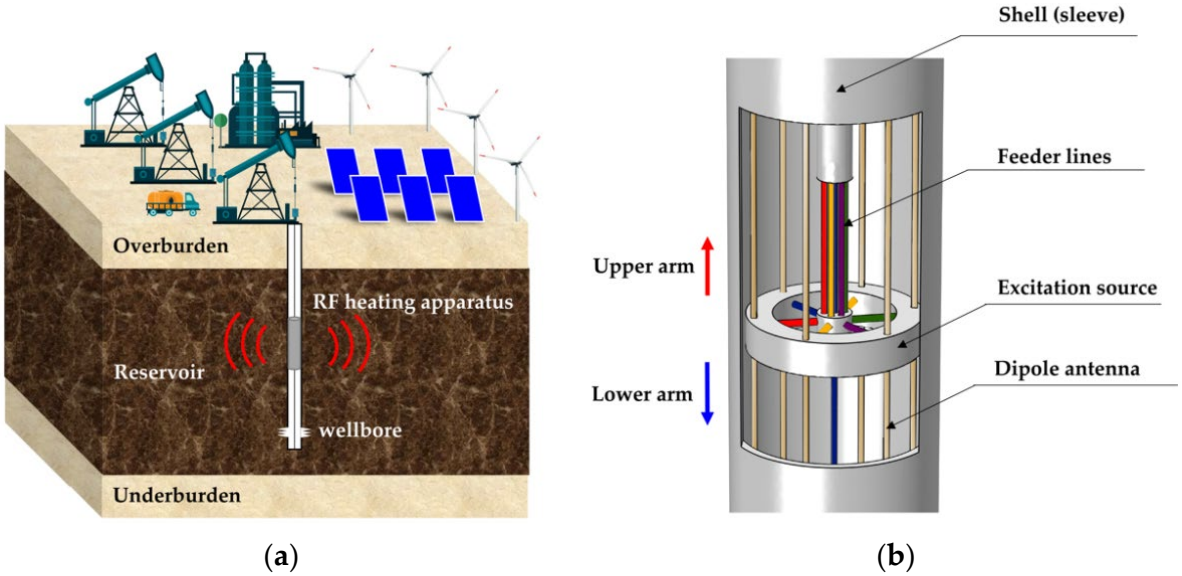


Figure 1. Schematic diagram of heavy oil recovery by high-frequency electromagnetic in situ heating [6]. (**a**) RF heating in a heavy oil reservoir. (**b**) Internal configuration of RF heating apparatus.

2. Progress of High-Frequency Electromagnetic In Situ Thermal Recovery and Its Prospects in Low-Carbon Situations

2.1. The Development History of High-Frequency Electromagnetic In Situ Thermal Methods for Heavy Oil

High-frequency electromagnetic in situ thermal recovery introduces high-frequency electromagnetic waves into the wellbore surroundings through downhole devices. These waves act on polar molecules (such as water molecules) within heavy oil reservoirs, converting electromagnetic energy into heat via dipole polarization, ionic conduction, and other mechanisms, thereby achieving rapid volumetric in situ heating of the reservoir [9]. This "thermal effect" reduces the viscosity and yield stress of heavy oil. Moreover, under the "non-thermal effects" of electromagnetism [10], heavy components like asphaltenes and resins undergo chemical cracking into lighter, shorter-chain components, irreversibly lowering the viscosity and yield stress. The concept was initially proposed by Ritchey in 1956 [11]. Between 1965 and 1990, Haagensen, Wilson, and Jeambey, among others [3], developed various downhole radiofrequency devices based on waveguides. In recent years, American and Canadian petroleum companies have pioneered designs of coaxial dipole antenna radiofrequency devices installed within wellbores (as shown in Figure 1b); notably, Cesar et al. [12] devised low dielectric filling materials to address overheating around the antenna that limited heating range and risked damaging the antenna and radiofrequency casing. Field tests by Sresty (1986) and Kasevich (1994) [9] in Utah and California, respectively, validated the energy-saving advantages of pure electromagnetic in situ heating. However, theoretical studies and field trials indicate that, unlike steam injection, which benefits from strong convective heat transfer, the pure high-frequency electromagnetic in situ thermal method has a limited heating radius in reservoirs [13,14] mainly due to the high-frequency electromagnetic wave attenuation, and cannot replenish sufficient reservoir energy for heavy oil production, particularly in energy-deficient reservoirs. These technological barriers hinder the direct application of high-frequency electromagnetic in situ thermal recovery for large-scale commercial exploitation of heavy oil reservoirs. To tackle this challenge, enhanced methods for electromagnetic in situ recovery of heavy oil under auxiliary reinforcement have become a focal point of current research. For example, given the strong absorptive properties of high-conductivity media such as nano-metal oxides [15,16] (e.g., iron oxide, nickel oxide) towards electromagnetic waves, their injection into heavy oil significantly enhances the heating radius of electromagnetic in situ recovery, though current research is primarily experimental and theoretical with no reported field trials. In 2010, North American companies including the Harris Corporation jointly developed the "Enhanced Steam Injection for Extra Heavy Oil (ESEIEH) method to enhance heavy oil recovery, which combines electromagnetic in situ heating with the injection of light hydrocarbon solvents [17,18]. These injected solvents not only dilute heavy oil to improve its flowability but also facilitate heat convection by conveying heat, thus enhancing the productivity increase from electromagnetic in situ heating; field testing in the Suncor Dover area of North America [9] revealed significantly higher efficiency compared to conventional SAGD heating. Solvent-assisted electromagnetic in situ recovery is viewed as a potential long-term alternative to traditional steam-based methods like SAGD. While these enhanced methods for electromagnetic in situ recovery of heavy oil can augment heating ranges and crude oil recovery rates, they pose issues of metallic pollution from nano-metal oxide injections or excessively high economic costs associated with injecting hydrocarbon solvents (e.g., propane, butane). Jamaloei [19] concluded after careful investigation of abundant research studies that the practical application of a high-frequency electromagnetic heating method could be more expensive than ohmic heating and conduction heating; and, enhancing real permittivity, lowering imaginary permittivity, and enhancing thermal conductivity can help to improve heavy oil recovery in high-frequency electromagnetic heating.

The development history of the high-frequency electromagnetic in situ thermal method for heavy oil is shown in Figure 2.

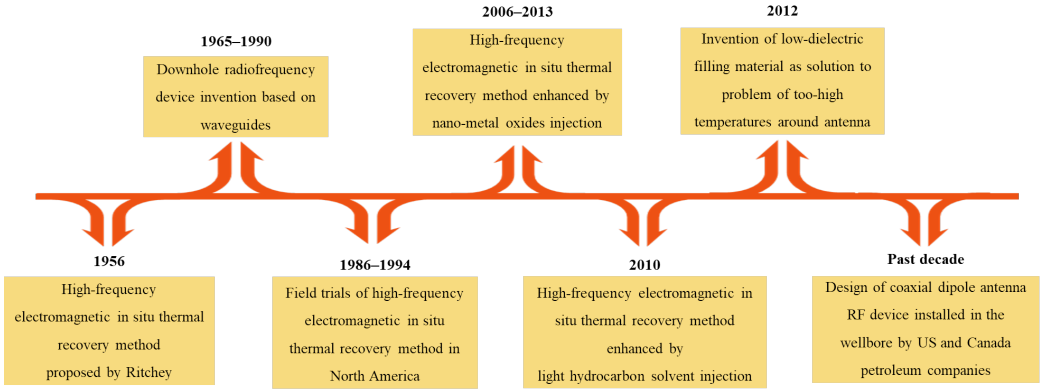


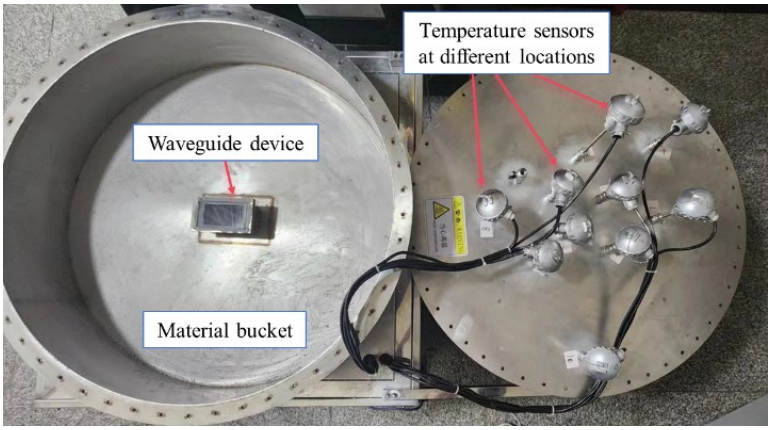
Figure 2. Development history of the high-frequency electromagnetic in situ thermal method of heavy oil.

