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The Numerical Simulation Study on the Heat Transfer Mechanism in Heavy Oil Reservoirs During In-Situ Combustion

Jiuzhi Sun [1], Bo Wang [1,*], Yunjie Shu [1,2], Yanchao Wang [1], Yi Pan [1] and Chao Tian [3]

[1] Department of Petroleum Engineering, Liaoning Petrochemical University, Fushun 113001, China; sjzzz89@163.com (J.S.); shuyunjie98@163.com (Y.S.); wangyanchao86412@163.com (Y.W.); panyi_bj@126.com (Y.P.)
[2] PetroChina Sichuan Marketing Company, Chengdu 610015, China
[3] Oil and Gas Gathering and Transportation Company, Petrochina Liaohe Oilfield Company, Panjin 124010, China; tianchao1234@126.com
* Correspondence: wang30227@aliyun.com

Abstract: The escalating energy demand has prompted nations to prioritize the development of high-viscosity and challenging-to-extract heavy and extra-heavy oil reserves. Consequently, the technique of in-situ combustion in oil reservoirs by injecting air to ignite heavy oil resources, leveraging the generated heat to enhance recovery rates, is a particularly critical extraction method. However, simulation studies of in-situ combustion techniques are still primarily conducted at a macroscopic level. Therefore, conducting more detailed numerical simulation studies holds significant importance. This paper establishes a mathematical model for heat transfer within reservoirs during in-situ combustion, thoroughly investigating the effects of inlet temperature, injection pressure, injection duration, and porosity on the heat transfer processes inside the reservoir. The research demonstrates that the reservoir's internal temperature gradually rises as the injection duration increases. Additionally, porosity (an increase from 0.1 to 0.3 enhances the heat propagation rate by 15%) and injection pressure (an increase from 5 MPa to 8 MPa boosts the heat propagation rate by 25%) significantly affect the heat transfer rate.

Keywords: in-situ combustion; heavy oil reservoirs; numerical simulation; mathematical model; heat transfer mechanisms

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1. Introduction

As a major global energy source, petroleum resources hold significant strategic importance [1]. With the depletion of conventional oil and gas resources worldwide and the increasing demand for crude oil, attention has shifted toward developing unconventional oil and gas resources, particularly heavy oil [2–5]. Heavy oil's high viscosity and low mobility make conventional extraction techniques ineffective, resulting in low recovery rates and high production costs [6–8]. Thermal enhanced oil recovery (EOR) methods—crucial approaches to address these challenges—utilize the in-situ combustion (ISC) technique to increase recovery rates by combusting the heavy components of crude oil, thereby improving the flow properties of heavy oil [9]. This process involves various displacement mechanisms, including heating and viscosity reduction, chemical modification, steam distillation, immiscible gas displacement, and CO_2 miscible displacement [10,11]. Compared to other methods, ISC technology consumes only about 20% of the fuel, effectively displacing residual oil with a theoretical recovery rate exceeding 70%. With its high displacement efficiency, ISC offers significant economic benefits [12]. However, the in-situ combustion

technique demands stringent operational conditions, and improper execution can damage reservoir structures [13,14]. In complex reservoirs, the stability of the combustion front directly impacts recovery rates and economic returns. In contrast, the coupling of heat transfer, fluid flow, and combustion processes, along with insufficient heat transfer mechanisms, limits the optimization and application of the technology [15].

As early as 1999, Ambastha and Kumar (1999) analyzed the impact of key factors such as air injection rate and fuel concentration on reservoir recovery by constructing numerical models and matching laboratory combustion tube test data [16]. Jia et al. (2017) explored the applicability of the kinetic model in the in-situ combustion (ISC) process, although they did not validate it under actual reservoir conditions [17]. Yang et al. (2019) used a numerical simulation model to study the ISC extraction process, analyzing the effects of geological and production parameters such as bottom water thickness, injection rate, and injection temperature on recovery efficiency [18]. Askarova et al. (2020) simulated the combustion behavior of isolated cave pore structures in carbonate reservoirs during ISC, providing a new perspective on the application of ISC in complex reservoirs [19]. Moussa et al. (2019) proposed a novel method to directly generate steam through downhole thermo-chemical reactions to reduce heat loss in conventional thermal recovery processes [20]. Antolinez et al. (2023) pointed out that, as an early thermal recovery technique, the selection and design of reservoirs faced during implementation remain bottlenecks in the commercialization of in-situ combustion [21]. Furthermore, Fang et al. (2024) studied the thermal oxidation characteristics of heavy oil and their impact on ISC, focusing on the kinetic parameters that affect the efficiency of enhanced oil recovery (EOR) technologies [22]. It is evident that current research on ISC technology in various countries encompasses numerical simulation, technological reviews, and innovative methods. Yet, there has been insufficient investigation into the movement patterns of the combustion front and its impact on the internal temperature field of the reservoir.

In order to explore the movement patterns of the combustion front and its impact on the internal temperature field of the reservoir, this study constructs a two-dimensional heat transfer model for crude oil combustion in underground heavy oil reservoirs. By developing a reasonable mathematical model and combining multiphase fluid dynamics with thermo-fluid-solid coupling theory, the model can more accurately describe the temperature, pressure, and stress field distributions in heavy oil reservoirs. Additionally, thermal property experiments were conducted on the selected heavy oil to analyze the impact of temperature on its viscosity, thereby evaluating the heat transfer efficiency of in-situ combustion.

Finally, the study utilized COMSOL Multiphysics (COMSOL, Inc., Burlington, MA, USA) to analyze the effects of various parameters, such as gas injection time, inlet temperature, porosity, inlet pressure, and injection rate, on the propagation pattern of the combustion temperature field in in-situ combustion processes. Previous studies have primarily focused on analyzing the heat transfer process at the macro level, whereas this research uses numerical simulations to explore the impact of multiple parameter variations on heat transfer efficiency. This has significant theoretical and practical implications for improving heavy oil recovery, extending the oilfield development cycle, and reducing production costs.

2. Thermal Property Analysis

Before performing numerical simulation analysis, a thermal property analysis was conducted on the heavy oil used in this paper. The target heavy oil was extracted from a certain type of heavy oil at the Extraction Plant in a northern oilfield in China. This heavy oil is solid at ambient temperature. The heating method was used to analyze the effect

of temperature on the viscosity of the heavy oil. To accurately describe the relationship between crude oil viscosity and temperature, a rotational viscometer was employed to precisely measure the viscosity of the heavy oil. The variation in heavy oil viscosity with temperature is shown in the Table 1.

Table 1. Heavy oil temperature-viscosity data.

Temperature/°C	Viscosity/mPa·s
20	10,396.7
40	3219.5
50	1327.9
60	225.6
80	113.7
100	76.5
120	43.7
140	29.5
160	21.2
180	9.6
200	7.5

It can be concluded that with the increase in temperature, the viscosity of the heavy oil decreases sharply. Heating reduces the viscosity of the heavy oil, enhancing its flowability, which significantly improves the oil recovery efficiency. Under high-temperature conditions, certain properties of heavy oil become similar to those of light crude oil.

An increase in temperature typically leads to a reduction in the viscosity of oil as the intermolecular forces weaken, allowing the molecules to move more freely. On the other hand, the chemical decomposition of oil may alter its chemical structure, further impacting its viscosity.

In the numerical simulation, the parameters of the heavy oil were set as follows (Table 2):

Table 2. Heavy oil thermal parameter design table.

Parameters	Units	Values
Poisson's Ratio	1	0.32
Density	Kg/m^3	0.88×10^3
Specific Heat Capacity	$J/(m^2 \cdot K)$	1.9
Thermal Expansion Coefficient	K^{-1}	1.1×10^{-3}
Thermal Conductivity	$W \cdot m^{-1} \cdot K^{-1}$	0.3

3. Mathematical Model

Considering the structural characteristics of subsurface heavy oil reservoirs, this study constructs a macroscopic two-dimensional simplified heat transfer model based on the in-situ combustion of crude oil within these reservoirs to simulate the reservoir conditions.

