Reservoir Science
http://dx.doi.org/10.62762/RS.2025.637298

RESEARCH ARTICLE

The Influence of Geological Factors and Transmission Fluids on the Exploitation of Reservoir Geothermal Resources: Factor Discussion and Mechanism Analysis

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Abstract

The geothermal resources present within the reservoir post-oil production in the oil field have hitherto been overlooked and underdeveloped, constituting a novel energy supplement for the maintenance of energy security. The present study constructed a geothermal transmission and exploitation model for oil reservoirs based on the geological environment and the characteristics of geothermal transmission media. This model can be used to analyse the impact of different factors on the efficiency of reservoir geothermal resources. Concurrently, a molecular dynamics model was constructed to reveal the geothermal transmission mechanism at a microscopic perspective, which will facilitate the optimisation of geothermal mining technology. The findings indicate that fluid viscosity hinders geothermal transmission, and the transmission medium of 40mPa·s increases the diameter range of geothermal transmission by 9m compared with 30mPa·s. Furthermore, the deflection angle of reservoir fractures is also not conducive to reservoir geothermal transmission. It has been demonstrated that an increase in the deflection angle results in a reduction of the transmission capacity, owing to substantial fluid filtration. The utilisation of reservoir geothermal resources provides fundamental data support for the rational application of energy and the assurance of energy security.

Keywords: geothermal transmission, reservoir energy extraction, fluid heat transfer, energy engineering, petroleum reservoir.

1 Introduction

The process of economic development is intrinsically associated with rising energy demand, which in turn poses a considerable challenge to the long-term sustainability of global economic growth [1, 2]. The gradual depletion of conventional fossil fuel reserves is expected to inevitably slow economic expansion. Consequently, this prospect has driven energy and materials scientists to undertake proactive research and development of alternative energy sources to mitigate the anticipated energy deficit [3, 4]. Two

Submitted: 14 July 2025
Accepted: 03 September 2025
Published: 29 September 2025

Vol. 1, **No.** 1, 2025.
10.62762/RS.2025.637298

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Citation
Wang, F., & Kobina, F. (2025). The Influence of Geological Factors and Transmission Fluids on the Exploitation of Reservoir Geothermal Resources: Factor Discussion and Mechanism Analysis. *Reservoir Science*, 1(1), 3–18.

locations have been identified as significant sources of alternative energy: (1) Geological new energy [5]. The recent discovery of unconventional shale resources and natural gas hydrates has undoubtedly offered a promising avenue to alleviate the shortage of fossil energy. Owing to their abundant reserves, these relatively clean energy sources enable efficient energy recovery without necessitating the development of entirely new reservoir stimulation techniques. However, the complex and harsh geological conditions of shale and hydrate reservoirs cannot be effectively addressed by conventional reservoir stimulation techniques to realize fracture propagation or reservoir modification. This necessitates the refinement and adaptation of established methodologies to overcome these challenges. (2) New energy [6, 7]. The advent of new energy sources, such as solar, wind and hydrogen energy, has led to a paradigm shift in energy research, owing to the exhaustion of conventional energy resources. This is undoubtedly also a key research area in response to CCUS and energy sustainability policies. Nevertheless, numerous defects and associated disadvantages that require immediate resolution also impede the large-scale utilisation of new energy as an alternative energy source [8, 9]. Firstly, the low collection efficiency of new energy sources, such as solar energy, wind energy and hydrogen energy, is clearly insufficient to meet normal production needs. This necessitates the update and iteration of new energy collection equipment and the search for efficient energy collection materials. Secondly, the low efficiency of energy storage equipment in terms of its capacity to store a significant amount of energy during periods of peak and valley demand means that it is unable to meet the energy demands experienced during valley periods [10, 11]. Moreover, the intermittent supply of new energy has been shown to reduce the stability of energy availability for industrial production. The inherent limitations of the two aforementioned alternative energy sources underscore the necessity for energy scientists to pursue the development of more stable and efficient forms of energy [12].

Geothermal energy is a relatively underexplored clean energy source that has received limited attention to date [13]. This lack of focus primarily stems from the complexity of the associated extraction and heat transfer processes. Nevertheless, geothermal energy holds considerable strategic importance as a supplementary energy resource, owing to its advantages of abundant reserves and environmental sustainability. Furthermore, the common reservoir transformation measures can be used to develop geothermal energy [14, 15]. The pore connectivity of the geothermal reservoir is a prerequisite for the stable and continuous output of geothermal energy by the heat transfer medium. The fracturing technology utilised in this study has been demonstrated to achieve effective crack expansion within the geothermal reservoir, thereby facilitating the rapid flow of the heat transfer fluid. However, the process of heat transfer between the fluid and solid medium of geothermal energy has been shown to induce alterations in the performance of the reservoir fluid (rheology, sand carrying and suspended sand, etc.). These alterations have been demonstrated to have a deleterious effect on the damage evolution and crack expansion of the reservoir rock. Furthermore, the disparities in the physical parameters (heat transfer coefficient, specific heat capacity) of the heat transfer fluid medium, in conjunction with the alterations in the parameters of the heat transfer medium engendered by heating, constitute pivotal factors influencing contemporary geothermal energy mining in the reservoir [16, 17]. This issue is highly relevant to the geothermal industry as a whole and must be addressed within the context of current geothermal energy extraction practices. Numerous numerical models have been developed in previous studies to investigate the efficient exploitation of geothermal reservoirs [18]. However, there are currently no good strategies or application cases to verify the efficient development of geothermal resources.

In this study, a comprehensive geothermal exploitation coupling model was developed, which integrates geological reservoir parameters and the medium fluid characteristics. This model aims to analyze the geothermal exploitation capacity and temperature distribution characteristics across various influencing factors. In parallel, the study applies microscopic molecular dynamics theory to investigate and elucidate the mechanisms behind heat transfer and geothermal medium flow under different environmental conditions. By leveraging this theory, the study uncovers the intricate molecular interactions that govern the performance of the heat transfer fluid in the geothermal reservoir.

Furthermore, a thorough comparison is conducted between the proposed geothermal exploitation model and experimental data, with the primary objective of validating the model's applicability in real-world scenarios. This comparison not only serves to confirm the model's accuracy but also highlights its practical relevance.

2 Numerical model

2.1 Temperature field between solid-liquid heat transfer in geothermal reservoirs

Solid–liquid and solid–solid heat transfer phenomena are intrinsic to all stages of geothermal exploitation, encompassing heat exchange processes within geological reservoirs. The efficiency of heat transfer between different media directly governs the overall efficiency of geothermal resource utilization. In many respects, the process of geothermal exploitation closely parallels that of oil extraction. Accordingly, the analysis of the geothermal reservoir temperature field requires a comprehensive consideration of heat transfer among the wellbore, the surrounding rock, and the injected fluid. Firstly, Equations 1 and 2 respectively demonstrate the transient heat conduction equations of the wellbore and reservoir for the heat transfer medium, considering the effects of thermal diffusion and convection [19].

$$\rho_f C_f \left(\frac{\partial T_w}{\partial t} + v_w T_w \frac{\partial T_w}{\partial z} \right) = -\frac{2U}{r_w} \left(T_w - T_r \Big|_{r=r_w} \right) \tag{1}$$

$$[(1-\phi)\rho_s C_s + \phi \rho_f C_f] \frac{\partial T_r}{\partial t} - \rho_f C_f \left(\frac{k_p}{\mu(T)} \right) \nabla T_r = \nabla \left(k_r \nabla T \right) \tag{2}$$

where ρ_f and C_f are the density and specific heat capacity of heat transfer fluid in reservoir, ρ_s and C_s are the density and specific heat capacity of rock solids in reservoir. T_w and T_r are the temperature of heat transfer medium and reservoir temperature. t and r are the heat transfer time and radial distance. U and ϕ are total heat transfer coefficient and porosity. k_p and μ are reservoir permeability and fluid viscosity. k_r is the thermal conductivity of reservoir.