2.2. Research Progress on the Coupled Heat and Mass Transfer Mechanisms of High-Frequency Electromagnetic In Situ Thermal Recovery of Heavy Oil

2.2.1. Physical Experimental Research Methods

In 1999, Hu et al. [20] conducted indoor physical simulations of N_2-assisted high-frequency electromagnetic thermal recovery for thin-layer heavy oil, demonstrating a recovery rate of 45%, significantly higher than the 20% achieved with N_2 injection alone and the 24% from electromagnetic heating alone. They further analyzed the impact of factors such as gas injection pressure, temperature, and electromagnetic frequency on recovery efficiency. However, due to the reason that pure nitrogen is easy to breakthrough in the oil reservoir, the question of how to inhibit nitrogen breakthrough, especially in the heterogeneous reservoir, is a big problem in field applications. In 2011, Greff and Babadagli [21] investigated the effects of microwave radiation on the recovery of heavy oil from a sand pack; it was found that the performance of oil recovery with nano-nickel catalysts is better due to the increased cracking of asphaltenic components taking place. In 2016, R. K. Santoso et al. [14] experimentally investigated the transport mechanisms of iron oxide nanoparticles in heavy oil and water, elucidating their role in enhancing high-frequency electromagnetic heating efficacy. It was concluded that the iron oxide nanoparticle vibration in the oil can be directly converted as heat energy to the oil, which can reduce the heat transfer loss. At the same year, Hu et al. [22] carried out a series of experiments studying the gravity drainage mechanism of solvent-enhanced electromagnetic in situ thermal recovery for heavy oil, examining how parameters like heating power, initial water saturation, solvent type, and injection mode influence recovery improvement. In 2018, Liao et al. [23] experimentally explored the impact of asphaltene deposits and dispersions in heavy oil on microwave heating efficiency, revealing that asphaltene dispersions exhibit higher microwave absorbance and lower electromagnetic penetration depth compared to settled asphaltene. In 2020, Wang [24] designed a physical simulation device for RF heating of heavy oil in wells, analyzing key factors affecting the electromagnetic heating of oil sands through experimentation. Most recently, in 2022, Gharibshahi et al. [25] performed in situ upgrading experiments on heavy oil, combining microwave RF heating with the injection of iron oxide-based magnetic nanocomposites, assessing the effects of nanocomposite concentration and heating power on heavy oil upgrading performance. In 2024, our research group from both the University of Science and Technology, Beijing, and the State Key Laboratory of Offshore Oil and Gas Exploitation in China developed equipment for physically simulating the high-frequency electromagnetic heating effect in the reservoirs. The equipment is mainly composed of a microwave generator, a waveguide device, ten temperature sensors, a material bucket, and an automatic control system (see Figure 3a). The material bucket can be filled with the mixture of sand, white oil, and water for simulating the oil formation (see Figure 3b), and can be heated by the high-frequency electromagnetic wave from the waveguide device at the center. The sand is quartz sand, the oil is industrial white oil of 5#grade A type, and the water is distilled water. The temperature measurement

points of the temperature sensor are evenly distributed at different angles according to the logarithm of the radial distance (see Figure 3c). Physical experiments of high-frequency electromagnetic heating were conducted using the equipment. Based on the principle of thermal expansion and contraction, the temperature sensor recorded the temperature data every half minute. Figure 4 shows the temperature rise data measured by ten temperature sensors located at different distances from the waveguide device under different fluid saturations of the mixture; the power is 1250 W, and the frequency is 2450 MHz. It can be concluded from Figure 4 that as the mixture loses water saturation, the temperature around the waveguide device rises more quickly in the material bucket. This can be attributed to the fact that water has larger specific heat capacity than oil.

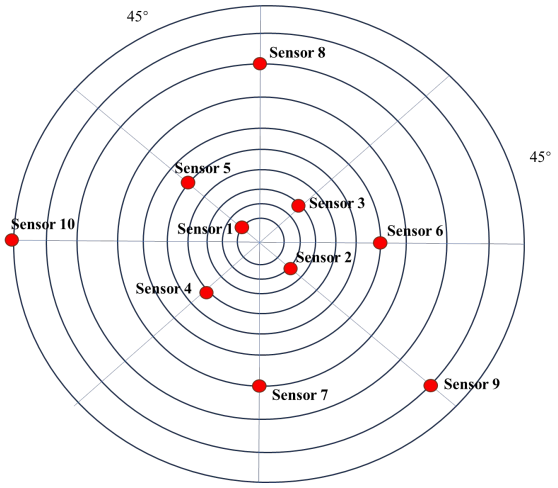


(**a**)



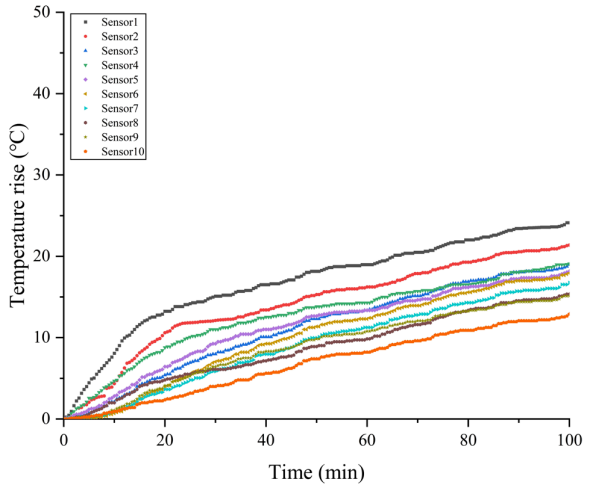
(**b**)

Figure 3. *Cont.*

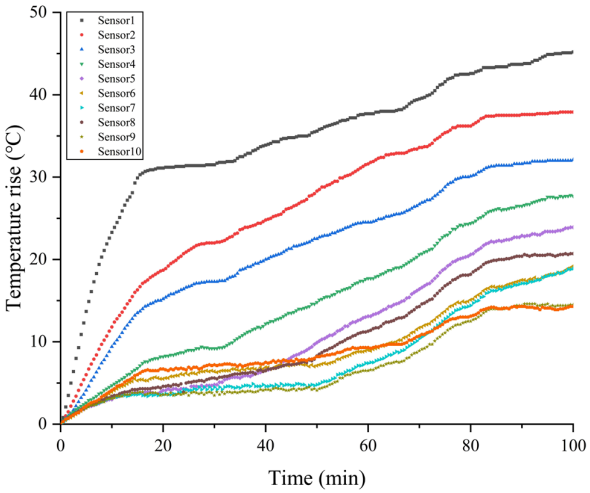


(**c**)

Figure 3. Physical simulation equipment for high-frequency electromagnetic heating of oil reservoirs. (**a**) Equipment with bucket unfilled. (**b**) Equipment with bucket filled. (**c**) Sensor distribution diagram.



(**a**)



(**b**)

Figure 4. Temperature rise data from physical experiments of high-frequency electromagnetic heating for two cases corresponding to different fluid saturation: (**a**) with 100% water saturation, (**b**) with 70% water saturation and 30% white oil saturation.

2.2.2. Mathematical Modeling Research Methods

In 1976, Abernethy [26] developed a series of radial heat and mass transfer models for high-frequency electromagnetic in situ thermal recovery of heavy oil, obtaining some analytical solutions to evaluate heating zones; heat radiation, heat convection, and heat conduction can be considered in these radial heat transfer models (see Figure 5), and their governing equations were expressed as follows [24]:

$$2\pi r h \rho_t S_t \frac{\partial T}{\partial t} = \underbrace{2\pi h K \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right)}_{\text{Heat conduction term}} + \underbrace{\frac{\alpha P_w \exp(-\alpha(r - r_w))}{4.18}}_{\text{Heat radiation term}} + \underbrace{\rho_o q_o S_o \frac{\partial T}{\partial r}}_{\text{Heat convection term}} \quad (1)$$

$$\alpha = 0.02\left(\frac{(2\pi f)^2 \mu \varepsilon}{2}\left(\left(1 + \frac{\sigma^2}{(2\pi f)^2 \varepsilon^2}\right)^{1/2} - 1\right)\right)^{1/2} \quad (2)$$

where r is the radial distance; T is the formation temperature; h is the thickness of formation with only connate water and oil; t is the time; K is the total heat conductivity; α is the power absorption coefficient; σ is electrical conductivity; μ is magnetic permeability of reservoir; ε is permittivity of reservoir; f is radio frequency; P_w is the total power radiated; r_w is the wellbore radius; $\rho_t S_t$ is the specific heat per unit volume of reservoir rock and fluid; ρ_o is the oil density; q_o is the oil flow rate; and S_o is the specific heat of oil. Figure 6 shows the effect of radio frequency on the temperature rise along the radial distance by electromagnetic heating, obtained from the model solution by finite difference method.