3.1. Calculation of Source Terms

This paper primarily focuses on the cracking of heavy components and the combustion reactions of coke in heavy oil under high-temperature conditions (low-temperature oxidation, fuel formation, and high-temperature oxidation). This process releases a significant amount of heat, which serves as the main heat source for maintaining the progression of the combustion front.

The in-situ combustion of heavy oil reservoirs can be represented by the following reaction equations:

The pyrolysis reaction equation of crude oil under anaerobic conditions

$$Crude.Oil \xrightarrow{r_{cf}} s_1LH + s_2HH + s_3Coke + s_4N + H_{cf} \quad (1)$$

The oxidation reaction equation of light oil

$$LH + s_5O_2 \xrightarrow{r_{LH}} s_6CO_x + s_7H_2O - H_{LH} \quad (2)$$

The oxidation reaction equation of heavy oil

$$HH + s_8O_2 \xrightarrow{r_{HH}} s_9CO_x + s_{10}H_2O - H_{HH} \quad (3)$$

The oxidation reaction equation of coke

$$Coke + s_{11}O_2 \xrightarrow{r_{co}} s_{12}CO_x + s_{13}H_2O - H_{co} \quad (4)$$

In the equations:
r_{cf}—reaction rate of coke formation, kg/m^3·s;
r_{LH}—reaction rate of light oil oxidation, kg/m^3·s;
r_{HH}—reaction rate of heavy oil oxidation, kg/m^3·s;
r_{co}—reaction rate of coke oxidation, kg/m^3·s;
H_{cf}—heat of coke formation reaction, kJ/kg;
H_{LH}—heat released by light oil oxidation, kJ/kg;
H_{HH}—heat released by heavy oil oxidation, kJ/kg;
H_{co}—heat released by coke oxidation, kJ/kg;
N—inert gas components;
CO_x—carbon-oxygen compounds produced during combustion,

$$1 \leq x \leq 2$$

s_n—stoichiometric coefficients of the chemical reactions, where

$$n = 1, 2, 3 \ldots 13.$$

Additionally, the injected high-temperature gases (ranging from 200 °C to 700 °C) also contribute a certain amount of heat. Due to chemical reactions such as cracking and oxidation at high temperatures, the system's composition undergoes significant changes, including the formation of light hydrocarbons, the generation of coke, and the release of gaseous products.

Based on the combustion properties of the reservoir crude oil, the reservoir can be divided into six distinct zones from the injection well to the production well: the burned zone, the combustion front (or fire front), the coking zone, the condensed water zone, the oil wall, and the unburned zone, as illustrated in Figure 1.

Chemical reactions are highly active at the combustion front, particularly near the inlet, where oxygen is heavily consumed. This results in low oxygen concentrations in the oil walls and unburned zones. In these regions, the oil saturation is high, leading to poor fluid mobility and minimal oxidation reactions. Additionally, pore blockage caused by coking often leads to the extinguishment of the combustion front when it advances into this zone.

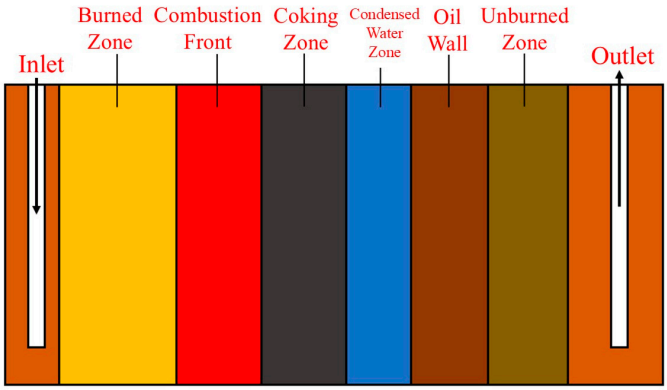


Figure 1. Division of Combustion Zones.

3.2. Mechanism of Porous Media in Reservoirs

Due to the small research scale of microscale simulation of fuel transformation in porous media and the methodological challenges involved, significant progress in this area has long been limited. To address this challenge, we applied a finite difference grid over the heavy oil reservoir to be simulated, using this grid system to approximate the spatial derivatives in the governing continuous equations. This discretization approach converts the continuous equations into finite difference equations, simplifying the differential problem into an algebraic one. By employing this method, the solution to the discretized problem approximates the solution to the original continuous problem, enabling the values at grid points to serve as approximate solutions to the actual problem [23].

In exploring porous media, adopting averaging theory aids in understanding their microscopic characteristics and linking these to macroscopic behavior. In practice, heterogeneous porous media display material property variations at the microscale, often manifested in the distribution of pore or particle sizes. We focus on variations in a single-phase medium at specific locations and attempt to describe the field variables of that phase at a given point. However, for actual porous media, such a level of description is impractical, as microscale parameters are often challenging to measure directly. Nevertheless, statistical averages of pore or particle sizes can be obtained. By applying averaging theory, these measurable averages can be incorporated into theoretical models, enabling a more accurate characterization of porous media [24].

The porous media structure of a reservoir primarily consists of the rock matrix and the crude oil within its pores, where the rock matrix contains numerous pores. The core of heavy oil thermal recovery technology lies in elevating the reservoir temperature to reduce the viscosity of the oil within the pores, thereby enabling its flow driven by increased pressure. The following assumptions are made: both the fluid and quartz sand are considered continuous and isotropic media, with the quartz sand remaining stationary. During the in-situ combustion process, each chemical component may exist in different physical phases, and these distinct phases, as well as the fluids and the embedded quartz sand, are assumed to be immiscible. This study does not consider the influence of capillary forces on pressure differences between phases; instead, it adopts the assumption that the pressures of all phases are equal.

Figure 2 reveals the complex interplay among various physical fields within porous media. These interactions manifest primarily as follows: deformation of the rock matrix alters the energy distribution, thereby affecting the thermodynamic state of the system. An increase in temperature leads to changes in the rock skeleton and pore structure, creating pressure differentials within the pores that modify fluid flow rates, ultimately influencing the rate and stability of temperature propagation in the porous medium. Additionally, rising

temperatures decrease the viscosity of heavy oil, enhancing its mobility and accelerating fluid flow within the porous media [25–27].

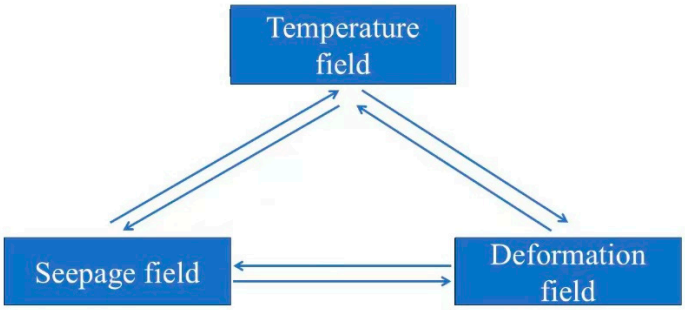


Figure 2. Fully Coupled Multiphase Flow Transmission Model.

In this process, thermo-solid coupling describes interactions between high-temperature fluids and rock particles, thermo-flow coupling involves the relationship between high-temperature fluids and the fluid velocity field, and flow-solid coupling focuses on the interactive effects between flow fields. Based on the forms of these interactions, couplings are categorized into "mechanical" and "parametric" types. Mechanical coupling refers to the displacement of rock particles caused by changes in temperature or pore pressure, which subsequently alters the pore structure, impacting permeability and porosity. These changes, in turn, affect pore pressure and the rate of heat transfer. Parametric coupling, on the other hand, acts through modifications in parameters like temperature and pressure, influencing the physical properties of the rock matrix and fluid [28]. For example, changes in fluid viscosity alter the flow field and impact heat distribution. Additionally, variations in rock matrix density, permeability, and porosity create coupling effects on both the flow field and heat transfer, enabling complex interactions among multiple physical fields.

3.3. Governing Equations

Considering that quartz sand is treated as an equivalent porous medium, the momentum conservation equation is transformed into Darcy's law, which is then incorporated into the mass and energy conservation equations. This results in a final mathematical model that requires only two fundamental equations: the mass conservation and energy conservation equations.