Furthermore, Equation 3 represents a heat transfer equation that explicitly incorporates both seepage and fluid viscosity. This equation can be utilised to analyse the heat transfer efficiency under varying seepage factors and fluid viscosities. However, the heat transfer equation in the wellbore is considered to be a transient heat transfer equation [20].

$$[(1-\phi)\rho_s C_s + \phi \rho_f C_f] \frac{\partial T_r}{\partial t} - \rho_f C_f \left(\frac{k_p}{\mu(T)} \nabla P \right) \nabla T_r = \nabla \left[(1-\phi) C_s + \phi k_f \nabla T_r \right] \tag{3}$$

where k_s and k_f are the solid thermal conductivity and fluid thermal conductivity. P is the pressure field of reservoir fluid.

Equations 1, 2, and 3 are applicable to power-law heat transfer media with low viscosity and laminar flow inside the reservoir. In the case of heat transfer media characterised by high-speed flow (high shear rate) and turbulent flow, it is necessary to derive alternative heat transfer equations.

2.2 Quality Control Equation between solid and liquid substances in geothermal reservoirs

The quality control of geothermal reservoirs is governed by the law of mass conservation, which characterizes the inflow, outflow, and storage variations of fluids—typically water or steam—within the reservoir (Equation 4) [21]. This equation states that the rate of change of fluid mass in the reservoir is equal to the net contribution of inflow and outflow mass fluxes, together with the source and sink terms.

$$\frac{\partial (\phi \rho)}{\partial t} + \nabla (\rho v) = q_m \tag{4}$$

where ρ and v are the density and fluid velocity of heat transfer medium. qm is the mass flow rate of injected or produced fluid.

Meanwhile, the flow of fluids in geothermal reservoirs is typically governed by Darcy's law (Equation 5) [22], which delineates the percolation behaviour of fluids within porous media. The substitution of the Darcy velocity into the mass conservation equation results in the derivation of the mass control equation in the geothermal reservoir. This equation facilitates a more precise description and calculation of the heat transfer efficiency of the heat transfer fluid in the geothermal reservoir.

$$\frac{\partial (\phi \rho)}{\partial t} - \nabla \left(\rho \frac{k_p}{\mu} \nabla (P - \rho g) \right) = q_m \tag{5}$$

where g presented the gravity acceleration under normal environmental factors.

The quality control equations employed in this study can be applied to any fluid-solid numerical model of reservoir transformation and energy storage processes. This provides a fundamental theoretical basis for geological transformation in a wide range of related disciplines, including geological engineering, mining engineering and petroleum engineering. Furthermore, the mass conservation equation referenced in this study does not encompass the evaporation of the heat transfer medium caused by geothermal heat, primarily due to the negligible impact of the relatively small evaporation amount.

2.3 Frictional behavior of heat transfer medium in reservoir fractures

The injection of a heat transfer medium along the wellbore or fracture of an injection well has been demonstrated to induce fluid flow in both the axial (z direction) and radial (r direction) directions. Axial flow propagates down the wellbore (Eq. 6), while radial flow causes the heat transfer fluid to seep through the wellbore wall (Equation 7) [23].

$$\rho_f\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+v_z\frac{\partial v_z}{\partial z}\right)=-\frac{\partial P}{\partial r}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{\partial^2 v_z}{\partial z^2}\right]+\rho_f g\cos\theta \tag{6}$$

$$\rho_f\left(\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}+v_z\frac{\partial v_r}{\partial z}\right)=-\frac{\partial P}{\partial r}+\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv_r)\right)+\frac{\partial^2 v_r}{\partial z^2}\right] \tag{7}$$

where θ presented the angle between the fluid flow direction and the vertical direction.

Furthermore, the heat transfer medium will be subject to the effects of friction (roughness or flow state) during the flow in the reservoir wellbore or fracture, resulting in significant filtrationes to the fluid flow. This phenomenon can be addressed by utilising Equation 8 [24]. We selected Equation 15 to solve the friction force of the heat transfer medium in the cracks based on the flow pattern and Reynolds number Re value of the heat transfer medium in the reservoir fractures. This helps to adjust the fluid medium composition in the reservoir fractures to reduce frictional resistance.

$$F_{\text{friction}}=-\frac{f\rho_f v_z^2|\mathbf{v_r}|}{4r_w} \tag{8}$$

where $F_{friction}$ presented the friction force of heat transfer medium during wellbore or crack flow process.

Equation 8 can be used to calculate the friction of low-velocity laminar fluid in the fracture that is displayed. It has been demonstrated that fracture expansion, oil displacement, geothermal extraction and fluid energy storage can all utilise Equation 8 to reveal the friction behaviour of fluid in reservoir fractures.

2.4 Determination of physical property parameters of coupling model

The physical parameters corresponding to the heat transfer medium in the geothermal reservoir can be determined and revealed by the following equations, which is crucial for calculating and analysing geothermal extraction efficiency and heat transfer rate under different factors.

As indicated in equation 9, the fluid viscosity of the heat transfer medium subsequent to heat exchange with the geothermal reservoir may be calculated and analysed.

$$\mu=\mu_0 e^{-\frac{T-T_0}{T_c}} \tag{9}$$

where μ_0 is the corresponding fluid viscosity at T_0 (Initial temperature). T is the real-time temperature of heat transfer medium after heat transfer in reservoir geothermal. T_c is the characteristic temperature used to characterize the sensitivity of viscosity to temperature changes.

$$\rho_f(T_r)=\rho_0 f_0\left[1-\beta(T_r-T_0)\right] \tag{10}$$

where $\rho_0 f_0$ is considered as the 1000 kg/m^3 (100°C), and β is the 2×10^{-4} K^{-1}. Equation 10 (Thermal Expansion Equation) expresses the fluid density, thereby providing real-time data on the fundamental fluid parameters for the overall heat transfer efficiency of a geothermal reservoir.

The specific heat capacity of both the heat transfer medium and the surrounding rock is a critical determinant of heat transfer efficiency within geothermal reservoirs, which in turn directly influences the developmental potential of geothermal resources. Equation (11) illustrates the relationship between the specific heat capacities of the fluid and the solid and the amount of absorbed heat, thereby revealing a positive proportional correlation between these parameters.

$$c=\frac{Q}{m\Delta T} \tag{11}$$

where Q is the the geothermal energy transferred by the heat transfer medium to the rock after flowing through the geothermal reservoir fractures or wellbore. m is the quality of the heat transfer medium or reservoir rock.

Equation (12) presents the total heat transfer coefficient U of the geothermal reservoir, which integrates the thermal resistances $(1/U)$ arising from fluid convection within the wellbore, conductive heat transfer through the wellbore wall (including the casing and cement sheath), and transient heat conduction in the surrounding reservoir formation.

$$\frac{1}{U} = \frac{1}{h_w} + \frac{r_w \ln\left(\frac{r_c}{r_w}\right)}{k_c} + \frac{r_w}{k_r f(t)} \tag{12}$$

where h_w is the fluid convection heat transfer coefficient. r_w and r_c are the wellbore inner radius and fracture inner radius. k_c is the thermal conductivity of the wellbore or heat transfer medium. k_r is the equivalent thermal conductivity of geothermal reservoirs, and it can be calculated by Equation 13.

$$k_r = (1-\phi)k_s + \phi k_f \tag{13}$$

Finally, the friction behaviour (Laminar Flow) of the heat transfer medium in the geothermal reservoir fractures and related parameters should also be considered and analysed, the friction coefficient f is demonstrated in equation 14.

$$f = \frac{64}{Re}, \quad Re = \frac{\rho_f v_z 2r_w}{\mu} \tag{14}$$

where Re is the Reynolds number. v is the fracture flow velocity of heat transfer medium.

Simultaneously, the friction coefficient of the heat transfer medium in the turbulent state within the reservoir fracture through the utilisation of Equation 15 [24, 25].