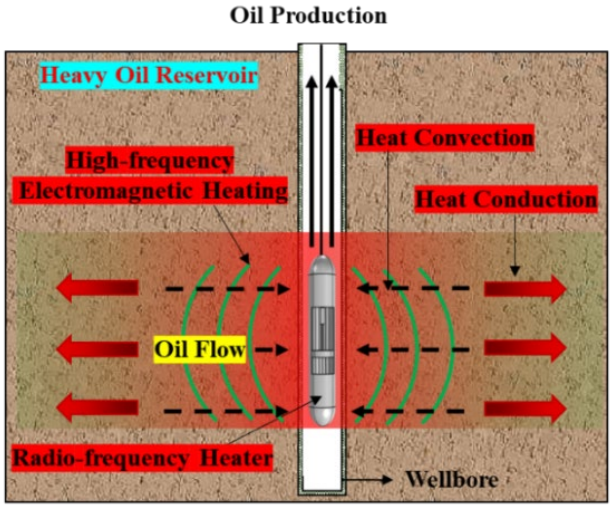


Figure 5. Heat and mass transfer model of EM heating.

In 2023, Dong et al. [27] derived a thermal source term based on complex Maxwell equations and established a radial heat transfer model for electromagnetic heating of heavy oil reservoirs, neglecting heat convection; analytical model solutions were obtained by using Bessel functions in order to analyze influencing factors on heating effect. However, in the radial model, the reservoir is homogeneous and isotropic, and multi-component fluid phase change behavior is also not considered. In 2016, Bogdanov et al. [28] combined the thermal recovery module STARS of CMG with the RF heating module of COMSOL Multiphysics by using the EMIR explicit coupled code written in MATLAB, enabling multiphase multicomponent numerical simulations of solvent (methane, ethane) injection-augmented electromagnetic heating of heavy oil; the research focused on the flow mechanism of solvents diffusing into the reservoir from the vapor chamber boundary. In 2016, Davletbaev et al. [29] conducted a numerical study on heavy oil production from a well with a hydraulic fracture under radio-frequency electromagnetic radiation in consideration of adiabatic ef-

fect and thermal expansion of oil. From 2018 to 2021, Wang et al. [24,30–32] accounted for the temperature-dependent dielectric constant of water and thermal conductivity of the reservoir, along with heat dissipation from over- and under-burden layers, conducting coupled electromagnetic field and temperature field numerical simulations for RF heated heavy oil, examining factors affecting temperature distribution. Also in 2018, Hu et al. [33] proposed a simplified semi-analytical mathematical model, akin to Steam Assisted Gravity Drainage, for solvent-assisted electromagnetic in situ recovery under assumptions excluding heat conduction, convection, and reservoir heat loss, and the impact of heating power, solvent type, and injection pressure on recovery efficiency were analyzed. In 2019, based on the Helmholtz equation for electromagnetic fields, in consideration of multiphase flow of oil, gas, and water, phase change, heat transfer, and time-space variations in dielectric properties, Ji et al. [34] established a fully implicit multiphase multicomponent numerical model for high-frequency electromagnetic heating of heavy oil; simulations revealed a dry zone with weak electromagnetic wave absorption above RF horizontal wells, allowing distant heavy oil zones to absorb more waves, thereby promoting gravity drainage at the gas-oil interface.

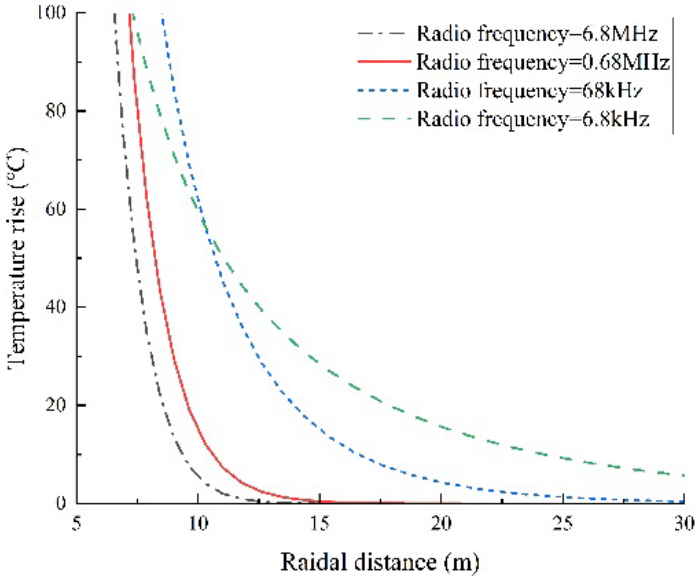


Figure 6. Radio frequency on EM heating effect.

In 2022, Zhang and Liu, among others [6], employed the finite element method for multi-physics field-coupling numerical simulation of high-frequency electromagnetic in situ recovery of heavy oil; it considered interactions among the reservoir's temperature field, electromagnetic field, and single-phase non-Darcy seepage flow field, especially the impact of temperature on the viscosity of heavy oil as a Bingham non-Newtonian fluid [35] and the threshold pressure gradient (TPG) to initiate non-Darcy flow (see Figure 7) along with the moving boundary conditions TPG imposes, and productivity influencing factors were discussed; in their study, more accurate Maxwell's equations [6] (see Equations (3) and (4)) were used for depicting electromagnetic wave propagation, and an external heat source term generated by electromagnetic wave were added into heat conduction equation. Through a numerical simulation study on a vertical well with electromagnetic heating, it was concluded that electromagnetic heating can largely increase the oil production rate by several times no matter if TPG is considered or not in the oil seepage flow, as shown in Figure 8; moreover, the TPG of Bingham non-Darcy flow has a seriously negative effect on the oil production rate. The existence of TPG hinders heavy oil flow ability, and thus can reduce the oil production. As the temperature rises due to electromagnetic heating, TPG of heavy oil will decrease [6], which can mitigate its adverse effect on productivity. Also in 2022, Wan et al. [36] introduced an efficient numerical simulation method for

multi-physical field coupling in geological energy extraction, combining control volume finite element and standard finite element methods. This approach ensures local mass and energy conservation while co-locating discrete variables of multiple physical fields at the same nodes, significantly enhancing the accuracy and reliability of numerical simulations.

$$\nabla \times \mu_r^{-1}(\nabla \times \mathbf{E}) - k_0^2\left(\varepsilon_r - \frac{j\sigma_r}{\omega\varepsilon_r}\right)\mathbf{E} = 0 \tag{3}$$

$$Q_e = \frac{1}{2}\mathrm{Re}(\sigma_r - j\omega\varepsilon_r)\mathbf{E}\cdot\mathbf{E}^* \tag{4}$$

where $\mathbf{E}$ is electric field vector; σ_r is relative electrical conductivity of reservoir; μ_r is relative magnetic permeability of reservoir; ε_r is relative permittivity of reservoir; k_0 is wave number; ω is angular frequency; j is imaginary unit; * denotes matrix transpose; and Q_e is the external EM heat source.

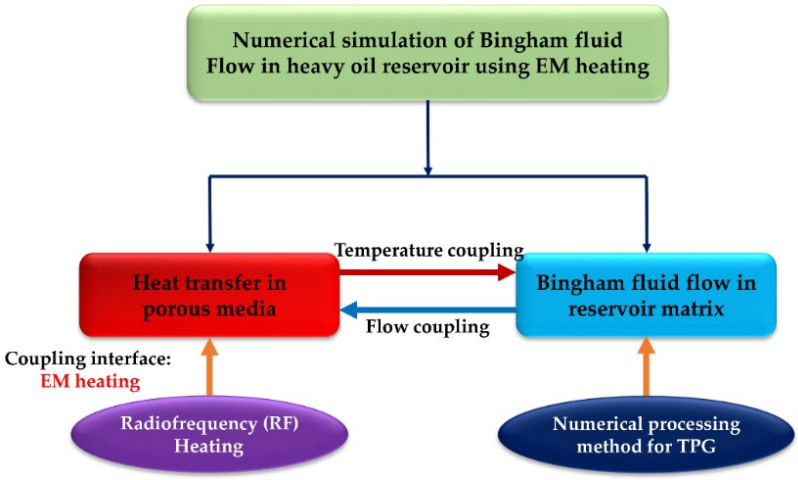


Figure 7. Diagram for multi-physics field-coupling numerical simulation of high-frequency electromagnetic in situ recovery of heavy oil [6].

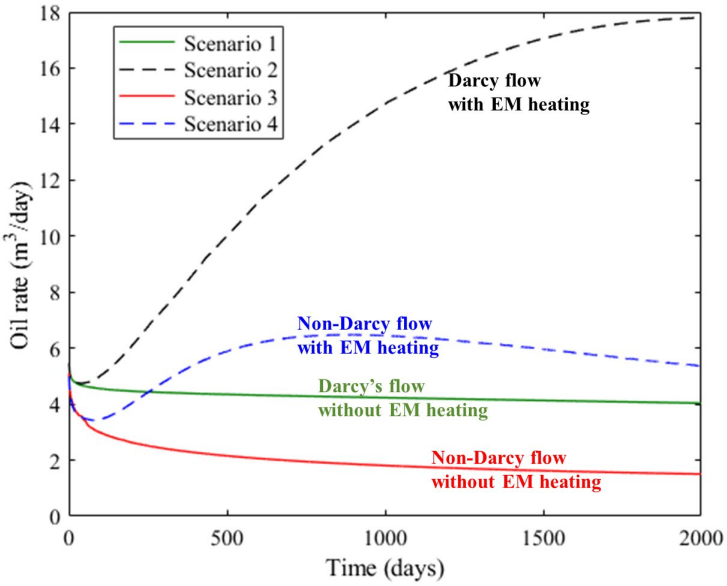


Figure 8. Oil rate increase through EM heating obtained from multi-field coupling numerical simulation [6].