(1) Mass Conservation Equation:

O_2, CO_x and N_2 are classified as non-condensable gases, existing solely in the gas phase. The mass conservation equations for these gases follow a consistent mathematical form.

$$\frac{\partial}{\partial \tau}(\phi S_g \rho_g y_i) = \frac{\partial}{\partial x}\left(\rho_g y_i \frac{K_g}{\mu_g}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial x}\left(\rho_g D_i \frac{\partial y_i}{\partial x}\right) + \psi_i \tag{5}$$

Water exists in both vapor and liquid phases within the system. The mass conservation equation for water can be expressed as:

$$\frac{\partial}{\partial \tau}\left[\phi\left(S_g \rho_y y_4 + S_w \rho_w\right)\right] = \frac{\partial}{\partial x}\left[\left(\rho_g \frac{k_g}{\mu_g} y_4 + \rho_w \frac{k_w}{\mu_w}\right)\frac{\partial \rho}{\partial x}\right] + \frac{\partial}{\partial x}\left(\rho_g D_4 \frac{\partial y_4}{\partial x}\right) + \varphi_4 \tag{6}$$

Oil exists in a single phase within the system, and its mass conservation equation can be expressed as:

$$\frac{\partial}{\partial \tau}(\phi S_o \rho_o) = \frac{\partial}{\partial x}\left(\rho_o \frac{k_o}{\mu_o}\frac{\partial \rho}{\partial x}\right) + \psi_s \tag{7}$$

Coke, as a fixed component, does not undergo mass transfer; therefore, its mass variation is solely due to chemical reactions. Its mass conservation equation can be expressed as:

$$\frac{\partial}{\partial t}(\phi_c \rho_c) = \psi_6 \tag{8}$$

In the equations above:
τ—time, s;
ϕ—porosity, dimensionless;
S—saturation, dimensionless;
ρ—density, kg/m^3;
y—mass fraction, dimensionless;
K—permeability, m^2;
μ—dynamic viscosity, kg/(m·s);
p—pressure, Pa;
x—distance from the combustion tube inlet, m;
D—mass diffusion coefficient, m^2/s;
ψ—chemical reaction mass source term, kg/$\left(\mathrm{m}^3 \cdot \mathrm{s}\right)$;
Subscripts $i = 1, 2, 3, 4, 5$ represent O_2, CO_x, N_2, water, and crude oil, respectively.
The subscripts g, w and o indicate gas phase, liquid phase, and oil phase, respectively.
(2) Energy Conservation Equation:

$$\begin{array}{c} \frac{\partial}{\partial x}\left[(1-\phi_0)\rho_r h_r + \phi_c \rho_c h_c + \phi\left(S_g \rho_g h_g + S_w \rho_w h_w + S_o \rho_o h_o\right)\right] = \\ \frac{\partial}{\partial x}\left[\left(\rho_g \frac{k_g}{\mu_g} h_g + \rho_w \frac{k_w}{\mu_w} h_w + \rho_o \frac{k_o}{\mu_o} h_o\right)\frac{\partial \rho}{\partial x}\right] + \frac{\partial \rho}{\partial \tau} + \frac{\partial}{\partial x} + \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + q_v \end{array} \tag{9}$$

In the equations above:
ϕ_0—initial porosity;
ϕ_C—mass fraction of coke;
h—specific enthalpy, J/kg;
T—temperature, °C;
λ—thermal conductivity, W/(m·°C);
q_V—heat generated per unit volume per unit time from chemical reactions, J/$\left(\mathrm{m}^3 \cdot \mathrm{s}\right)$;
The subscripts r and c denote quartz sand and coke, respectively.

In this study, these reaction rate constants primarily depend on temperature, as changes in temperature directly affect the activation energy of chemical reactions, thereby influencing the reaction rates. According to the Arrhenius equation, the relationship between the reaction rate constant k and temperature T is expressed as:

$$k = Ae^{-\frac{E_a}{RT}} \tag{10}$$

In the equations above:
A—apparent frequency factor, with the same unit as k;
E_a—activation energy, J·mol^{-1};
R—gas constant, J·mol^{-1};
T—absolute temperature, °C.

At the same time, we also considered the effect of pressure on the reaction rate. In particular, in multiphase fluid systems, changes in pressure can affect the solubility of gases and the concentration of reactants, thereby further influencing the rate of chemical reactions.

3.4. Model Development

The main body of the model is a rectangular reservoir with dimensions L = 500 mm (length) and H = 300 mm (height). Considering that the original reservoir contains porous

media, the model includes several irregular circular porous media to simulate pore formation. A single gas injection scheme is applied, where hot gas is injected into the formation from an injection port located at the upper left. The initial pressure of the model is set at $P_0 = 5$ MPa and the initial temperature at $T_0 = 20$ °C. The model also includes an irregularly distributed rock matrix with porous media, as shown in Figure 3.

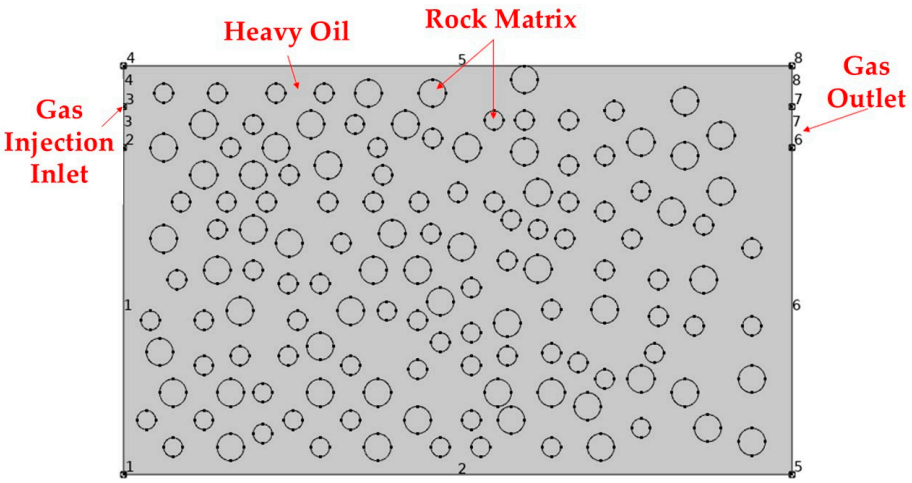


Figure 3. Schematic Diagram of the 2D Reservoir Model.

3.5. Initial Conditions and Boundary Conditions

For the reservoir physical model setup, the initial conditions are defined as an initial pressure $P_0 = 5$ MPa and an initial temperature $T_0 = 20$ °C. The porosity of the porous media is set to 0.3, and the density of the reservoir rock matrix is 2.4×10^6 kg/m^3. The specific heat capacity of the rock matrix is 833.3 J/(kg·K), and its thermal conductivity is 1.85 W/(m·K). The specific heat capacity of the crude oil within the reservoir is 2100 J/(kg·K), and the thermal conductivity of the fluid within the reservoir is 0.15 W/(m·K). By setting these parameters, a reasonable and accurate reservoir physical model can be constructed, providing a solid foundation for subsequent numerical simulations and theoretical analyses.

At the combustion chamber inlet during the ignition period, the mass flux densities of gas and water are q_a and q_w, respectively, with oxygen maintained at 21% by volume and the remainder being nitrogen. The initial pressure is $P_0 = 5$ MPa, the initial temperature is $T_0 = 20$ °C, the porosity of the porous medium is 0.3, and the initial oil saturation S_{oi} and water saturation S_{wi} are 0.

At $x = 0$,

$$y_{o_2} = 21\% \tag{11}$$

$$y_{N_2} = 79\% \tag{12}$$

$$P(x, t = 0) = 5 \text{ MPa } T(x, t = 0) = 20 \text{ °C} \tag{13}$$

$$S_{oi}(x, t = 0) = 0 \; S_{wi}(x, t = 0) = 0 \tag{14}$$

At the combustion chamber inlet, the temperature T is maintained at the maximum value T_{max}, and the pressure equals the ambient pressure P_b. After reaching a steady state, the inlet becomes an adiabatic boundary, meaning no heat transfer is allowed. This can be expressed as:

$$T(x = 0, t) = T_{max}(during\ ignition) \tag{15}$$

$$\frac{\partial T}{\partial x}(x = 0, t) = 0 \ (adiabatic\ condition,\ after\ steady\ state) \tag{16}$$

$$P(x = 0, t) = P_b \tag{17}$$

At the combustion chamber outlet, the pressure also equals the ambient pressure P_b. It is assumed that no additional heat or material flows in or out, making the outlet an adiabatic boundary as well:

$$P(x = L, t) = P_b \tag{18}$$

$$\frac{\partial T}{\partial x}(x = L, t) = 0 \tag{19}$$

3.6. Grid Independence Test

In the numerical simulation of in-situ combustion in the reservoir, the grid division of the model is based on the sequence type controlled by the physical fields. A tetrahedral grid is used to divide the unstructured mesh, with the conventional element size chosen for the grid. The specific model established is shown in Figure 4.