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\zeta}{2r_w 3.7} + \frac{2.51}{Re\sqrt{f}}\right) \tag{15}$$

where ζ presented the surface roughness.

Equations (9) and (10), which describe the relationship between fluid viscosity and heat transfer, can be applied not only to examine the interaction between geothermal energy and heat transfer media, but also to analyze and quantify the reservoir stimulation efficiency of oilfield working fluids, along with associated performance parameters such as fluid filtration and seepage.

Table 1. Physical parameters of heat transfer medium (modified component water).

Physical parameters	Numerical indicators
Fluid viscosity/ mPa·s (300K)	35
Flow rate / m^3/min	4.2
Thickener content/wt%	1.6
Fluid state	Transparent gel

Furthermore, the heat transfer medium of geothermal resources is an ultrapure water mixed fluid containing a cross-linker, which is the object of the research. The relevant physical parameters are shown in Table 1.

2.5 Model geometry and boundary conditions

The geological geometry model for reservoir geothermal exploitation is constructed to a depth of 1000 m. The model simultaneously defines the injection and production wells for the heat transfer medium, with a wellbore radius specified as 0.2 m. Additionally, the initial density and temperature of the heat transfer medium are set to 1000 kg/m^3 and 279 K, respectively. This facilitates the transportation and injection operation of the heat transfer medium in the injection well. In conclusion, the driving geometry model of the geothermal reservoir is defined as an isotropic brittle material area with a diameter of 300m. This facilitates analysis and exploration of the entire geothermal conversion process of the reservoir medium from the injection well to the production well.

For the geothermal reservoir geometry model shown in Figure 1, the boundary conditions between distinct phases and materials constitute essential prerequisites for accurately simulating geothermal energy transport and fluid flow within the reservoir.

The geothermal energy stored in the reservoir is transferred to the heat transfer medium within the wellbore through the coupling between the heat flux across the wellbore wall and the reservoir temperature field, as described by Equation 16.

$$q_w = U\left(T_w - T_r\Big|_{r=r_w}\right) \tag{16}$$

Furthermore, the heat transfer medium injected into the reservoir must also account for the reservoir's temperature boundary conditions, which inherently involve the solid–liquid heat flux coupling at the

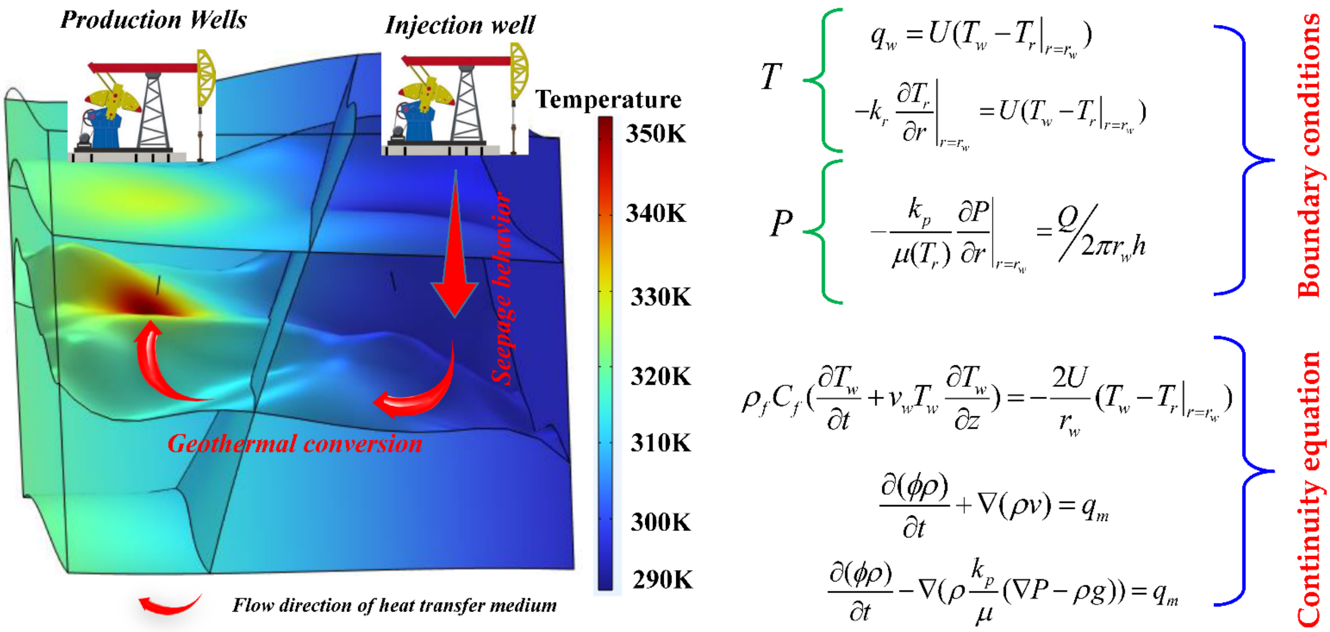

Figure 1. Geothermal development process, boundary conditions and governing equations of geothermal reservoirs.

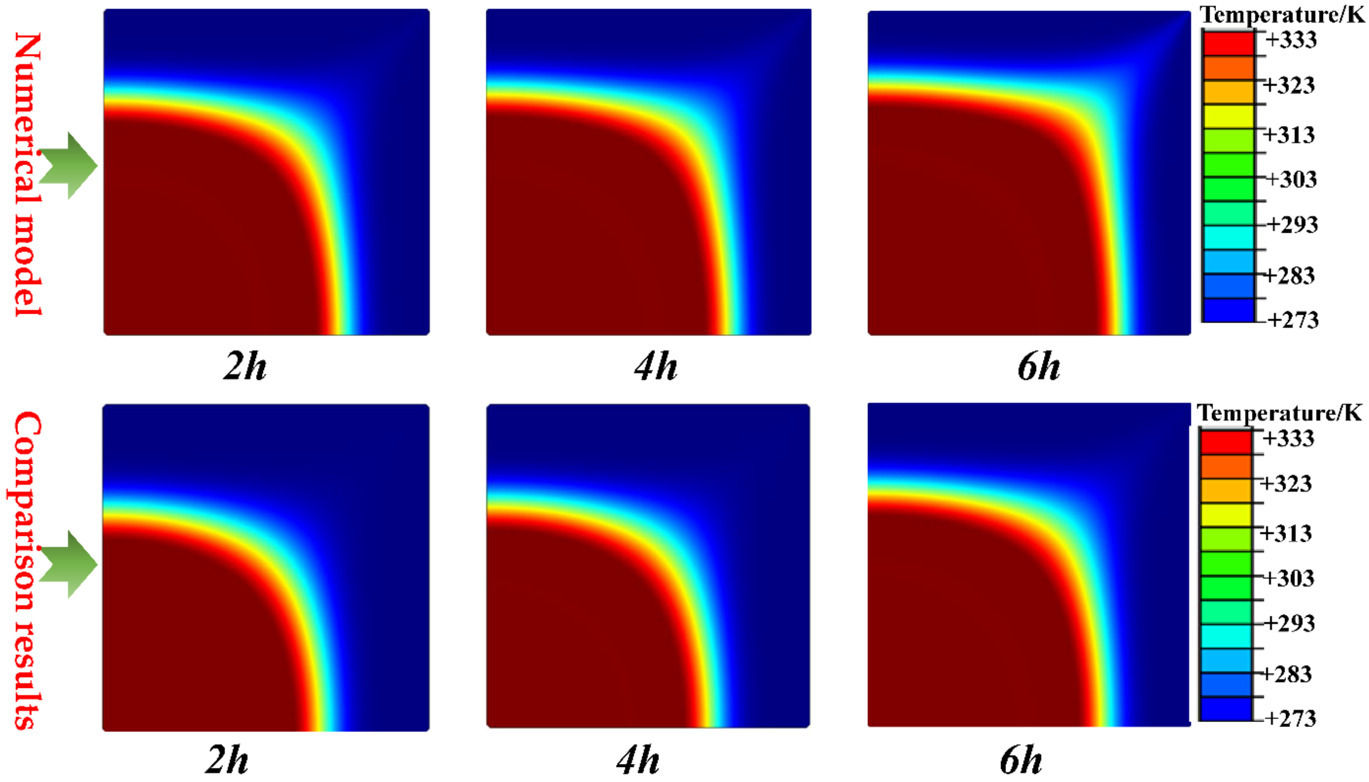

Figure 2. Adaptive verification of numerical models.