2.3. Research Progress on the Mechanism of Enhancing Heavy Oil Recovery by CO_2/N_2 Injection in Thermal Recovery Processes

The studies summarized herein provide substantial evidence that CO_2 and N_2 injection can enhance heavy oil recovery through thermal methods [37–46], with the mechanisms outlined as follows: (1) through material supplementation replenishing reservoir energy to boost production capacity; notably, N_2, being an inert gas, can mitigate pipeline corrosion; (2) CO_2, due to its solubility in heavy oil, not only improves oil flowability but also promotes oil expansion, enhancing its elastic energy; (3) CO_2 extracts light components from heavy oil, which alters the gas-to-liquid mobility ratio and reduces the interfacial tension of multiphase fluids; and gas breakthrough can be inhibited; (4) enabling geological storage of CO_2, thereby mitigating greenhouse effects; (5) the recovered CO_2 and N_2 are readily recyclable for reuse. High-frequency electromagnetic heating experiments have demonstrated that N_2 injection significantly enhances crude oil recovery rates. In 2014, Hamdi and Foo [42] conducted numerical simulations on liquid CO_2-assisted enhancement of traditional Steam Assisted Gravity Drainage for heavy oil recovery; They analyzed the heat and mass transfer evolution mechanism after CO_2 injection, and it was revealed that this method improved recovery by 2% compared to SAGD while reducing heat loss by 16%. Also in 2014, Naderi and Babadagli [42] performed alternating solvent and steam injection experiments on loose sandstone cores with different wettabilities. They found that CO_2 solvent injection increased heavy oil recovery comparably to propane and butane solvents, but was more affected by core wettability.

From 2020 to 2023, Zhou, Jang, et al. [43,44] developed a coupled mathematical model based on molecular diffusion equations and the Peng-Robinson equation of state to describe the dissolution and diffusion of CO_2 components across the gas-oil interface into heavy oil. They proposed a method to determine the diffusion coefficient of CO_2 in heavy oil by using PVT gas phase pressure decay experiments. In 2019, taking the J6 block of Xinjiang Oilfield in China as the research object, Xi et al. [45] conducted three-dimensional physical simulation experiments on the CO_2-assisted steam flooding technique for heavy oil reservoirs. Their results showed that after adjusting perforation, CO_2-assisted steam flooding facilitated both lateral expansion of the steam chamber in the lower part of the injection well and gravity drainage from the steam chamber in the higher part of the production well. Moreover, CO_2 at the top of the steam chamber acted as thermal insulation, lowered steam partial pressure, and improved steam thermal efficiency. Field application demonstrated a 5.4% increase in recovery degree, achieving an ultimate recovery of 66.5%. In 2020, Hao et al. [41] studied the physical simulation of CO_2/N_2 mixed gas cyclic injection into heavy oil reservoirs, and it was demonstrated that the synergistic effect of CO_2 solubility-induced viscosity reduction and reservoir energy enhancement by N_2 injection effectively increased heavy oil recovery. In 2021, Wang et al. [46] investigated the mechanism of CO_2 cyclic injection to enhance recovery in heavy oil reservoirs through high-temperature and high-pressure PVT and sand-filled tube displacement experiments. The pilot test in Dagang Oilfield indicated significant production enhancement from CO_2 cyclic injection. In 2022, Yang et al. [47] proposed a new method for calculating phase behavior equations closely related to the viscosity-reducing and swelling mechanism of solvent (hydrocarbons, CO_2, N_2, etc.)-enhanced steam flooding for heavy oil recovery. This method could accurately calculate phase boundaries, densities, viscosities, and solubilities. Furthermore, they calculated the diffusion coefficients of CO_2 and light hydrocarbons using the pressure decay method combined with the Peng–Robinson equation of state [48,49] and a one-dimensional diffusion model, facilitating the application in numerical simulations of heavy oil thermal recovery. In 2023, Xia et al. [50] carried out physical simulation experiments on CO_2, natural gas, and N_2 cyclic injection in heavy oil reservoirs. Their results indicated that CO_2 injection had slightly better recovery enhancement than natural gas, while N_2 injection had the poorest effect. These studies, encompassing mechanistic experiments, numerical modeling analysis, and field applications, collectively demonstrate that CO_2/N_2 injection

can significantly enhance oil recovery and thermal energy utilization efficiency in heavy oil reservoirs subjected to thermal recovery methods.

2.4. Research Prospects in Low-Carbon Situations and Challenges

2.4.1. Research Prospects in Low-Carbon Situations

Conventional thermal recovery methods, such as steam injection, struggle to meet societal demands under the low carbon goals of today's world. Although novel high-frequency electromagnetic in situ thermal recovery methods can overcome some limitations of traditional techniques, their limited electromagnetic heating range and insufficient energy for later production necessitate auxiliary enhancement measures for large-scale application. Currently, reports exist on the mechanism of enhancing heavy oil electromagnetic in situ thermal recovery through N_2 injection, hydrocarbon solvent injection, or injection of nano-metal oxides. Among these, N_2 injection has been restricted to a few simple physical simulation studies. However, these enhanced electromagnetic thermal recovery methods face issues, such as with the easy breakthrough of pure N_2, excessively high economic costs, or severe environmental metal pollution. As per the aforementioned progress in mechanism research, injecting a CO_2-N_2 mixture into heavy oil reservoirs offers multiple benefits, including increasing reservoir energy, reducing heavy oil viscosity, expanding the heated reservoir area, decreasing heat loss, suppressing gas breakthrough, and reducing carbon. Consequently, CO_2/N_2-enhanced heavy oil thermal recovery not only contributes to improving oil recovery and thermal energy utilization efficiency in heavy oil reservoirs, but also facilitates the geological sequestration of the greenhouse gas CO_2. However, it also brings some dangers, such as CO_2 leaks, environmental degradation, and health concerns. Development of techniques for measurement, monitoring and verification of geological CO_2 storage at field-level are very significant for assessing CO_2 storage safety and associated risks [51].

Additionally, CO_2-N_2 can be prepared at low energy cost through industrial exhaust gas separation, offering a cheap gas source that is also recyclable. However, most current studies on CO_2/N_2-enhanced heavy oil thermal recovery mechanisms focus on traditional steam injection methods. Given this context, researching a new method of CO_2-N_2-enhanced high-frequency electromagnetic in situ thermal recovery of heavy oil might represent a future research trend in environmentally friendly and low-carbon heavy oil thermal recovery technology. Research status and characteristics of enhanced thermal recovery methods for heavy oil are shown in Table 1.

Table 1. Research status and characteristics of enhanced thermal recovery methods for heavy oil.

Auxiliary Enhancement Measures / **Heavy Oil Thermal Recovery Methods**	**Nanometal Oxide Injection**	**Hydrocarbon Solvent Injection**	**N_2 Injection**	**CO_2-N_2 Mixture Injection**
Electromagnetic In Situ Heating	Improves heating effect but causes environmental metal pollution.	Significantly improves heating effect but has high economic cost.	Helps to improve thermal recovery effectiveness, but pure nitrogen is prone to breakthrough.	Research gap.
Traditional Steam Injection	Not applicable.	Significantly improves recovery effect.	Helps to improve thermal recovery effectiveness, but pure nitrogen is prone to breakthrough.	Significantly enhances thermal recovery efficiency, facilitates carbon dioxide geological sequestration, yet is prone to corroding pipelines and incurs high costs.

2.4.2. Research Challenges

Future research should focus on the coupled heat and mass transfer mechanism of CO_2-N_2-enhanced high-frequency electromagnetic in situ thermal recovery of heavy oil, the multi-physics filed coupling theory and engineering methodologies in order to form a new heavy oil thermal recovery technology that integrates the advantages of efficiency, a low carbon footprint, environmental friendliness, economy, and energy conservation. This technology research holds promise in effectively addressing the severe problems associated with existing enhanced electromagnetic in situ thermal recovery methods, potentially providing advanced theoretical foundations and technological support for green, large-scale commercial exploitation of challenging heavy oil resources in the low-carbon scenarios. Some research challenges for the technology of CO_2-N_2-enhanced high-frequency electromagnetic in situ thermal recovery of heavy oil are suggested as follows:

(a) The process of CO_2-N_2-enhanced heavy oil electromagnetic in situ thermal recovery is a complex heat and mass transfer process under multi-physics coupling [52]. It primarily involves the dissipation of high-frequency electromagnetism in the reservoir (electromagnetic field), the heat generation from electromagnetic dissipation and heat transfer in the reservoir (temperature field), changes in the non-Darcy seepage capacity of heavy oil and multiphase flow (seepage field), phase change of fluids and diffusion of CO_2, N_2, and volatile light components in multiphase fluids (composition field), as well as the complex interactions between these physical fields, as illustrated in Figure 9. These physical fields and their high-temperature and high-pressure property characteristics can be influenced by other fields or even by changes within their own fields. For instance, the dielectric properties [28–31] of formation water, heavy oil, and rock samples (such as permittivity and electrical conductivity), thermal properties (specific heat, thermal conductivity), can vary with temperature or electromagnetic frequency; the viscosity, yield stress, and threshold pressure gradient of non-Darcy seepage flow of heavy oil can change with temperature, CO_2, N_2, or concentration of light components in heavy oil; changes in heavy oil composition are related to the electromagnetic non-thermal effects [10]; temperature changes can affect the porosity and permeability of rocks; the CO_2-N_2-heavy oil-water mixture can undergo phase changes with variations in temperature and pressure; the diffusion coefficients [47] of CO_2, N_2, etc., in heavy oil are influenced by temperature and pressure. Accurate measurement of the property characteristics and coupling relationships of multiple physical fields during the process of CO_2-N_2-enhanced heavy oil electromagnetic in situ thermal recovery is a fundamental prerequisite for establishing a multi-physics coupled theoretical model for this process, which is essential to solve on-site engineering and technical problems.