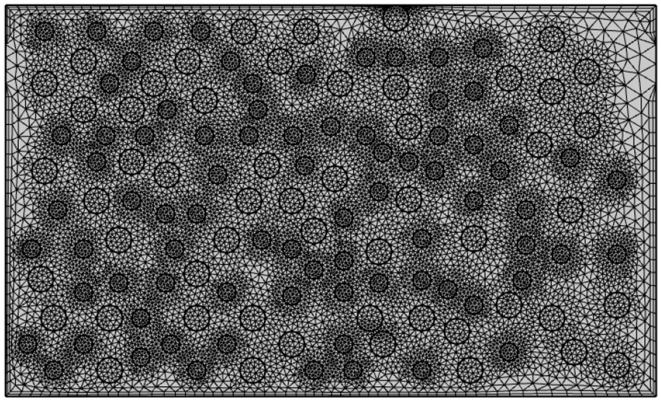


Figure 4. Grid Division of the Two-Dimensional Simplified Geometric Model.

To ensure the reliability of the fluid simulation results, this study performed a grid independence test on the numerical model and optimized the grid quality. Based on the computational requirements of the model, three models with different grid densities were selected for numerical simulation experiments, consisting of 10,242, 22,762, and 36,796 grid elements, respectively. By comparing the simulation data at the same monitoring point for these three grid densities (see Figure 5), the results show that while the overall trends of the models with different grid numbers are similar, there are subtle differences. Specifically, the model with 10,242 grid elements exhibits a faster temperature change rate, while the model with 36,796 grid elements shows a more gradual temperature variation trend. The temperature distribution obtained from the model with 22,762 grid elements falls between the other two models, and the temperature distribution patterns across all three models are quite similar, converging toward the same trend to a certain extent. When the grid count is 10,242, the model exhibits significant deviations. Although increasing the grid count to 22,762 and 36,796 leads to consistent solution results, the computational load also increases, and the improvement in accuracy becomes limited. Therefore, this study selected a model with 22,762 grid elements to balance efficiency and accuracy.

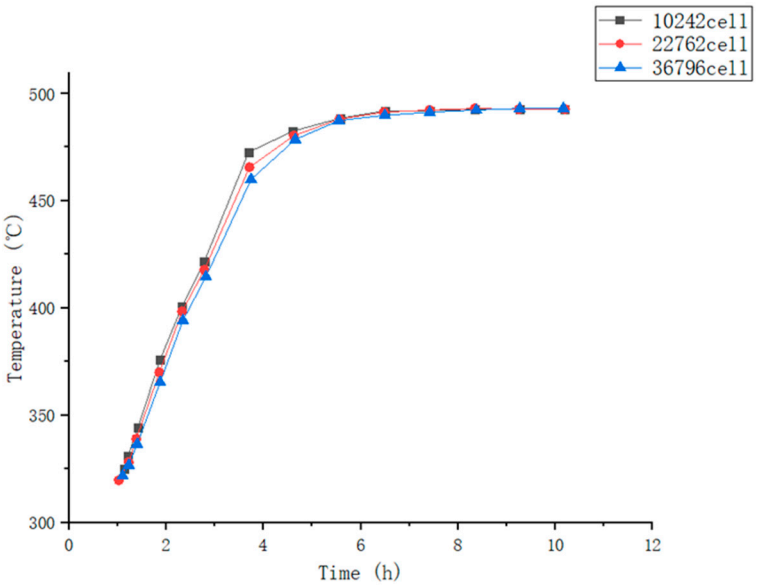


Figure 5. Grid Independence Verification.

4. Results Analysis

In this section, a numerical simulation of the heat transfer model for an in-situ combustion reservoir is performed, reflecting the actual operating conditions of the heating process in a heavy oil reservoir.

The increase in temperature during the calculation process is likely due to the continuous heat generation from the combustion reactions triggered by the injected air in the simulated fire flooding of the oil reservoir, which causes the temperature inside the reservoir to rise. The generation and accumulation of this heat is the primary reason for the temperature increase in the simulation. The high temperatures produced during combustion not only transfer heat to the surrounding media through thermal conduction but may also influence the temperature field of the entire reservoir through convection mechanisms. The simulation produces a vector diagram of the velocity field within the reservoir, as shown in Figure 6.

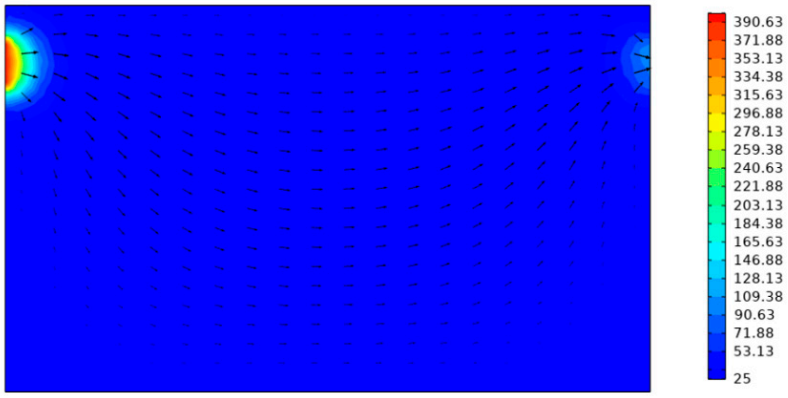


Figure 6. Velocity Vector Diagram.

Figure 6 presents the velocity vector diagram of the in-situ combustion reservoir model. The velocity vectors are most concentrated near the inlet of the model. Moving in the direction of gas flow—from the lower left to the upper right—the density of the velocity vectors gradually decreases, with the reduction rate in the horizontal direction being slower than in the vertical direction. Particularly in the upper left region of the contour map, the distribution of velocity vectors is sparse, indicating a significant change

in the horizontal pressure gradient, leading to higher velocity variations. Additionally, the 3D flow field distribution shows a higher density of vectors around pores and fracture throats, suggesting higher flow rates in these areas.

Based on this, the evolution of combustion and heat transfer in heavy oil reservoirs is studied using Multiphysics theory and numerical simulation techniques. In the thermal recovery of heavy oil, reservoir temperature is typically controlled by adjusting the injection gas [29]. A mathematical model was developed using computer simulation to regulate reservoir temperature. Simulations were stopped based on the achievement of steady-state conditions where further changes in temperature and combustion fronts were minimal. Additionally, simulations were concluded once the predefined simulation duration was reached, corresponding to typical operational times observed in field applications. This approach aligns with methodologies employed in studies referenced in the literature [16–22], where similar criteria were utilized to determine the cessation of simulations, ensuring consistency and comparability across related research efforts.

The control parameters, such as inlet temperature, injection pressure, injection duration, and reservoir porosity, were chosen based on their significance in in-situ combustion processes and their typical ranges in experimental and field studies. For example, references [18,30–32] all discuss these control parameters. Each parameter was varied systematically to understand its effect on the heat transfer and combustion dynamics within the reservoir. The parameters were selected to replicate realistic operational conditions that could influence the performance and efficiency of the in-situ combustion process.