surface of the reservoir fractures, as represented by Equation (17).

$$-k_r \frac{\partial T_r}{\partial r}\bigg|_{r=r_w} = U\left(T_w - T_r\bigg|_{r=r_w}\right) \tag{17}$$

Both the injection and production wells need to be considered in the pressure boundary conditions, for which Equations 18 and 19 are required for description and analysis.

$$-\frac{k_p}{\mu(T)}\frac{\partial P}{\partial r}\bigg|_{r=r_w} = \frac{Q}{2\pi r_w h}, \quad Q = 0.01\,\mathrm{m^3/s} \tag{18}$$

$$-\frac{k_p}{\mu(T)}\frac{\partial P}{\partial r}\bigg|_{r=r_w} = \frac{Q}{2\pi r_w h} \tag{19}$$

The boundary conditions of the geological model for geothermal energy extraction employed in this study are comparable to those applied in fluid–solid coupling models within other geological and petroleum engineering contexts, thereby providing a valuable reference for analyzing fluid flow and heat transfer processes in typical geological reservoirs.

2.6 Adaptability Validation of Investigation Methodology

Figure 2 presents a comparison between the numerical simulation results and the experimental data for the geothermal reservoir depicted in Figure 1, thereby effectively validating the applicability of the constructed geometric model for geothermal energy exploitation. The coefficient of determination R^2(0.996) and the average relative error (4.6%) between the experimental data and the numerical model validate the accuracy of the aforementioned conclusions, providing an important reference for the application of the numerical model illustrated in Figure 1 to geothermal energy extraction. The similar trends observed in both datasets indicate that the numerical model exhibits strong adaptability to the reservoir environment in terms of energy conversion and formation transformation. Meanwhile, the slight discrepancies between the two datasets are primarily attributed to the moderate adjustments in boundary conditions and governing equations introduced in this study's numerical model, which were entirely absent in the prior research.

3 Results ans discussion

3.1 Rheological parameters of heat transfer fluid

The flow parameters of the heat transfer medium directly govern the flow behavior and heat transfer efficiency of the fluid within reservoir fractures. Moreover, frictional resistance is a critical parameter closely associated with fluid viscosity and the Reynolds number of the fluid. It has been demonstrated by preceding studies that the flow parameters of the reservoir fluid (i.e. fluid viscosity, rheological index and consistency coefficient) are all affected by the reservoir environment (i.e. reservoir temperature). It is imperative to investigate the impact of the flow parameters associated with the heat transfer medium following geothermal heating of the reservoir on friction resistance and heat transfer efficiency. As illustrated in Figure 3, the dynamic viscosity and friction resistance of the flow medium are observed to vary with geothermal heating of the reservoir at varying temperatures. A clear divergence in trend lines is evident between the two parameters and the medium temperature. Firstly, the viscosity of the flow medium decreases continuously with the heating temperature; however, the geothermal temperature above 333K can significantly reduce the flow viscosity of the heat transfer medium. However, a lower geothermal temperature does not lead to a significant decrease in the viscosity of the heat transfer medium, primarily due to changes in intermolecular interaction forces induced by geothermal heating. From a microscopic perspective, the Arrhenius equation effectively characterizes the influence of thermal energy on intermolecular interactions, providing important insights into the inverse relationship between reservoir temperature and fluid viscosity at the macroscopic scale [26].

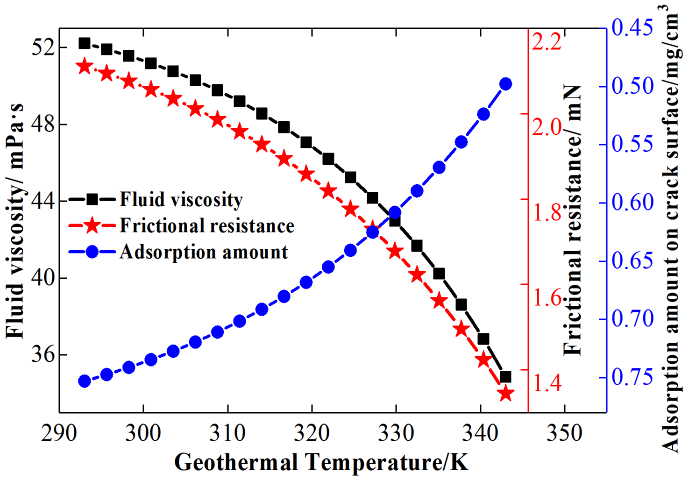

Figure 3. Variation trends of rheological parameters, adsorption capacity and surface friction resistance of heat transfer media at different geothermal temperatures.

As shown in Figure 4, the microscopic morphological changes and adsorption behavior of the heat transfer media in geothermal reservoir fractures further illustrate the impact of temperature on fluid properties. At low geothermal temperatures, the intermolecular distance within the heat transfer medium is relatively reduced, thereby enhancing intermolecular interactions and facilitating the formation of chemical bonds. Furthermore, the like-charges carried by the molecules exert minimal repulsive forces under low-temperature conditions, thereby stabilizing the already-formed intermolecular bonds. Conversely, elevated geothermal temperatures have been shown to increase the repulsive forces between similarly charged molecules, with the potential to disrupt pre-existing intermolecular bonds. Furthermore, the enhanced molecular