(b) The high-temperature and high-pressure physical simulation experiments for CO_2-N_2-enhanced electromagnetic in situ thermal recovery of heavy oil involve several key heat and mass transfer mechanisms [53–55]. An experimental apparatus for physical simulation of the SAGD-inspired thermal recovery mode with dual horizontal wells, one for injection and one for production, is shown in Figure 10. Taking a vertical reservoir cross-section of a dual horizontal well configuration analogous to SAGD as an example (see Figure 11), these mechanisms include the volume heating of the heavy oil reservoir in situ by high-frequency electromagnetic waves emitted from a dipole antenna installed in a wellbore, which increases the mobility and elastic energy of the heavy oil and affects the porosity and permeability of the reservoir. Injecting CO_2-N_2 into the wellbore equipped with the antenna not only replenishes the reservoir's energy and boosts production but also creates a high-temperature and high-pressure gas cavity around the wellbore. Within this cavity, a low-dielectric dry zone [33] composed of CO2 and N2 reduces the dielectric loss near the wellbore, enhances the heated reservoir range of the electromagnetic waves, and prevents local overheating that could compromise the stability of the wellbore. The gas cavity dynamically expands into the deeper heavy oil reservoir with concurrent heat

and mass transfer. Therefore, the stability of the developed gas cavity is helpful for improving the effect of high-frequency electromagnetic in situ thermal recovery. Unexpected complications during field operations may be an underdeveloped gas cavity or instability in the developed gas cavity. At the boundary of the gas cavity, the dissolution and diffusion of CO2 into the deeper heavy oil enhances its mobility and elastic energy [41]. CO2 also extracts the lighter components of the heavy oil; it can reduce the gas–liquid mobility ratio and interfacial tension of multiphase fluids, and inhibit gas breakthrough. The superimposed gas cavity heats the underlying heavy oil reservoir, initiating a gravity drainage mechanism, while the insulating effect of the CO_2-N_2-filled cavity above prevents heat loss. CO2 also dissolves and diffuses in the formation water. There are multiple component multiphase flows, non-Darcy flow of non-Newtonian heavy oil, and other complexities. These mechanisms are interrelated, and collectively control the efficiency of heavy oil extraction and thermal energy utilization. Based on mathematical models, similarity rules [56] can be derived to design and conduct high-temperature and high-pressure physical simulation experiments. These experiments aim to elucidate the coupled heat and mass transfer mechanisms of CO_2-N_2-enhanced electromagnetic in situ thermal recovery of heavy oil across multiple physical fields. By identifying the controlling factors for heavy oil production capacity, recovery rate, energy utilization efficiency, and CO2 storage efficiency, these experiments provide a critical theoretical foundation for the optimization of new thermal recovery technologies and the evaluation of their performance.

(c) A multi-physics coupled mathematical model for CO_2-N_2-enhanced heavy oil electromagnetic in situ thermal recovery involves complex heat and mass transfer processes under the influence of multiple physical fields interacting with each other. The electromagnetic field heats the reservoir volume in situ, where the electromagnetic frequency influences the reservoir's dielectric properties, thereby affecting the heating efficiency. Heat is then transferred via convection and conduction, impacting the temperature field. The electromagnetic "non-thermal effects" [10] and the increase in temperature reduce the viscosity, density, and threshold pressure gradient of the non-Newtonian heavy oil non-Darcy seepage flow. However, increased temperatures simultaneously decrease the solubility of gaseous CO2, N2, and light components in the heavy oil and formation water, affecting diffusion rates; it will lead to increased viscosity and density of the heavy oil, changes in capillary forces at multiphase fluid interfaces, and thus cause alterations in reservoir pressure, fluid phases, and fluid saturation. Increased temperatures also affect the porosity, permeability, dielectric, and thermal properties of the reservoir, influencing the multiphase flow field, composition field, and electromagnetic field. Changes in fluid saturation lead to modifications in the reservoir's dielectric and thermal properties, which affect the in situ heating efficiency of the electromagnetic waves and the heat dissipation process; thereby, the electromagnetic and temperature fields are affected (as depicted in Figure 9). The dynamic changes in reservoir properties can be tested experimentally, and their mathematical formula can be applied into the mathematical modeling. Therefore, integrating theories from electromagnetics, heat and mass transfer, fluid mechanics, and thermodynamics, a comprehensive multi-component multiphase mathematical model that describes the dynamic coupling of the electromagnetic field, temperature field, seepage flow field, and composition field can be established. Coupled with an efficient numerical simulation method for heat and mass transfer under multi-physics conditions, such a model can provide an essential engineering tool for optimizing and evaluating the effectiveness of new thermal recovery technologies for heavy oil. It is worth mentioning that applying artificial intelligence techniques in combination of physical constraints [57] can be used to improve the accuracy and efficiency of numerical simulation of the complicated multi-physics field coupling for the high-frequency electromagnetic in situ thermal recovery technology for heavy oil. The model can be validated against the real-world data through the comparison of the numerical

simulation results with the actual data obtained from heavy oil fields. Numerical stability of the numerical simulation method should be guaranteed so as to ensure robustness across different reservoir conditions.

(d) Engineering methods for CO_2-N_2-enhanced electromagnetic in situ thermal recovery of heavy oil can be elucidated through field-scale numerical simulations, aiming to establish methodologies for thermal recovery process optimization and reservoir suitability assessment. Initially, field-scale numerical simulations for CO_2-N_2-enhanced heavy oil electromagnetic in situ thermal recovery are conducted. These simulations reconstruct the spatiotemporal distributions of the electromagnetic field, temperature field, seepage flow field, and composition field. Analysis of the simulations reveals the temporal and spatial evolution patterns of the steam chamber, the dry zone within the chamber, and the effective mobilization area, which significantly impact thermal recovery efficiency. These patterns are further investigated under various influencing factors such as thermal recovery modes (e.g., huff and puff [58] of vertical well, huff and puff of horizontal well, dual horizontal wells mimicking SAGD [59] with one well injection and one well production, and multilateral wells for injection and production, see Figure 12), production regimes, well placement, and inter-well spacing, to understand the multi-physics regulation mechanisms. Subsequently, orthogonal numerical simulation experiments can be designed with objectives such as production capacity, recovery factor, energy utilization efficiency, CO2 storage efficiency, and economic benefits. These numerical simulation experiments, combined with the understanding of multi-physics heat and mass transfer coupling mechanisms and regulation strategies, facilitate studies on optimization of thermal recovery modes, injection-production regimes, well placement, and inter-well spacing. Process scheme optimizations for CO_2-N_2-enhanced electromagnetic in situ thermal recovery of heavy oil under different reservoir conditions are carried out. Reservoir conditions include dielectric and thermal characteristics of the reservoir (including over-burden and under-burden layers), multiphase and multicomponent flow and diffusion characteristics, reservoir thickness and heterogeneity, reservoir geometry, and external boundary conditions (such as the presence of edge or bottom water). Comparisons with traditional thermal recovery methods (like steam flooding and cyclic steam stimulation) are made regarding the optimization goals to comprehensively evaluate the reservoir suitability of the CO_2-N_2-enhanced electromagnetic in situ thermal recovery process.