4.1. Effect of Injection Time on the Temperature Field of the Reservoir

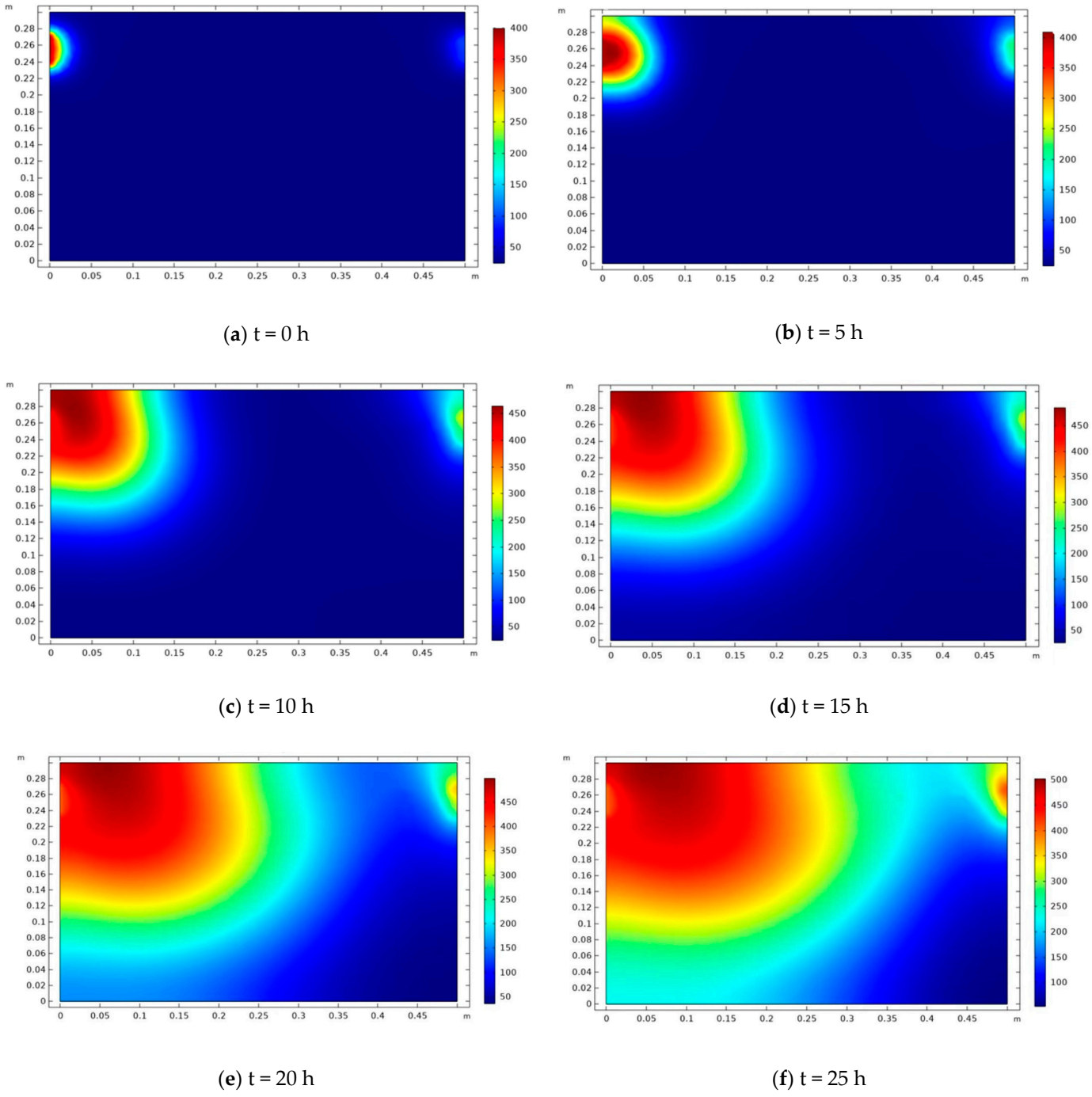
As the heating process continues within a heavy oil reservoir, the viscosity of the heavy oil changes, which in turn affects the fluid flow rate and the rate of temperature propagation within the reservoir. A series of calculations were performed to explore the impact of gas injection duration on reservoir characteristics. Under conditions of an injection temperature $T = 400$ °C, injection pressure of $P = 5$ MPa, injection rate of $v = 1200$ mL/min, and reservoir porosity of 0.1, temperature contour maps of the reservoir were obtained at reaction times $t = 0, 5, 10, 15, 20$ and 25 h.

When selecting the time step size, in order to ensure the stability and accuracy of the numerical simulation, we tested multiple time step sizes with a fixed grid resolution. By comparing the simulation results of the reservoir temperature field for different time steps, we observed that although a smaller time step can improve accuracy, it significantly increases the computational cost. On the other hand, a larger time step may lead to instability in the numerical solution. Ultimately, we chose a moderate time step that not only ensures the accuracy of the simulation results but also optimizes computational efficiency [30].

This study examines the effect of heating duration on the reservoir's thermal characteristics, with the relevant results shown in Figure 7.

It is known that the physical properties of heavy oil, such as viscosity, decrease with rising temperature, thereby enhancing its mobility. As seen in Figure 7, the heat transfer rate gradually accelerates with the extension of the injection time. This is consistent with Zhao Yang's findings in his study on the in-situ combustion process in the Du 66 block [18]. Additionally, due to the influence of gravity, the rate of heat transfer in the vertical direction is higher than that in the horizontal direction. When the injection-production cycle is extended, the crude oil is heated by the high-temperature fluid, causing its viscosity to decrease and flow rate to increase, which accelerates heat transfer in the oil reservoir. Under the influence of gravity, the viscosity-reduced heavy oil tends to flow

downward, resulting in a higher heat propagation rate in the vertical direction compared to the horizontal direction.



(**a**) t = 0 h (**b**) t = 5 h

(**c**) t = 10 h (**d**) t = 15 h

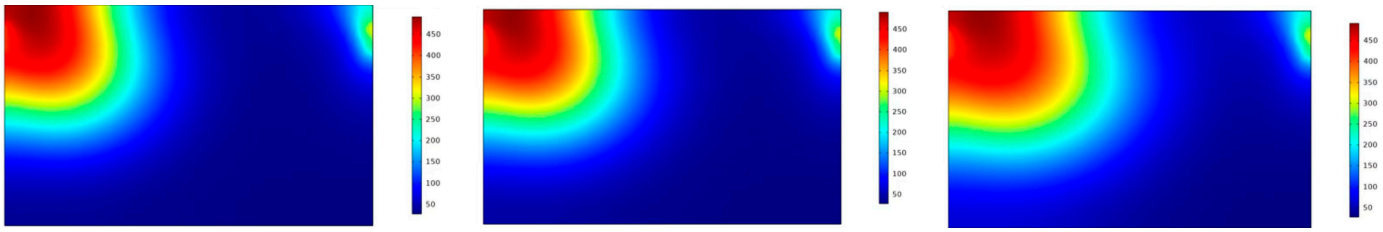
(**e**) t = 20 h (**f**) t = 25 h

Figure 7. The Increase in Gas Injection Time Results in Changes in the Reservoir Temperature Field.

4.2. Effect of Porosity on the Temperature Field of the Reservoir

This study begins with the fundamental properties of heavy oil reservoirs, specifically porosity, which is the ratio of the total pore volume to the total volume of the oil layer. Porosity reflects the ease with which injected gases can flow through the oil and gas reservoir, indicating the intensity of the permeability. As porosity increases, the permeability also increases. Therefore, porosity not only plays a significant role in the flow rate but also has a substantial impact on the temperature of the reservoir. The simulation results, with an inlet gas injection temperature of $T = 400$ °C, an inlet pressure of $P = 5$ MPa, an injection

rate of $v = 1200$ mL/min, and a reaction time of $t = 15$ h, show the final temperature changes for porosity values of $\Phi = 0.1, 0.2$ and 0.3. The results are presented in Figure 8.



(**a**) $\Phi = 0.1$ (**b**) $\Phi = 0.2$ (**c**) $\Phi = 0.3$

Figure 8. The Variation of Reservoir Temperature Field with Different Porosities.