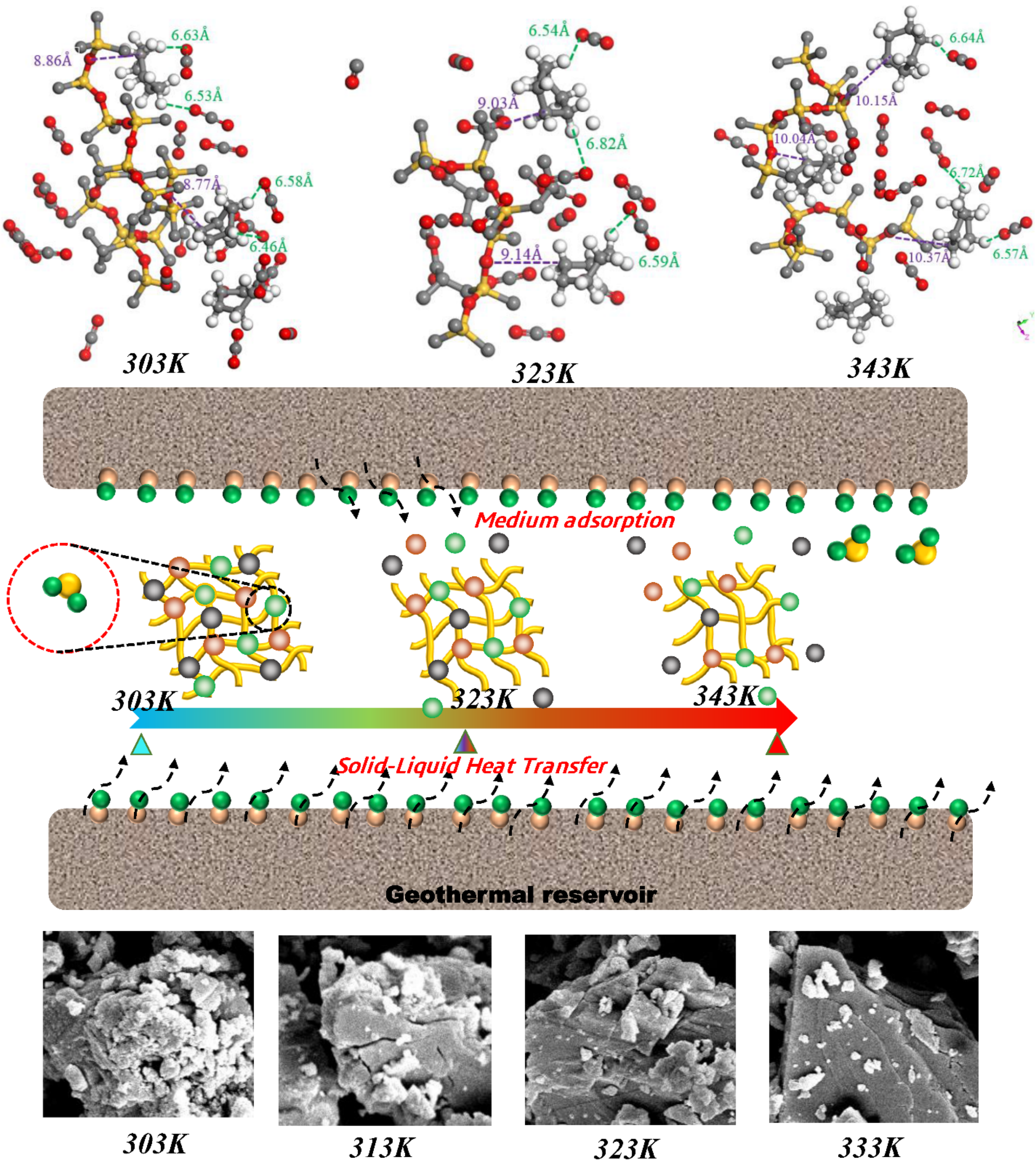

Figure 4. Microscopic morphological changes and adsorption behavior of heat transfer media in geothermal reservoir fractures.

kinetic activity induced by elevated temperatures promotes irregular molecular motion, thereby further increasing the likelihood of bond stretching or breakage. It is well established that the microscopic network formed by chemical bonding (intermolecular hydrogen bonds) among molecules constitutes the fundamental microstructural basis of macroscopic fluid viscosity [27]. Consequently, the disruption of these bonds at elevated geothermal temperatures inevitably leads to a reduction in fluid viscosity. The resultant low-viscosity heat transfer medium flows more rapidly from the reservoir to the production well, thereby providing a favorable physical basis for enhancing the efficiency of geothermal energy extraction.

Secondly, the frictional resistance experienced by the heat transfer medium within reservoir fractures is significantly influenced by geothermal temperature variations. The inverse relationship between temperature and friction has emerged as a key factor driving efficient geothermal energy extraction. The friction encountered by the flowing medium in the fracture is primarily attributed to molecular adsorption on the fracture surface at the microscale. Specifically, medium molecules adhere to the rock surface via intermolecular forces—particularly interactions between polar functional groups—thereby increasing flow resistance. In low-temperature reservoirs, the reduced molecular kinetic energy enhances the adsorption tendency of the heat transfer medium, making desorption less likely during flow. As a result, greater frictional resistance is observed under low-temperature conditions, which adversely affects both the mobility and heat transfer efficiency of the medium within the geothermal reservoir. However, elevated geothermal heat has been observed to induce a heightened degree of molecular activity in the heat transfer medium molecules, which, in turn, gives rise to violent Brownian motion. The irregular microscopic motion of high-activity molecules at elevated temperatures within geothermal systems is of particular concern. This motion increases the risk of molecules desorbing from the reservoir rock surface. Additionally, the increasing intermolecular repulsion at high temperatures leads to an increased probability of medium molecules desorbing. Consequently, the smaller adsorption and larger molecular desorption capacity formed by high-temperature geothermal reservoirs help reduce flow resistance, providing practical basic data for the efficient exploitation of geothermal resources.

Consequently, the temperature environment of the geothermal reservoir exerts an adverse effect on the viscosity of the medium fluid. However, the reduction in friction caused by the continuous decrease in fluid viscosity significantly accelerates the fluid flow rate. It is possible to bring more geothermal heat into the production well through material heat transfer as a heat transfer medium [28]. This can be used to achieve efficient exploitation of geothermal resources. Furthermore, the low adsorption of the medium at high geothermal temperatures also helps to achieve reservoir protection and smooth transmission fractures.

3.2 Filtration Behavior of heat transfer fluid

Geothermal reservoirs bear a resemblance to conventional oil reservoirs in that the working fluids also exhibit filtration behaviour in reservoir rocks. This phenomenon exerts a substantial influence on the heat transfer of heat transfer media and the efficiency of geothermal extraction. As illustrated in Figure 5, the filtration behaviour of heat transfer fluids in different geothermal reservoirs is shown to be dependent on porosity. Furthermore, an analysis and exploration of the geothermal distribution of geothermal reservoirs is also presented. As demonstrated in Figure 5, an evident inverse correlation exists between the porosity of geothermal reservoirs and the filtration amount of heat transfer fluids. This indicates that an increase in porosity is not conducive to the migration of heat transfer fluids along reservoir fractures. It is hypothesised that the presence of more heat transfer media in larger pores will impede the process of extracting geothermal heat from the production well by the heat transfer fluid. However, the fluid filtration caused by smaller porosity is relatively weak, and larger fluid filtration is shown in reservoir porosity above 15%. It has been demonstrated that a reduction in porosity can impede the permeation of heated transmission medium through the reservoir rock pores. This phenomenon can result in a substantial volume of fluid being compelled to traverse the reservoir fractures, ultimately reaching the production well. However, the larger reservoir porosity will cause a large amount of transmission medium that originally flowed to the production well to flow into the surface pores. This will inevitably result in fluid filtration, which will have a negative impact on the transmission and exploitation of geothermal fluids.

Furthermore, the geothermal reservoir temperature exerts a substantial influence on the medium filtration, which, to a certain extent, also modifies the efficiency of reservoir geothermal extraction. The relationship between reservoir temperature and fluid filtration has been the subject of numerous studies, including those focusing on geothermal reservoirs. The positive proportional relationship between geothermal reservoir temperature and fluid filtration (Figure 6) is of significance for the efficient exploitation of geothermal resources [29]. However, adjusting the material composition of the heat transfer medium is also an important measure to alleviate high filtration.

The relationship between geothermal reservoir

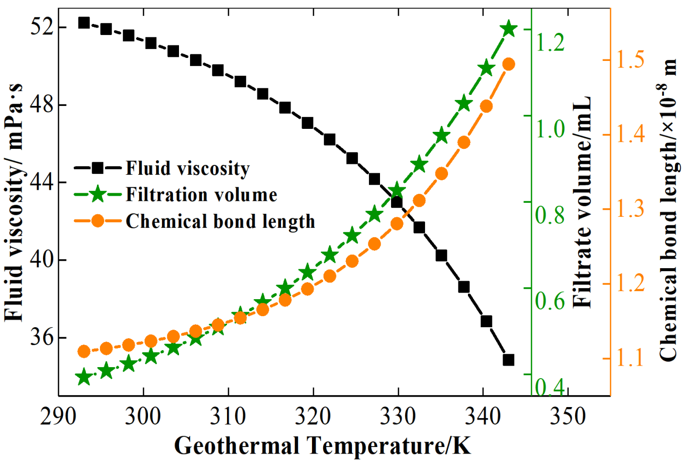

Figure 5. Effects of geothermal reservoirs on filtration behavior and microscopic parameters of heat transfer fluids.