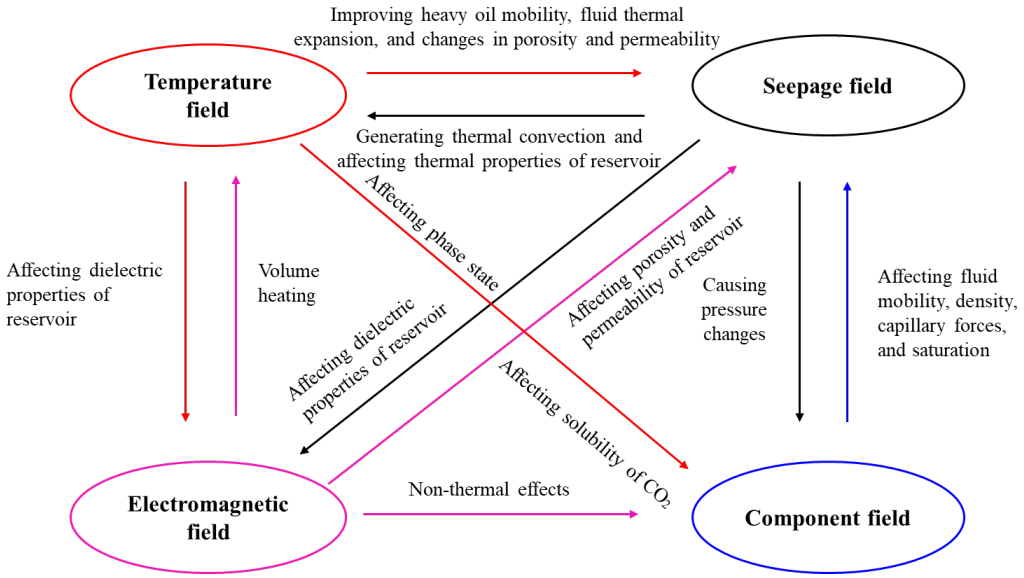


Figure 9. Schematic diagram of multi-physics coupled heat and mass transfer for in situ thermal recovery enhanced by CO_2-N_2 injection in heavy oil reservoirs.

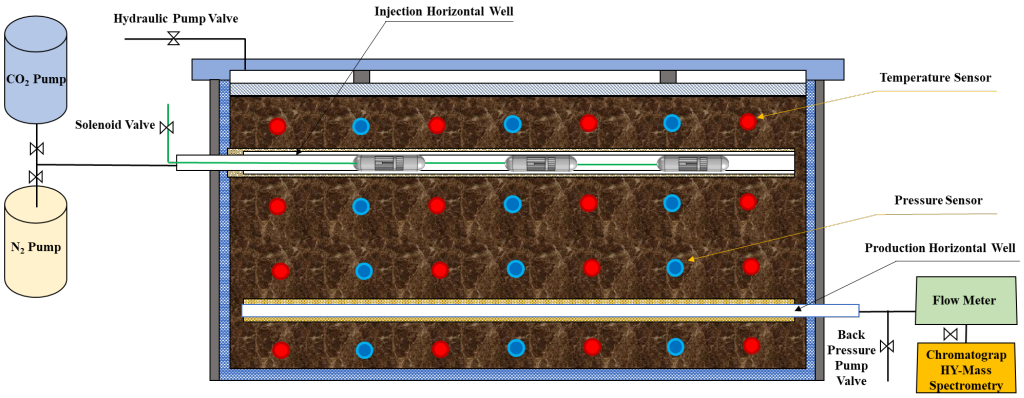


Figure 10. Experimental apparatus for physical simulation of SAGD-inspired thermal recovery mode with dual horizontal wells, one for injection and one for production.

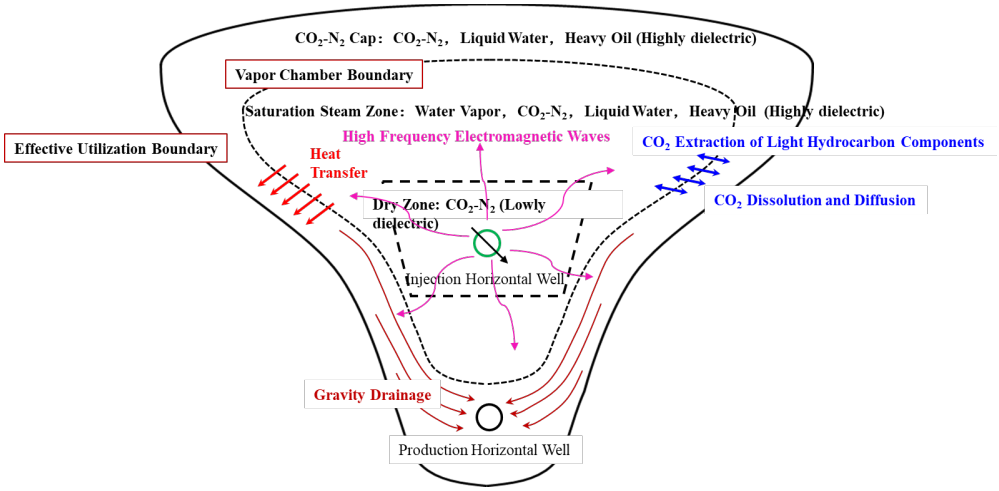


Figure 11. Schematic diagram of the mechanism of CO_2-N_2-enhanced high-frequency electromagnetic in situ thermal recovery of heavy oil (using a vertical reservoir cross-section of a dual horizontal well configuration analogous to SAGD as an example).

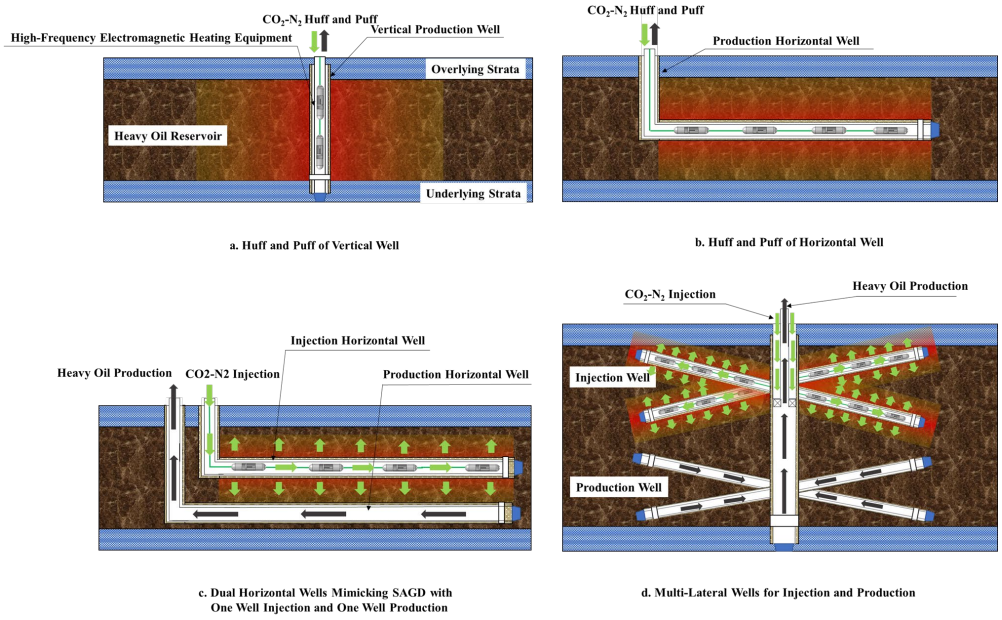


Figure 12. Schematic diagram illustrating different exploitation patterns of high-frequency electromagnetic in situ thermal recovery enhanced by CO_2-N_2 injection for heavy oil.

3. Conclusions

Conventional thermal recovery methods, such as steam injection, suffer from significant drawbacks, including massive water consumption, high carbon emissions, substantial heat losses, and lower economic viability, making them increasingly incompatible with current global demands for low-carbon social and economic development. High-frequency electromagnetic in situ heating can circumvent some of these limitations. However, due to technological bottlenecks such as limited heating ranges of high-frequency electromagnetics and insufficient energy for later production stages, supplementary enhancement measures are required for the method to achieve effective large-scale applications. Enhanced electromagnetic in situ heating methods for the development of heavy oil reservoirs under auxiliary measures have thus become a focal point of current research. To date, reports exist primarily on the use of nitrogen (N_2) injection, hydrocarbon solvent injection, or injection of nanometal oxides as auxiliary enhancements for electromagnetic in situ heating of heavy oil. Among these, studies involving N_2 injection have been limited to a small number of basic physical simulations. Nevertheless, these enhanced electromagnetic thermal recovery methods face challenges such as the easy breakthrough of pure N_2, excessively high economic costs of hydrocarbon solvent injection, or severe environmental pollution due to metal contamination.

Injecting a CO_2-N_2 mixture into heavy oil reservoirs offers multiple benefits, including boosting reservoir energy, reducing heavy oil viscosity, expanding the reservoir heating zone, minimizing heat loss, inhibiting gas breakthrough, and reducing carbon emissions. Consequently, CO_2/N_2 injection-enhanced thermal recovery of heavy oil not only contributes to increased oil recovery and improved thermal energy utilization efficiency but also facilitates the geological sequestration of the greenhouse gas CO_2 through the solubility of CO_2 in water and heavy oil, and the geophysical chemical reaction of CO_2 with minerals in the reservoir. However, current research on CO_2/N_2-enhanced thermal recovery of heavy oil is largely confined to traditional methods such as steam injection.