The results shown in Figure 8 reveal that under consistent operating conditions, the porosity of the reservoir significantly impacts the speed of temperature propagation. Specifically, an increase in porosity leads to a faster temperature propagation rate, and this rate exhibits a clear functional dependence on porosity. A higher reservoir porosity implies that the fluid occupies a larger volume, which corresponds to a greater proportion of heavy oil in the reservoir, thereby promoting faster temperature propagation. Due to the heating effect of high-temperature fluids, the viscosity of heavy oil decreases, and the flow rate increases, which enhances its heat transfer efficiency. Moreover, in a porous medium, higher porosity results in a greater amount of heavy oil, and when the fluid is heated, its capacity for heat transfer increases. The results indicate that porosity is directly and linearly related to the heat transfer coefficient.

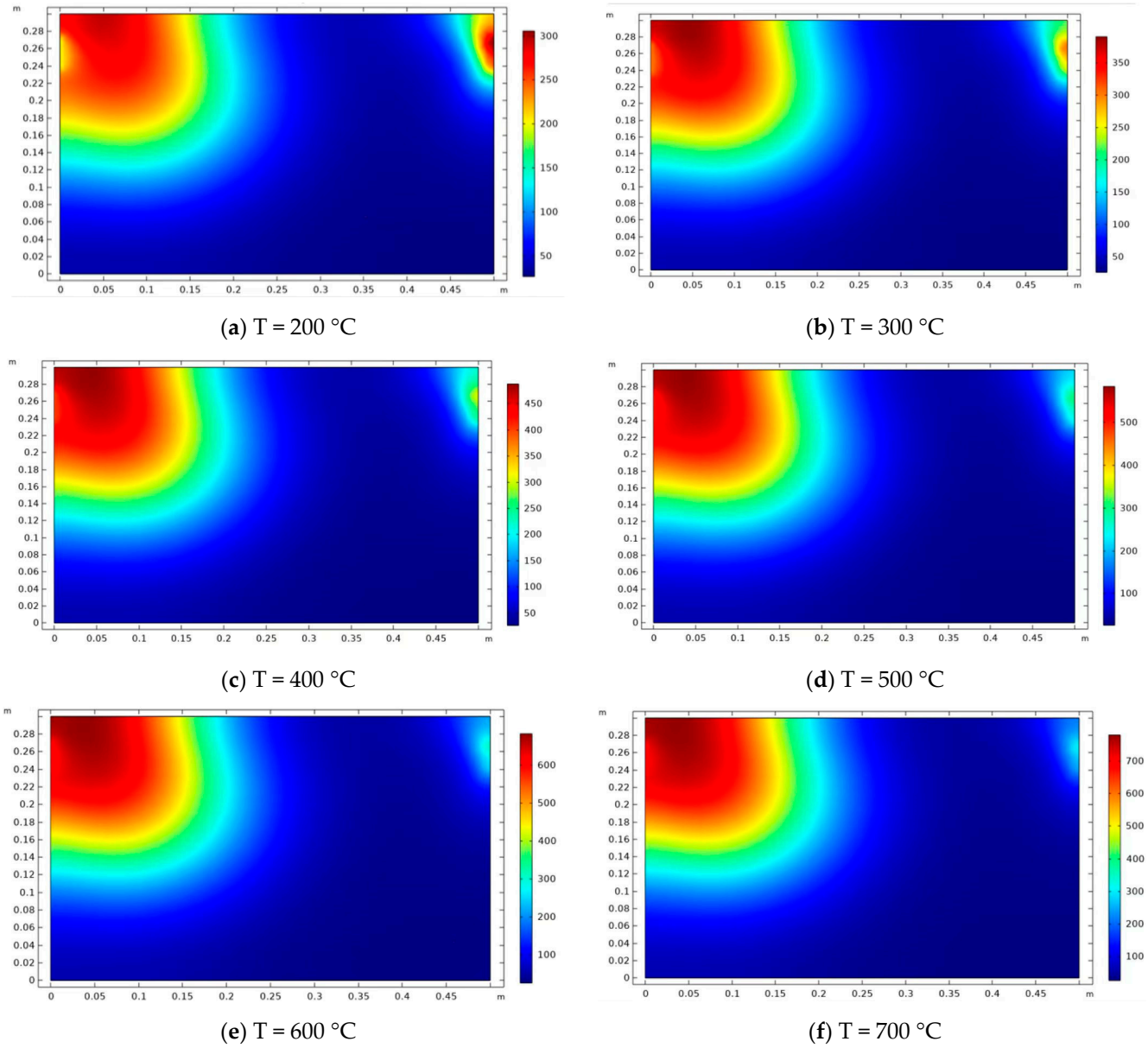
This finding aligns with Bai Yu's research at Xi'an Petroleum University on the influence of porosity on fire flooding [31]. The increase in porosity enhances the amount of hydrocarbons that the rock can store, thereby improving the extraction efficiency of fire flooding. Additionally, there is a positive correlation between porosity and permeability: the higher the porosity, the higher the permeability, which facilitates the injection of oxygen into the formation and accelerates the heat transfer rate [32].

4.3. Effect of Inlet Temperature on the Temperature Field of the Reservoir

During the in-situ combustion process, the temperature of the injected air is closely related to the viscosity of the heavy oil, which in turn affects the heat transfer capacity of the reservoir. To better understand the specific impact of different injection temperatures on the heating process within the reservoir, a series of simulation calculations were performed. In these simulations, the injection conditions were kept consistent: inlet pressure $P = 5$ MPa, injection rate $v = 1200$ mL/min, and reaction time $t = 15$ h, with a reservoir porosity of 0.3. Numerical simulations were conducted for reservoir temperatures at inlet air temperatures of $T = 200$ °C, 300 °C, 400 °C, 500 °C, 600 °C and 700 °C. The results of the heat transfer state in the reservoir after 15 h are shown in Figure 9.

Through the analysis of the physical properties of heavy oil, it was found that the viscosity of heavy oil is significantly influenced by external temperature. In other words, as the external temperature increases, the viscosity of the heavy oil decreases. The results shown in Figure 9 indicate that at the same time point, as the initial temperature of the injected gas increases, the rate of temperature propagation within the reservoir also increases, but the increase is relatively small. The physical properties of heavy oil reveal that temperature is a key factor in determining its viscosity; as the temperature rises, the viscosity of the heavy oil decreases. When the environmental temperature is $T = 70$ °C, further increases in temperature cause the viscosity reduction to slow down, and the viscosity gradually approaches a stable value. When the temperature reaches $T \geq 200$ °C,

additional heating has almost no further effect on the viscosity of the heavy oil. This suggests that further increasing the inlet temperature during the reservoir heating process has a limited impact on the heat transfer rate of the reservoir's porous medium. Nonetheless, raising the inlet temperature still results in an increase in the internal temperature of the reservoir.



(**a**) T = 200 °C (**b**) T = 300 °C

(**c**) T = 400 °C (**d**) T = 500 °C

(**e**) T = 600 °C (**f**) T = 700 °C

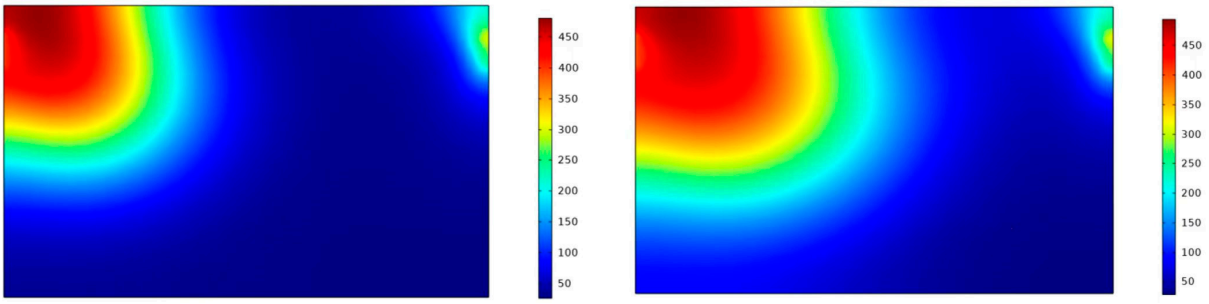
Figure 9. Temperature Variation in Heavy Oil Reservoirs with Different Injection Temperatures.