temperature and the filtration behaviour of heat transfer medium can be explained and analysed by the interaction of heat transfer medium molecules and the change of microscopic chemical bonds. The molecules of the heat transfer medium form a three-dimensional grid model based on van der Waals force, which helps to bind the molecules of the heat transfer medium to each other and produce many macroscopic parameters, such as excellent fluid viscosity and low filtration behaviour. At low geothermal temperatures, the energy transferred to the medium molecules is insufficient to facilitate substantial molecular activity. This, in turn, can impede the occurrence of excessive Brownian motion of molecules, thereby preventing the drag or stretching of intermolecular bonds. Furthermore, the weaker intermolecular repulsion between medium molecules with reduced molecular activity serves to mitigate the propensity for molecules to displace from one another. Consequently, intermolecular bonds are unable to be subjected to significant dragging and stretching. The two aforementioned weaker interactions serve to reduce the possibility of medium molecules breaking bonds and presenting a free state at low geothermal temperatures. This, in turn, reduces the probability of free medium molecules achieving fluid filtration through the pores on the fracture surface. However, an increase in geothermal reservoir temperature will result in a molecular state that is completely different from the low geothermal temperature. This can be revealed by the Arrhenius equation (Figure 6). At elevated temperatures, reservoir rocks have been observed to transfer more heat to medium molecules. This transfer invariably causes the medium molecules to move more violently. The irregular movement of medium molecules, characterised by elevated molecular activity, has been shown to accelerate the stretching or even breaking of intermolecular chemical bonds. At elevated temperatures, high-activity molecules are observed to form more free molecules by pulling off chemical bonds. Furthermore, the same charges carried by the same medium molecules induce high-temperature heat transfer to form greater repulsion of the same charges [30]. This will inevitably increase the risk of stretching or even breaking chemical bonds between medium molecules at high temperatures. The two aforementioned forces will inevitably result in the dissolution of additional chemical bonds due to elevated geothermal temperatures, thereby exposing a greater number of free molecules. It has been demonstrated by preceding studies that the filtration of free molecules into reservoir rocks is most efficient when these molecules pass through the pores on the surface of the fracture. It can thus be concluded that, despite the attainment of higher flow speeds (Figure 3) and reduced adsorption amounts (Figure 4) at elevated geothermal temperatures, the substantial fluid filtration behaviour hinders the effective utilisation of geothermal energy.

3.3 Analysis of factors affecting geothermal extraction efficiency

3.3.1 Influence of reservoir pressure on geothermal extraction efficiency

The internal pressure of the geological reservoir exerts a substantial influence on the fluid parameters of the heat transfer medium and the extraction efficiency of geothermal resources, as demonstrated in Figure 7. As demonstrated in Figure 7 and Table 2, it is evident that the alteration in reservoir pressure does not contribute to the effective extraction of geothermal resources. Furthermore, a substantial inverse proportional relationship is observed between these two parameters. The determination of the aforementioned relationship can be attributed to the influence of geothermal reservoir pressure on the rheological parameters of the heat transfer medium, which directly changes fluid flow resistance (Equation 15) and fluid viscosity. However, it is important to note that a decrease in reservoir pressure will not have a significant impact on the extraction efficiency of geothermal energy. Conversely, an increase in reservoir pressure will result in a substantial reduction in extraction efficiency.

The impact of reservoir pressure on geothermal

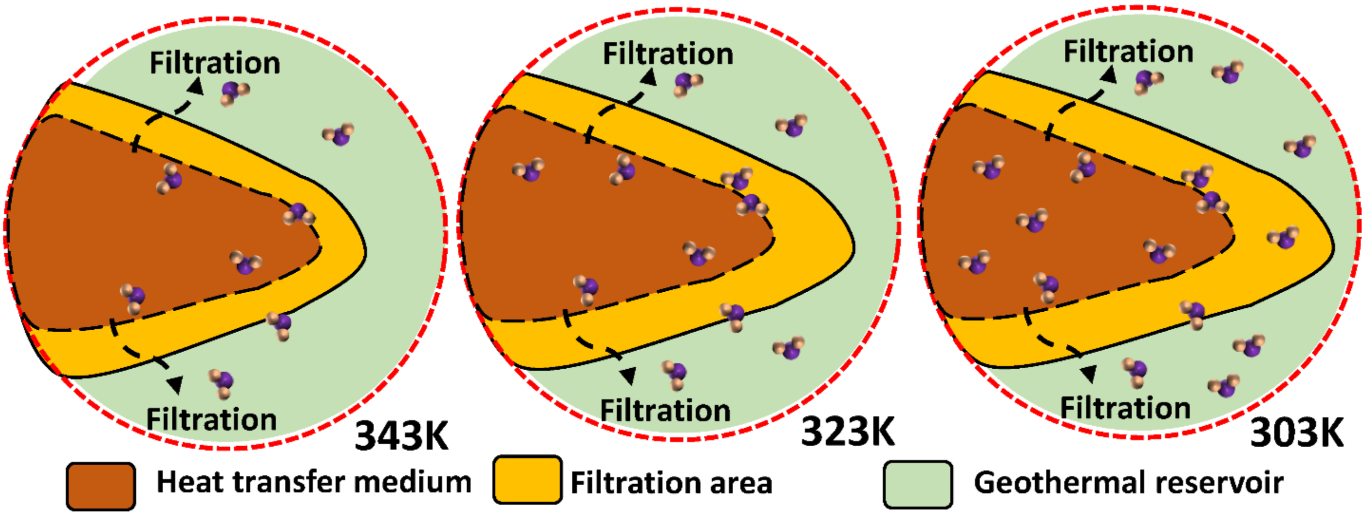

Figure 6. Filtration behavior and microscopic molecular distribution of heat transfer media.