This paper naturally introduces a novel technology for CO_2-N_2-enhanced electromagnetic in situ thermal recovery of heavy oil under a low-carbon scenario, which integrates numerous advantages including high efficiency, low carbon footprint, environmental friendliness, economic viability, and energy conservation. This technology holds promise to overcome the technical bottlenecks of pure electromagnetic in situ heavy oil recovery methods and the shortcomings of existing enhanced electromagnetic in situ heavy oil recovery methods. For the new technology of CO_2-N_2-enhanced heavy oil electromagnetic in situ thermal recovery, future research prospects and challenges are detailed from four aspects: measurement of property characteristics and coupling relationships of multiple physical fields involved in CO_2-N_2-enhanced electromagnetic in situ thermal recovery of heavy oil; high-temperature and high-pressure physical simulation experiments to elucidate heat and mass transfer mechanisms; development of multi-physics coupled mathematical model; and engineering methodologies. These areas of focus are critical for advancing the technology towards practical applications and ensuring its effectiveness in improving heavy oil recovery while meeting environmental and economic criteria.

Author Contributions: Conceptualization, W.L. and Y.Y.; methodology, W.L. and Y.Y.; validation, M.S.; formal analysis, W.L., C.L. and M.S.; investigation, Y.Y., W.L., J.Y., C.L., Y.C. and M.S.; data curation, Y.Y.; writing—original draft preparation, W.L., Y.Y. and Z.M.; writing—review and editing, W.L., Y.Y. and Z.M.; visualization, W.L. and Z.M.; supervision, W.L.; project administration, Y.Y., J.Y., Y.C., M.L. and X.Y.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by State Key Lab of Offshore Oil and Gas Exploitation in China, grant number CCL2023RCPS0166RQN.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Yuan, S.; Wang, Q. New progress and prospect of oilfields development technologies in China, Petrol. *Explor. Dev.* **2018**, *45*, 698–711. [CrossRef]
2. Guan, W.; Jiang, Y.; Guo, E.; Wang, B. Heavy oil development strategy under the "Carbon Peaking and Carbon Neutrality" target. *Acta Pet. Sin.* **2023**, *44*, 826–840.
3. Xiong, R.; Guo, J.; Kiyingi, W.; Gao, C.; Wang, L.; Luo, J.; Song, H.; Wang, X. Technical transformation of heavy/ultra-heavy oil production in China driven by low carbon goals: A review. *J. Clean. Prod.* **2024**, *458*, 142531. [CrossRef]
4. Xu, Z.; Ding, Y.; Tao, L.; Hu, Z.; Zhang, X.; Bai, J.; Shi, W.; Li, J.; Li, S. Low-carbon development strategy to achieve heat conversion in heavy oil reservoirs: In-situ combustion. *Geoenergy Sci. Eng.* **2024**, *240*, 213055. [CrossRef]
5. Wang, L.; Guo, J.; Li, C.; Xiong, R.; Chen, X.; Zhang, X. Advancements and future prospects in in-situ catalytic technology for heavy oil reservoirs in China: A review. *Fuel* **2024**, *374*, 132376. [CrossRef]
6. Zhang, Q.; Liu, W.; Taleghani, A.D. Numerical study on non-Newtonian Bingham fluid flow in development of heavy oil reservoirs using radiofrequency heating method. *Energy* **2022**, *239*, 122385. [CrossRef]
7. Hu, L.; Li, H.; Babadagli, T.; Xie, X.; Deng, H. Thermal stimulation of shale formations by electromagnetic heating: A clean technique for enhancing oil and gas recovery. *J. Clean. Prod.* **2020**, *277*, 123197. [CrossRef]
8. Sivakumar, P.; Krishna, S.; Hari, S.; Vij, R.K. Electromagnetic heating, an eco-friendly method to enhance heavy oil production: A review of recent advancements. *Environ. Technol. Innov.* **2020**, *20*, 101100. [CrossRef]
9. Bera, A.; Babadagli, T. Status of electromagnetic heating for enhanced heavy oil/bitumen recovery and future prospects: A review. *Appl. Energ.* **2015**, *151*, 206–226. [CrossRef]
10. Zhang, H.; Feng, B.; Jiang, H.; Wei, A. Mathematic model of the effect of microwave on heavy oil. *Spec. Oil Gas Reserv.* **2006**, *05*, 100–110.
11. Ritchey, H.W. Radiation heating. USA Patent Application Serial No. 2,757,738, 1956.
12. Cesar, O.; Pedro, V.; Gunther, H.; James, D.; Ronald, B.; Lee, D.; Michal, O. Materials. Well Designs and Numerical Simulations for the Construction of a Low Loss Zone for Radiofrequency Downhole Heating. In Proceedings of the SPE Canada Heavy Oil Conference, Virtual, 28 September–2 October 2020. SPE-199946.
13. Xiao, J.; Wang, Z.; Dong, X. Simulation experiments of radio frequency heating of heavy oil assisted by additives and related influencing factors. *Pet. Geol. Oilfield Dev. Daqing* 2023, *in press*.
14. Santoso, R.K.; Rachmat, S.; Resha, A.H.; Putra, W.D.K.; Hartowo, H.; Setiawati, O. An Investigation of Fe2O3 Nanoparticles Diffusion into Oil for Heat Transfer Optimisation on Electromagnetic Heating for Well Stimulation and EOR. In Proceedings of the SPE Asia Pacific Oil & Gas Conference and Exhibition, Perth, Australia, 25–27 October 2016. SPE-182152.
15. Santoso, R.K.; Rachmat, S.; Putra, W.D.K.; Resha, A.H.; Hartowo, H. Numerical modeling of nanoparticles transport in porous media for optimisation in well stimulation and EOR using electromagnetic heating. In Proceedings of the SPE Asia Pacific Oil & Gas Conference and Exhibition, Perth, Australia, 25–27 October 2016. SPE-182182.
16. Vakhin, A.V.; Khelkhal, M.A.; Mukhamatdinov, I.I.; Mukhamatdinova, R.E.; Tajik, A.; Slavkina, O.V.; Malaniy, S.Y.; Gafurov, M.R.; Nasybullin, A.R.; Morozov, O.G. Changes in Heavy Oil Saturates and Aromatics in the Presence of Microwave Radiation and Iron-Based Nanoparticles. *Catalysts* **2022**, *12*, 514. [CrossRef]
17. Trautman, M.; Ehresman, D.; Edmunds, N.; Taylor, G.; Cimolai, M. Effective Solvent Extraction System Incorporating Electromagnetic Heating. USA Patent Application Serial No. 8,776,877 B2, 17 November 2010. p. 086569.
18. Hu, L.; Li, H.A.; Babadagli, T.; Ahmadloo, M. Experimental investigation of combined electromagnetic heating and solvent-assisted gravity drainage for heavy oil recovery. *J. Petrol. Sci. Eng.* **2017**, *154*, 589–601. [CrossRef]
19. Jamaloei, B.Y. Electromagnetic Heating for Heavy- Oil and Bitumen Recovery: Experimental, Numerical, and Pilot Studies. *SPE Res. Eval. Eng.* **2022**, *25*, 433–454. [CrossRef]
20. Hu, Y.; Jha, K.N.; Chakma, A. Heavy-oil recovery from thin pay zones by electromagnetic heating. *Energy Sources* **1999**, *21*, 63–73.
21. Greff, J.H.; Babadagli, T. Use of nano-metal particles as catalyst under electromagnetic heating for viscosity reduction of heavy oil. In Proceedings of the International Petroleum Technology Conference, Bangkok, Thailand, 15–17 November 2011.
22. Hu, L.; Andy Li, H.; Babadagli, T.; Ahmadloo, M. Experimental Investigation of Combined Electromagnetic Heating and Solvent Assisted Gravity Drainage for Heavy Oil Recovery. *SPE* **2016**, SPE-180747.
23. Liao, H.; Morte, M.; Hascakir, B. Effect of Crude Oil Composition on Microwave Absorption of Heavy Oils. In Proceedings of the SPE Western Regional Meeting, San Jose, CA, USA, 23–26 April 2019. SPE-190089.
24. Wang, Z. Basic Research on the Downhole Radio Frequency Heating Technology. Ph.D. Thesis, China University of Petroleum, Beijing, China, 2020.
25. Gharibshahi, R.; Omidkhah, M.; Jafari, A.; Mehrooz, N. Parametric optimization of in-situ heavy oil upgrading using simultaneous microwave radiation and magnetic nanohybrids via Taguchi approach. *Fuel* **2022**, *325*, 124717. [CrossRef]
26. Abernethy, E.R. Production increase of heavy oils by electromagnetic heating. *J. Can. Petrol. Technol.* **1976**, *15*, 91–97. [CrossRef]
27. Dong, X.; Duan, Z.; Nie, T.; Gao, D. An analytical model for reservoir temperature during electromagnetic heating based on power transmission. *Appl. Therm. Eng.* **2023**, *219*, 119441. [CrossRef]
28. Bogdanov, I.; Cambon, S.; Mujica, M.; Brisset, A. Heavy Oil Recovery via Combination of Radio-Frequency Heating with Solvent Injection. In Proceedings of the SPE Canada Heavy Oil Technical Conference, Calgary, AB, Canada, 7–9 June 2016. SPE-180709.