4.4. Effect of Injection Rate on the Temperature Field of the Reservoir

During the in-situ combustion process, the injection rate of the gas is a crucial controllable parameter, and its appropriateness directly determines the success or failure of the experiment. If the injection rate is set improperly, it may cause the oxygen to prematurely break through to the production well, triggering a sharp rise in temperature in certain areas of the wellbore. This not only risks experimental failure but could also, in extreme cases, lead to high-temperature combustion that damages the wellbore structure.

In this model calculation process, increasing the injection rate of the high-temperature gas reduces the viscosity of the heavy oil, thereby improving its flow properties and decreasing the consumption of fuel in the reservoir. Experimental findings show that as

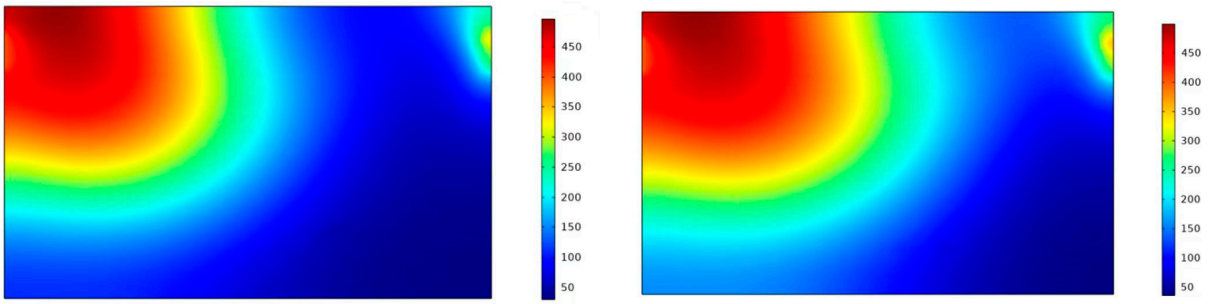
the injection rate increases, the forward propagation rate of the fire front increases almost linearly. A validated numerical simulation model was used to study the impact of the injection rate on the temperature transfer within the reservoir during in-situ combustion. The simulation was conducted under the following conditions: inlet temperature $T = 400$ °C, inlet pressure $P = 5$ MPa, reaction time $t = 15$ h, and reservoir porosity of 0.3. The injection rates of 1000, 1200, 1600, and 1800 mL/min were tested, and the temperature transfer in the reservoir at times $T = 10$ h and $T = 20$ h for each injection rate was compared. The results are shown in Figures 10–13.



(**a**) Injection Rate = 1000 mL/min t = 10 h

(**b**) Injection Rate = 1000 mL/min t = 20 h

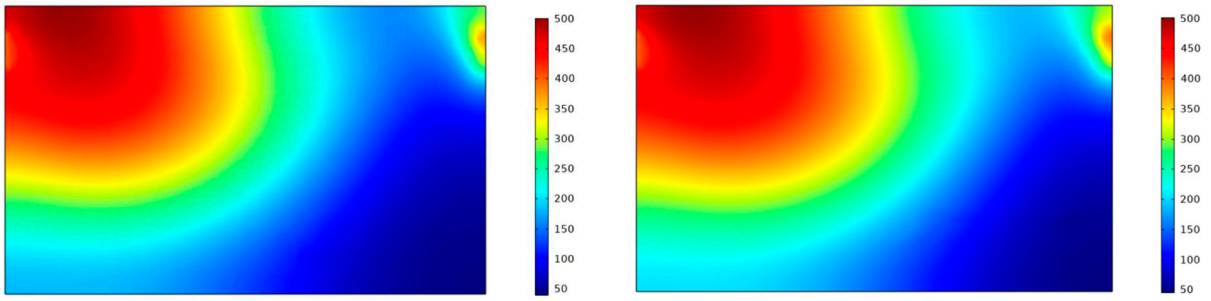
Figure 10. The Temperature Variation in the Reservoir at an Injection Rate of 1000 mL/min.



(**a**) Injection Rate = 1200 mL/min t = 10 h

(**b**) Injection Rate = 1200 mL/min t = 20 h

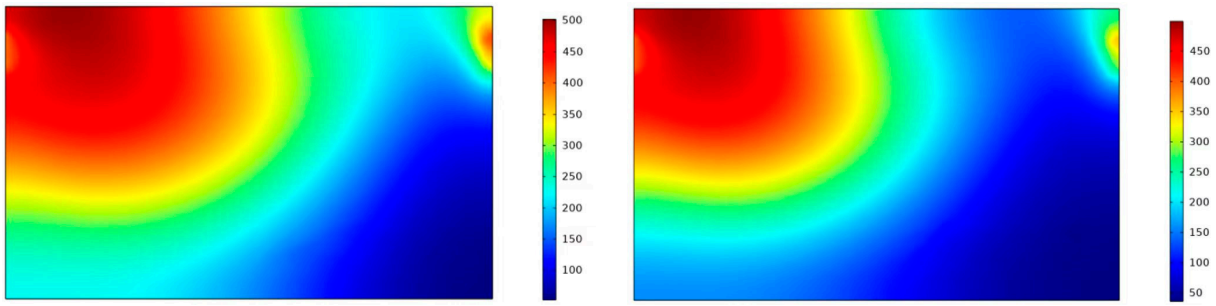
Figure 11. The Temperature Variation in the Reservoir at an Injection Rate of 1200 mL/min.



(**a**) Injection Rate = 1600 mL/min t = 10 h

(**b**) Injection Rate = 1600 mL/min t = 20 h

Figure 12. The Temperature Variation in the Reservoir at an Injection Rate of 1600 mL/min.



(**a**) Injection Rate = 1800 mL/min t = 10 h

(**b**) Injection Rate = 1800 mL/min t = 20 h

Figure 13. The Temperature Variation in the Reservoir at an Injection Rate of 1800 mL/min.

As shown in Figures 10–13, within the range of injection rates that can sustain high-temperature combustion, the higher the injection rate, the faster the temperature transfer. However, the injection rate has a greater effect on combustion time. Within a certain range, as the injection rate increases, the maximum temperature of the reservoir remains relatively unchanged. However, when the injection rate is below a certain threshold, the temperature decreases significantly, which is due to insufficient injection, leading to incomplete combustion. On the other hand, an excessively high injection rate can also cause the reaction to stop prematurely because the excessive injection removes too much heat, resulting in inadequate fuel for the reaction. This finding is consistent with Jin X.'s conclusions from using the Numerical Simulator CMG STARS to study the influence of injection parameters [33].

The propagation speed of the fire front is directly proportional to the injection rate. As the injection rate increases, the temperature transfer rate in the early stages is faster. However, due to the premature consumption of reactants in the reservoir, the model terminates earlier than expected.