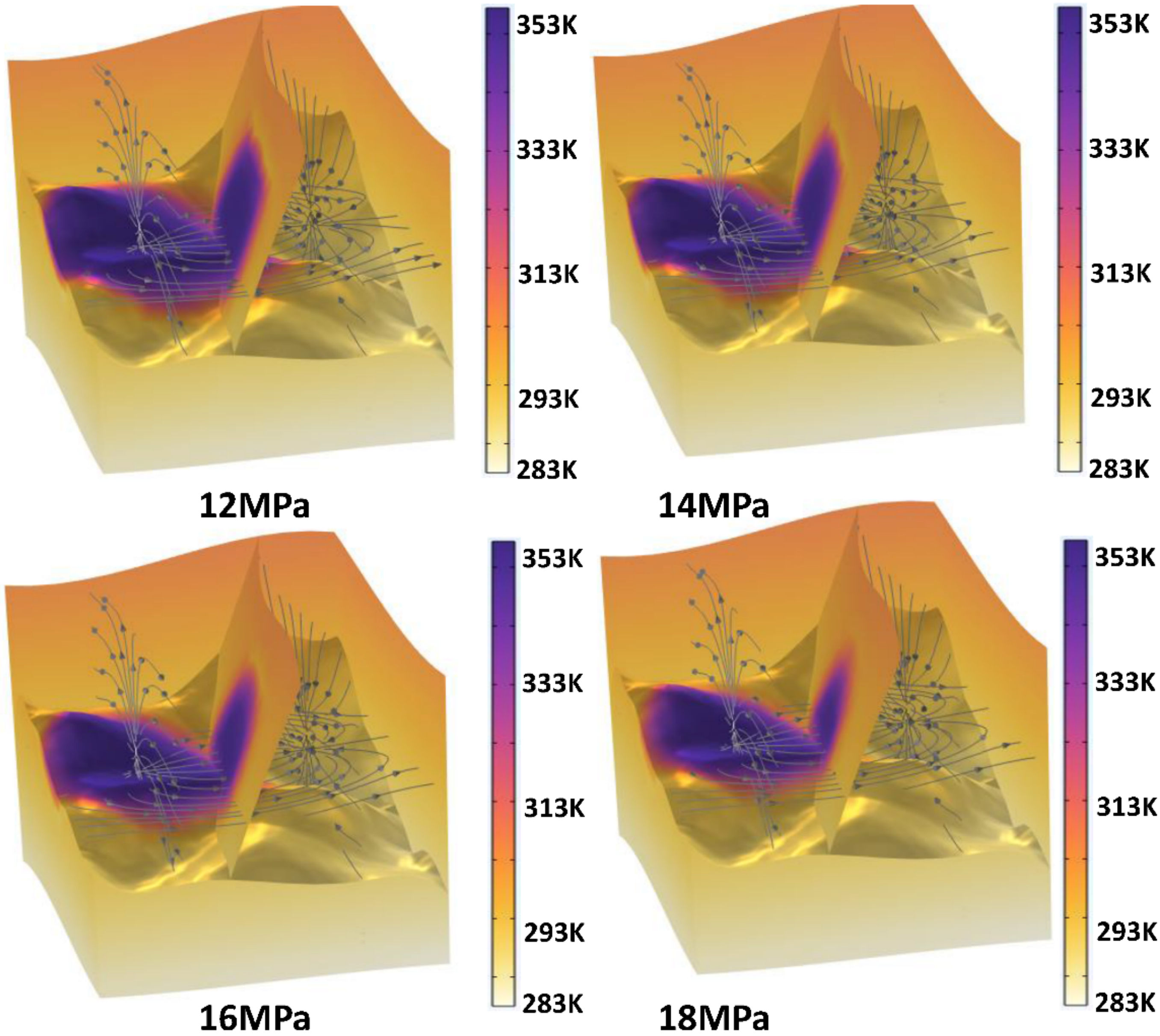

Figure 7. Geothermal temperature distribution under different reservoir pressures.

Table 2. Effects of reservoir pressure on viscosity, filtration and adsorption of geothermal fluids.

Evaluation parameters	12MPa	14MPa	16MPa	18MPa
Fluid viscosity/ mPa·s	52	54	57	62
Filtration volume/ mL	1.2	1.1	0.95	0.7
Adsorption quality/ mg/m^3	0.6	0.65	0.75	0.9

energy extraction is predominantly influenced by alterations in fluid viscosity, which in turn directly dictates the transmission rate of geothermal energy. It has been demonstrated by preceding studies that an elevation in reservoir pressure can result in an augmentation of fluid viscosity, a phenomenon that is predominantly facilitated by the extrusion and formation of microscopic chemical bonds. In the context of low reservoir pressure, the separation between molecules in the heat transfer medium is substantial, thereby impeding the formation and interaction of intermolecular chemical bonds. On the macroscopic level, it is impossible to promote an increase in fluid viscosity, which will inevitably result in a decrease in fluid resistance. Concurrently, the reduction in reservoir pressure also diminishes the adsorption of medium molecules on the fracture surface, thereby establishing the necessary conditions for the rapid flow of heat transfer medium in geothermal reservoir fractures. Consequently, in circumstances where reservoir pressure is low, a comparatively substantial fluid velocity may be established due to the diminished fluid viscosity and resistance. This, in turn, facilitates the transportation of geothermal heat from the heated heat transfer medium to the production well. However, the reduced formation of intermolecular bonds under low reservoir pressure is likely to impede the connectivity of additional free molecules, potentially leading to rock filtration of the heat transfer medium. Despite the fact that greater fluid filtration under low pressure is not conducive to fluid flow and medium heat transfer rate, the relevant laws in Figures 3 and 5 demonstrate that the effect of fluid filtration on medium flow is significantly weaker than the effect of fluid viscosity and molecular adsorption on fluid flow. Consequently, while fluid filtration behaviour can be established under low pressure, this does not impede the larger flow rate and medium heat transfer flow capacity.

The presence of high geothermal reservoir pressure has been shown to result in a markedly divergent fluid flow and heat transfer efficiency in comparison to the low-pressure state. This has been demonstrated to be disadvantageous to the flow of geothermal energy and its development. Firstly, high pressure exerts a compressive force on molecules, thereby reducing their distance and consequently generating intermolecular forces. It has been established that, under conditions of elevated pressure, a significant quantity of free medium molecules form chemical bonds and microscopic three-dimensional grid structures with one another. This process invariably results in a reduction in the number of free molecules and macroscopic fluid viscosity. The reduction of a large number of free molecules weakens the rock filtration of the medium, which is evidently a favourable aspect for promoting the development of geothermal resources. Nevertheless, the rising fluid viscosity in the presence of elevated pressure represents the primary impediment to geothermal heat transfer and energy development. This phenomenon can lead to the formation of a substantial adsorption layer and the subsequent resistance to flow of medium-sized molecules on the surface of geothermal reservoir rocks. Additionally, the geological environment of the geothermal reservoir can be subject to significant damage and the formation of fractures due to the adsorption of medium-sized molecules. In summary, although an increase in reservoir pressure can significantly increase the viscosity of the medium, the large flow resistance is not conducive to the fracture flow of heat transfer medium and geothermal exploitation. While reservoir pressure can facilitate the effective utilisation of geothermal energy with regard to fluid viscosity and filtration behaviour, high adsorption has the potential to result in flow resistance and fracture pollution. This, in turn, will impede the exploitation and expansion of geothermal energy. Consequently, the selection of a heat transfer medium comprising a reduced number of polar groups will invariably result in the occurrence of surface adsorption of cracks that is of an extremely weak nature.

3.3.2 *Influence of deflection angle of reservoir fracture on geothermal extraction efficiency*

Efficient energy conversion in geothermal reservoirs requires the heat transfer medium to transport thermal energy through both solid and liquid phases within reservoir fractures, necessitating consideration of the influence of fracture morphology on heat transfer performance. As a nonnegligible geological parameter, the fracture deflection angle significantly affects various fluid properties—such as shear behavior, fluid filtration, and flow resistance—which in turn directly influence the efficiency of geothermal energy transmission. Figure 8 and Table 3 illustrates the