29. Davletbaev, A.; Kovaleva, L.; Zainulin, A.; Kireev, V.; Babadagli, T.; Minnigalimov, R. Modeling heavy-oil recovery using electromagnetic radiation/hydraulic fracturing considering adiabatic effect and thermal expansion. In Proceedings of the SPE Heavy Oil Conference and Exhibition, Kuwait City, Kuwait, 6–8 December 2016. SPE-184161.
30. Wang, Z.; Gao, D.; Fang, J. Numerical simulation of RF heating heavy oil reservoir based on the coupling between electromagnetic and temperature field. *Fuel* **2018**, *220*, 14–24. [CrossRef]
31. Wang, Z.; Guo, Q.; Zhao, Q.; Jiang, H.; Li, B.; Zhang, J.; Zhao, L.; Men, M.; Wang, G.; Ye, C.; et al. Performance evaluation of combined radio frequency heating and conductive medium injection for heavy oil recovery. *J. Petrol. Sci. Eng.* **2021**, *201*, 108535. [CrossRef]
32. Wang, Z.; Gao, D.; Diao, B.; Tan, L.; Zhang, W.; Liu, K. Comparative performance of electric heater vs. RF heating for heavy oil recovery. *Appl. Therm. Eng.* **2019**, *160*, 114105. [CrossRef]
33. Hu, L.; Andy Li, H.; Babadagli, T.; Ahmadloo, M. A semianalytical model for simulating combined electromagnetic heating and solvent-assisted gravity drainage. *SPE J.* **2018**, *23*, 1248–1270. [CrossRef]
34. Ji, D.; Harding, T.; Chen, Z.; Dong, M.; Liu, H. Modelling of Electromagnetic Heating Process and its Applications in Oil Sands Reservoirs. In Proceedings of the SPE Reservoir Simulation Conference, Galveston, TX, USA, 10–11 April 2019. SPE-193905.
35. Kong, X. *Advanced Porous Flow Mechanics*, 3rd ed.; University of Science and Technology of China Press: Hefei, China, 2020.
36. Wan, Y.; Wu, N.; Chen, Q.; Li, W.; Hu, G.; Huang, L.; Ouyang, W. Coupled thermal-hydrodynamic-mechanical–chemical numerical simulation for gas production from hydrate-bearing sediments based on hybrid finite volume and finite element method. *Comput. Geotech.* **2022**, *145*, 104692. [CrossRef]
37. Zhao, J.; He, Y.; Wang, J.; Peng, M.; Yang, J.; Zeng, F. Effect of in-situ emulsification on CO_2/N_2-based cyclic solvent injection process for enhancing heavy oil recovery and CO_2 storage. *Chem. Eng. Sci.* **2024**, *295*, 120185. [CrossRef]
38. Wang, Z.; Du, H.; Li, S.; Li, S. Experimental study on gas-assisted cyclic steam stimulation under heavy-oil sandstone reservoir conditions: Effect of N_2/CO_2 ratio and foaming agent. *Geoenergy Sci. Eng.* **2023**, *228*, 211976. [CrossRef]
39. Lin, Z.; Lu, X.; Wang, X.; Chang, Y.; Kang, K.; Zeng, F. Effect of N_2 impurity on CO_2-based cyclic solvent injection process in enhancing heavy oil recovery and CO_2 storage. *Energy* **2024**, *290*, 130227. [CrossRef]
40. Lun, Z.; Wang, H.; Zhang, C.; Li, B.; Liu, Y.; Li, Z. Mechanism of CO_2 and Chemical Additive Synergetic Enhanced Steam Flooding in Heavy Oil Reservoirs. *J. China Univ. Pet.* **2023**, *47*, 72–79.
41. Hao, H.; Hou, J.; Huang, H.; Zhao, F.; Liu, H. Feasibility of CO_2/N_2 Hybrid Gas Huff and Puff for Enhancing Recovery in Shallow Heavy Oil Reservoirs of Jidong Area. *Oilfield Chem.* **2020**, *37*, 80–85.
42. Hamdi, Z.; Foo, F.K. Cold CO_2 and steam injection for heavy oil recovery. In Proceedings of the International Petroleum Technology Conference, Dhahran, Saudi Arabia, 13–15 January 2020.
43. Zhou, X.; Jiang, Q.; Yuan, Q.; Zhang, L.; Feng, J.; Chu, B.; Zeng, F.; Zhu, G. Determining CO_2 diffusion coefficient in heavy oil in bulk phase and in porous media using experimental and mathematical modeling methods. *Fuel* **2020**, *263*, 116205. [CrossRef]
44. Jang, H.W.; Yang, D. Determination of the concentration-dependent effective diffusivity of CO_2 in unconsolidated porous media saturated with heavy oil by considering the swelling effect. *Int. J. Heat. Mass. Tran.* **2023**, *201*, 123552. [CrossRef]
45. Xi, C.; Qi, Z.; Zhang, Y.; Liu, T.; Shen, D.; Mu, H.; Dong, H.; Li, X.; Jiang, Y.; Wang, H. CO_2-Assisted Steam Injection Technology for Late Stage of Steam Flooding in Heavy Oil Reservoirs. *Petrol. Explor. Dev.* **2019**, *46*, 1169–1177. [CrossRef]
46. Wang, X.; Zhang, Y.; Zhang, J.; Cheng, H.; Ji, H.; Wang, W.; Li, H.; Liang, C.; Li, C.; Zhang, L. EOR mechanisms of CO_2 huff and puff process for heavy oil recovery. *J. China Univ. Pet.* **2021**, *45*, 102–111.
47. Yang, D.; Li, Y.; Huang, D. Quantification of Phase Behaviour and Physical Properties of Alkane Solvents/CO_2/ Water/Heavy Oil Systems under Equilibrium and Nonequilibrium Conditions. In Proceedings of the Canadian Energy Technology Conference, Calgary, AB, Canada, 16–17 March 2022. SPE-208968.
48. Chen, Z.; Huan, G.; Ma, Y. *Computational Methods for Multiphase Flows in Porous Media*; SIAM: Philadelphia, PA, USA, 2006.
49. Liu, L.J.; Yao, J.; Sun, H.; Huang, Z.Q.; Yan, X.; Li, L.L. Compositional modeling of shale condensate gas flow with multiple transport mechanisms. *J. Petrol. Sci. Eng.* **2019**, *172*, 1186–1201.
50. Xia, Z.; Zhao, J.; Liu, F.; Qin, E.; Cai, B.; Wang, Q. Evaluation of Gas Injection Huff-and-Puff Suitability in Heavy Oil Reservoirs of Turpan-Hami Exploration Area. *Xinjiang Pet. Geol.* **2023**, *44*, 341–346.
51. Nath, F.; Mahmood, M.N.; Yousuf, N. Recent advances in CCUS: A critical review on technologies, regulatory aspects and economics. *Geoenergy Sci. Eng.* **2024**, *238*, 212726. [CrossRef]
52. Li, G.; Guan, X.; Wang, H.; Du, S.; Wu, D.; Chen, J. Simulation of Radio Frequency Heating of Heavy Oil Reservoir Using Multi-Physics Coupling of Reservoir Simulation with Electromagnetic Solver. In Proceedings of the SPE Reservoir Simulation Conference, Galveston, TX, USA, 10–11 April 2019. SPE-193836.
53. Bogdanov, I.; Torres, J.A.; Corre, B. Numerical simulation of electromagnetic driven heavy oil recovery. In Proceedings of the SPE Improved Oil Recovery Symposium, Tulsa, OK, USA, 14–18 April 2012. SPE-154140.
54. Bapat, S.; Akhter, N. Optimization of heavy oil recovery by radio frequency heating: A theoretical approach with experimental modeling. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 11–14 November 2019.
55. Xu, Z.; Zhou, L.; Ma, S.; Qin, J.; Huang, X.; Han, B.; Yang, L.; Luo, Y.; Liu, P. Study on CO_2 Huff-n-Puff Development Rule of Horizontal Wells in Heavy Oil Reservoir by Taking Liuguanzhuang Oilfield in Dagang as an Example. *Energies* **2023**, *16*, 4258. [CrossRef]

56. Wang, Y.; Wu, T.; Liu, T.; Sha, J.; Ren, H. Numerical simulation and experimental verification of the steady-state heat transfer similarity theory based on dimensional analysis. *Case. Stud. Therm. Eng.* **2024**, *60*, 104714. [CrossRef]
57. Zhou, L.; Sun, H.; Fan, D.; Zhang, L.; Imani, G.; Fu, S.; Yang, Y.; Zhang, K.; Yao, J. Flow prediction of heterogeneous nanoporous media based on physical information neural network. *Gas Sci. Eng.* **2024**, *125*, 205307. [CrossRef]
58. Wang, Z.; Lu, H.; Zhao, C.; Zhu, E. Investigating phase dynamics of reservoir fluids in CO_2 huff-n-puff enhanced oil recovery. *Geoenergy Sci. Eng.* **2024**, *238*, 212925. [CrossRef]
59. Liu, M.; Zhao, G. A performance comparison study of electromagnetic heating and SAGD process. In Proceedings of the SPE Heavy Oil Conference-Canada, Calgary, AB, Canada, 11–13 June 2013. SPE-165547.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.