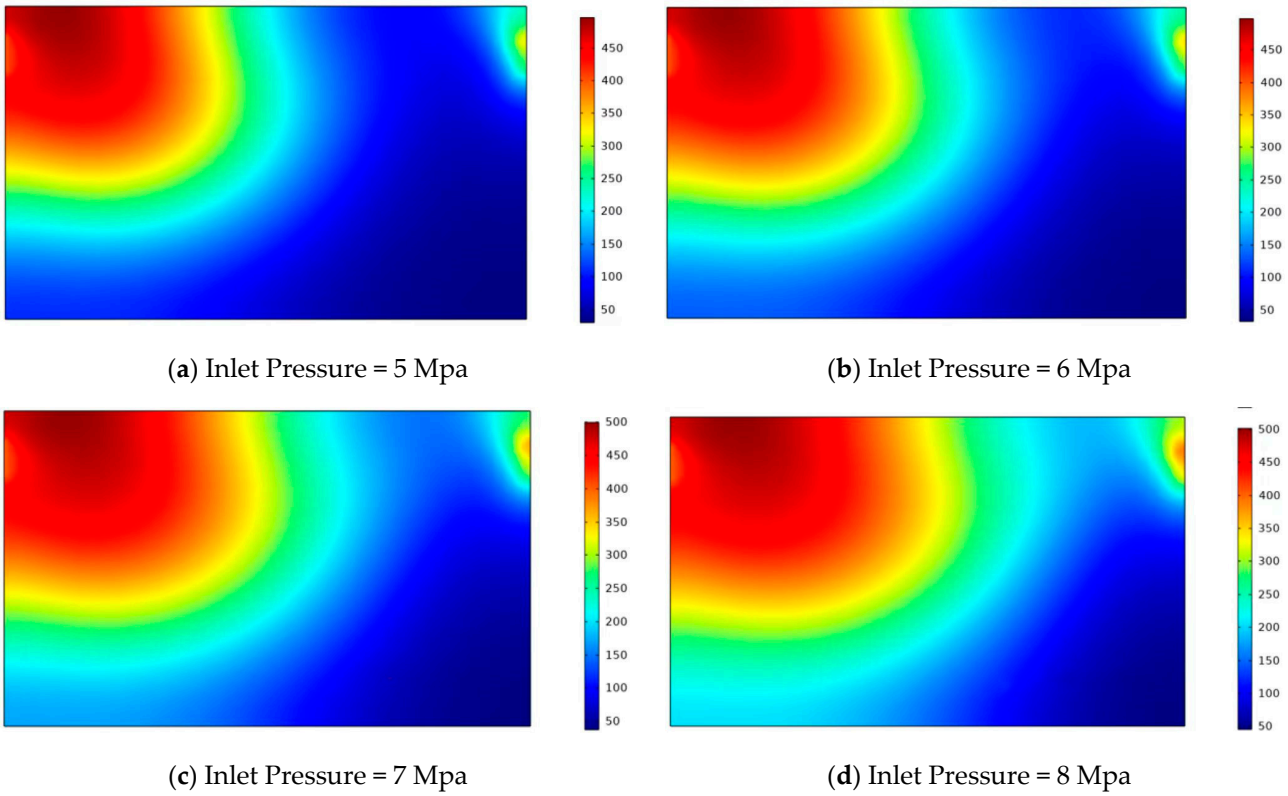
4.5. Effect of Inlet Pressure on the Temperature Field of the Reservoir

In addition to the intrinsic properties of the reservoir, external conditions such as inlet pressure have a significant impact on the heat transfer process within the porous medium of the reservoir. According to Darcy's Law, adjusting the inlet pressure during the heating process can alter the reservoir's seepage characteristics. Modifying the inlet pressure will change the seepage rate within the reservoir, directly influencing the heat transfer effect inside the reservoir.

To address this issue, this study investigates the effect of inlet pressure on the heat transfer behavior within the reservoir. The following calculations were performed: numerical simulations were conducted under the following conditions: inlet gas temperature $T = 400$ °C, injection rate $v = 1200$ mL/min, reaction time $t = 10$ h, and reservoir porosity of 0.3. The heat transfer effects within the reservoir were compared for different inlet pressures ($P = 5$ MPa, 6 MPa, 7 MPa, and 8 MPa). Figure 14 shows the temperature transfer behavior of the porous medium in the reservoir under varying inlet pressures.

As the inlet pressure increases, the pressure gradient inside the heavy oil reservoir also increases, which leads to an enhancement in the fluid's flowability. As shown in Figure 14, at the same time point, with increasing inlet pressure, the high-temperature region within the porous medium of the reservoir gradually expands, and the reservoir temperature correspondingly rises. This indicates that the increase in inlet pressure accelerates the fluid flow velocity within the reservoir's porous medium, which, in turn, accelerates the temperature propagation rate. Increasing the injection well pressure results in a sharp increase in the initial thermal energy at the production well, but the increased pressure

primarily affects the initial stage of heat production. Additionally, increasing the pressure causes the injected fluid to penetrate further into the reservoir, thus accelerating the thermal breakthrough process.



(**a**) Inlet Pressure = 5 Mpa (**b**) Inlet Pressure = 6 Mpa

(**c**) Inlet Pressure = 7 Mpa (**d**) Inlet Pressure = 8 Mpa

Figure 14. Temperature Variation in Heavy Oil Reservoirs with Different Inlet Pressures.

According to Darcy's Law, the fluid flow velocity in the in-situ combustion reservoir is directly proportional to the pressure gradient, and under constant conditions, there is a linear relationship between inlet pressure and fluid flow velocity [34]. Therefore, increasing the inlet pressure effectively enhances the flow velocity of the fluid within the reservoir. As the flow velocity increases, the heat exchange efficiency within the reservoir improves, which accelerates both thermal conduction and convective heat transfer processes, further promoting fluid flow and convective heat transfer within the reservoir. Meanwhile, as the inlet pressure increases, the heat exchange area on the surface of the oil and gas reservoir also expands, and the heat transfer rate increases with higher inlet pressures. Experimental results show that the pressure differential between the pores significantly affects the seepage rate—i.e., as the pressure differential increases, the seepage velocity increases, which speeds up the heat transfer during the flow process [35]. Therefore, it is evident that the heat transfer rate within the reservoir is positively correlated with the pressure differential between the pores: the greater the pressure differential, the faster the heat transfer rate.

5. Conclusions and Outlook

In this study, we validated the effectiveness of the numerical model by comparing our conclusions with those of other researchers. Additionally, experimental data were used to verify the numerical simulations. However, due to equipment limitations in the experiments, the experimental conditions could not fully match those of the numerical simulations. This method provides support for the applicability of the numerical model but does not fully validate it.

5.1. Conclusions

Based on the fundamental theories of the reservoir's porous medium and the coupling mechanism between the temperature field, seepage field, and deformation field, this study constructs a coupled thermal-fluid-solid mathematical model for the reservoir, integrating the theories of heat and mass transfer, thermodynamics, fluid mechanics, and geomechanics. Using this model, the complex physical fields generated during the combustion heat transfer process in heavy oil reservoirs and their impact on the reservoir temperature field were numerically simulated. The following conclusions were drawn:

(1) As the injection duration increases, the heat transfer efficiency in the porous medium of the reservoir gradually improves. Due to the effects of gravity, the heat transfer efficiency of the reservoir's porous medium in the vertical direction exceeds that in the horizontal direction.

(2) The heat transfer efficiency in the reservoir increases with the internal porosity and the temperature of the injected high-temperature fluid. However, once the temperature reaches a certain level, further increases have little effect on the heat transfer efficiency.

(3) The injection rate impacts the reservoir's temperature transfer, with higher injection rates leading to faster temperature propagation. However, if the injection rate is too low, insufficient injection results in incomplete combustion in the reservoir. Conversely, an excessively high injection rate leads to little change in the maximum temperature of the reservoir but causes the reaction to terminate prematurely. This is because excessive injections carry away too much heat, leading to a lack of fuel for the reaction.

(4) In the reservoir environment, the fluid flow velocity is directly proportional to the pressure gradient, meaning an increase in the pressure gradient results in a corresponding increase in flow velocity. Furthermore, the inlet pressure of the reservoir fluid maintains a linear relationship with its flow velocity. If other conditions remain unchanged, increasing the inlet pressure can effectively promote fluid flow within the reservoir. As the flow velocity increases, the heat exchange efficiency of the reservoir also improves, which includes accelerated thermal conduction and convective heat transfer processes, thereby enhancing both the flow velocity and the convective heat transfer efficiency within the reservoir. In summary, increasing the inlet pressure is an effective method to promote heat transfer and fluid flow within the reservoir.

5.2. Outlook

This study uses numerical simulation methods to investigate the thermal transfer characteristics of heavy oil reservoirs during the fire flooding process and has made preliminary progress in revealing the thermal transfer laws of heavy oil reservoir formations. However, there are some limitations in the current research, and further in-depth studies on reservoir formations in geological settings are needed. Specifically, the following aspects require further exploration:

(1) The study focused on the general heat transfer behavior in homogeneous reservoirs. However, real-world reservoirs exhibit significant spatial variability in porosity, permeability, and fluid composition. Further research is needed to examine how heterogeneity affects thermal propagation and heat transfer efficiency.

(2) The current model assumes single-phase fluid flow in the reservoir, while, in practice, reservoirs contain multiphase fluids (oil, water, gas). A more comprehensive model that includes the effects of multiphase flow, especially in the presence of gas injection, could provide more accurate predictions of heat transfer behavior and combustion efficiency.

(3) The study simplified the combustion reactions in the reservoir; however, the kinetics of the combustion process, including the effects of temperature, pressure, and fluid composition on reaction rates, could be more accurately modeled for a better understanding of the fuel consumption and heat generation rates during in-situ combustion.

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