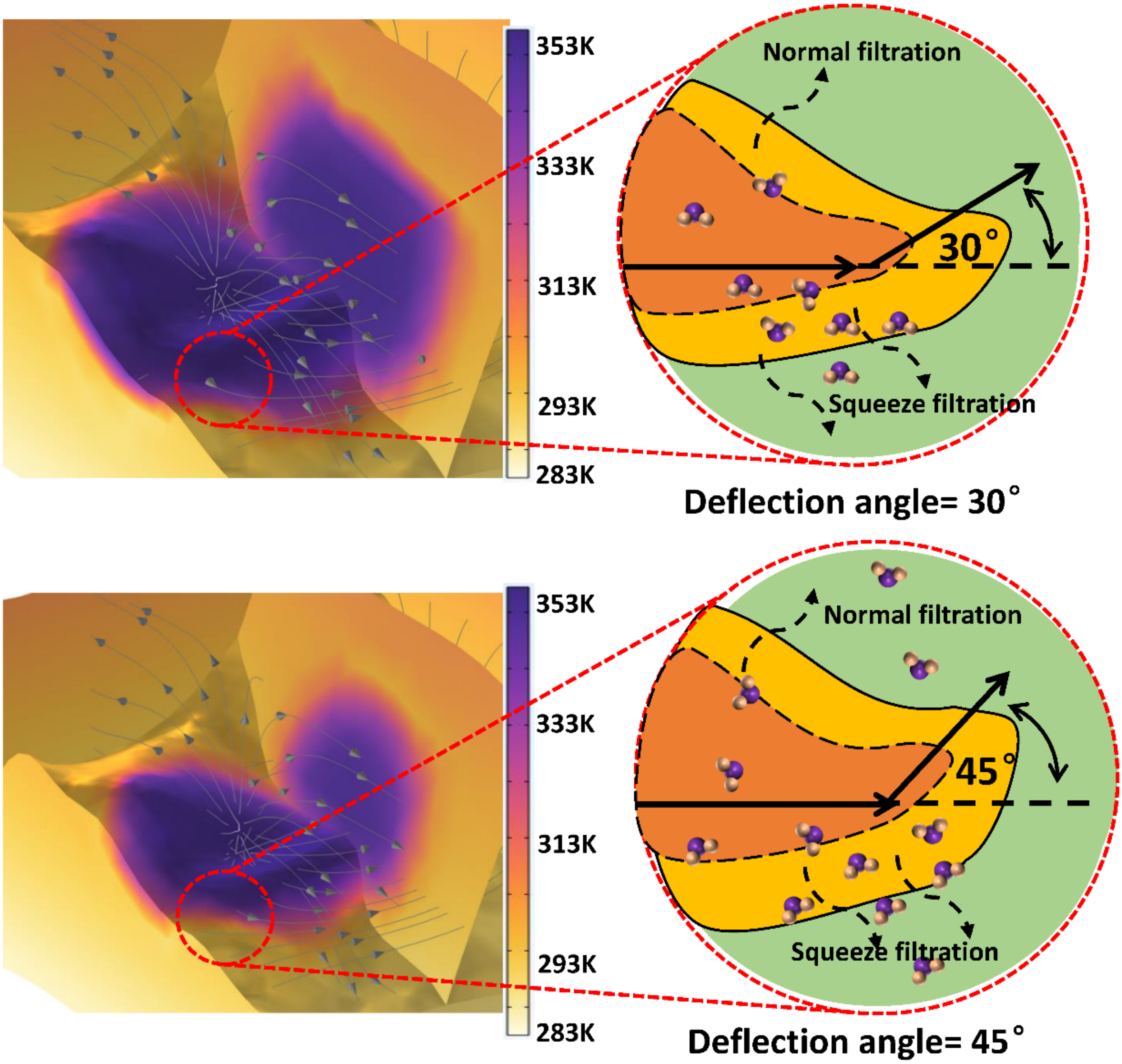

Figure 8. Effect of deflection angle on temperature distribution of heat transfer medium in geothermal reservoir.

variation in fluid filtration and flow resistance as a function of fracture deflection angle across different geothermal reservoirs. These curves provide a fluid-dynamic perspective for analyzing changes in geothermal energy extraction efficiency.

Table 3. Effects of deflection angle on viscosity, filtration and adsorption of geothermal fluids.

Evaluation parameters	0°	15°	30°	45°
Fluid viscosity/ mPa·s	52	50	47	40
Filtration volume/ mL	2	2.5	3.2	4.4
Adsorption quality/ mg/m^3	0.72	0.81	0.92	1.1

As demonstrated in Figure 8, the fracture deflection angle of the geothermal reservoir has the capacity to induce two phenomena: firstly, the continuous increase of the reservoir fluid loss volume, and secondly, the rock adsorption amount of the medium molecules. However, the apparent viscosity of the heat transfer medium gradually decreases due to the increase of the fracture deflection angle of the geological reservoir, which may be attributed to the severe external shear of the fluid under a large deflection angle. The deflection angle and the heat transfer medium loss demonstrate a roughly consistent sine function (sin), indicating minimal fluid loss in the absence of bending (sin0=0). It is important to note that the slight loss of vertical fractures is attributable to the normal loss caused by the fracture pressure of the heat transfer medium itself, which is present in most reservoir fractures. However, an increase in the fracture deflection angle will result in a significant quantity of heat transfer medium being compressed into a specific volume of liquid under the influence of injection pressure. This process directly releases the fluid content and flow energy in the reservoir fracture. It has been established that a 15° fracture deflection angle will cause the heat transfer medium flowing in the reservoir fracture to be blocked due to a change in flow direction. This will inevitably result in a small amount of medium fluid being squeezed into the fracture rock after touching the deflected reservoir fracture surface (sin15°=0.258). Concurrently, reservoir fractures exhibiting larger deflection angles will invariably precipitate enhanced filtration of the heat transfer medium into the geothermal reservoir, concomitantly engendering a reduction in flow capacity. Consequently, a diminished quantity of heat transfer medium will be able to enter the production well along the reservoir fracture, thereby enabling geothermal exploitation.

3.4 Sustainability of Geothermal Resource Extraction

The sustained temperature of geothermal reservoirs has become an important indicator for evaluating the sustainability of geothermal energy extraction, with the medium temperature in production wells at different times serving as a crucial reference point for assessing the sustainability of geothermal energy supply from reservoirs. As illustrated in Figure 9, the trend of medium temperature changes in production wells at different mining periods directly determines the geothermal development potential of the corresponding block. As demonstrated in Figure 9, the impact of heat transfer media under varying reservoir pressures on the temperature change of the produced medium exhibits a progressively diminishing temperature change trend during the course of geothermal energy development. The continuous decrease in the value temperature is attributed to the gradual consumption of energy in the geothermal reservoir, which coincides with the non-renewable nature of conventional energy. However, the discrepancy in medium temperature in production wells under varying pressures is attributed to medium filtration and energy recovery in reservoir fractures. Furthermore, under conditions of elevated pressure, a greater quantity of heat transfer media is able to infiltrate the reservoir rock, thereby reducing the energy output in the medium and consequently diminishing the efficiency of geothermal mining, as well as reducing the time required for completion of the mining operation. However, under conditions of low pressure, although high mining efficiency can be achieved in a short time, the rapid decrease in medium temperature also shortens the geothermal mining time. Consequently, despite the clean energy nature of geothermal resources, their non-renewable nature also determines the energy attenuation and factor intervention in the development process.

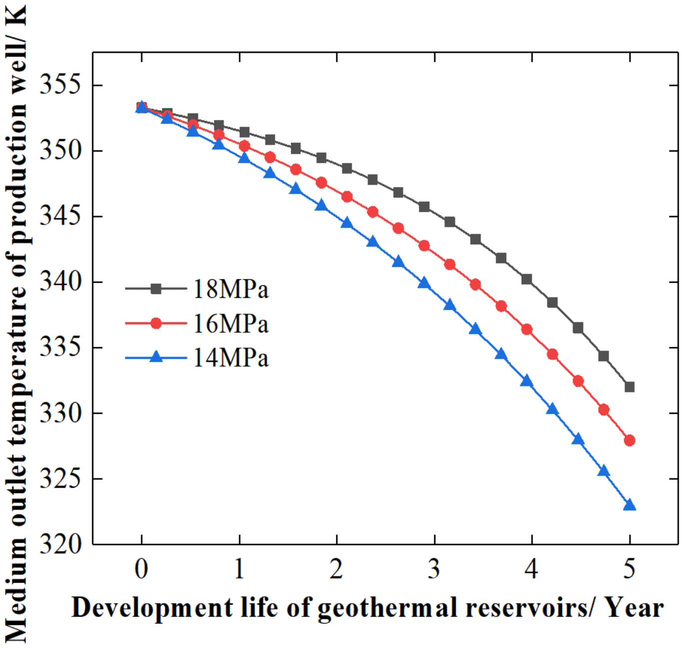

Figure 9. The trend of development life of geothermal reservoirs with reservoir pressure.

Therefore, in view of the non-renewable characteristics of geothermal energy, external clean energy sources such as wind or solar energy can be stored in geothermal reservoirs as high-temperature fluids. This would serve to supplement the shortcomings caused by the continuous reduction of geothermal resources. The bidirectional development of geothermal resource exploitation and energy storage projects, as previously mentioned, has the potential to achieve closed-loop energy utilisation, thereby contributing to the maintenance of ecological sustainability through the aforementioned measures.

4 Conclusion

This study contributes to mitigating the growing scarcity of conventional fossil energy by exploring geothermal energy extraction from reservoirs in abandoned oil fields, which holds significant implications for ensuring energy security and sustaining economic growth. The geothermal reservoir energy development coupling model proposed herein more accurately represents the real-world conditions of geothermal exploitation. Furthermore, the efficiency of geothermal energy extraction is primarily governed by the fluid properties and filtration behavior of the heat transfer medium, which are effectively characterized using a three-dimensional grid-based theoretical framework. Additionally, analysis of various influencing factors on the outlet temperature of geothermal fluids indicates that fluid viscosity and molecular adsorption have a much greater impact on geothermal development compared to permeability effects. Therefore, utilizing heat transfer media with low viscosity and minimal adsorption characteristics can significantly enhance geothermal energy recovery.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported by the "Tianchi Talents" Young Doctor Introduction Program Project.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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