

Article

Role of Nanofluids in Heat Extraction for Mid-Deep Geothermal Wells: Numerical Study on Thermofluidic Characteristics

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Abstract

Global climate change has intensified the need for clean and stable energy sources. Geothermal energy, with its consistent availability, is crucial for the transition to renewable energy systems. This study aims to numerically evaluate the enhancement of heat extraction in a mid-deep coaxial geothermal heat exchanger (GHE) when using water-based Al_2O_3 and SiO_2 nanofluids. A comprehensive 1D pipe flow- and 3D subsurface heat transfer-coupled model was developed and validated against field experimental data. The results demonstrate that the nanofluids significantly enhanced heat extraction. The water- SiO_2 nanofluid achieved the highest outlet temperature, exceeding pure water by approximately 0.2°C after 2000 h. A lower inlet temperature of 5°C increased heat extraction by 88.57% compared to 25°C , despite a lower outlet temperature. The thermal influence radius expanded from <2 m at 300 h to ~ 6 m at 1800 h. This study provides quantitative insights and a validated framework for optimizing GHE performance through nanofluid selection and operational control.

Keywords: coaxial borehole heat exchanger; numerical simulation; medium-deep geothermal energy; heat extraction performance



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1. Introduction

Global climate change poses severe challenges to human society and significantly affects the development and survival of various countries [1,2]. To alleviate the influence of climate change on the world, 194 countries have signed the Paris Agreement [3,4]. As part of the resulting energy structure transformation, many countries are gradually reducing their reliance on traditional fossil fuels and are instead vigorously developing renewable energy [5,6]. Although renewable energy sources, such as solar energy, have attracted much attention, their intermittency and instability remain major challenges for grid balance. Against this backdrop, geothermal energy, as a widely distributed, abundantly stored, and stable energy form that is not affected by the day-night cycle or weather conditions, is vital for stabilizing diversified energy structures [7,8].

To maximize the utilization of geothermal energy and minimize the footprint of its above-ground equipment, heat exchange tubes are directly embedded into underground structures, forming heat exchangers with partial geotechnical engineering structures. This technology is stable, has good heat transfer performance, and can reduce the footprint of above-ground building equipment, making it widely applicable in urban areas with dense populations [9]. Embedding heat exchangers into the ground falls within the scope of energy-related geotechnical engineering. As early as 1996, Austria and Switzerland had embedded heat exchange tube loops into partition walls as heat exchangers [5], and subsequently, heat exchange tubes were also buried to perform heat exchange in the design of the Dietrich Line and the Shanghai Museum [10,11].

This technology of extracting heat from the deep layers of the earth for heating and cooling buildings has certain drawbacks, namely, that the low permeability of geothermal reservoirs restricts heat transfer [12,13]. Usually, to enhance the heat extracted from deep geothermal reservoirs, hydraulic fracturing or acidizing is employed to generate a fracture network, allowing working fluids to pass through the geothermal reservoir [14,15]. However, this approach poses the problem of thermal short-circuiting, which leads to a sudden temperature drop in the mining well and eventually terminates the operation. Therefore, improving the heat transfer performance of the working fluid can enhance the efficiency of the exploitation of deep geothermal resources. Eastman et al. [16] first defined nanofluids as conventional liquids in which metal oxides or metal particles smaller than 100 nanometers are suspended. Adding nanoparticles to the base circulating fluid improves its thermophysical properties and heat transfer characteristics [17,18]. This has led to the widespread use of nanofluids in heat transfer enhancement [19–21]. Their excellent heat transfer performance also makes them suitable for improving the heat transfer in deep geothermal reservoir fractures [22–25]. Liu et al. [26] proposed an advanced closed-loop geothermal system (ACGS) and analyzed its efficiency. Their results showed that complex fractures improve heat extraction by 321.77%.

To enhance the efficiency of heat exchange, researchers have added nanoparticles to heat transfer fluid [27]. Pisarevsky et al. [28] tested the heat transfer performance of water-based nanofluids with concentrations ranging from 2% to 8% in a coaxial geothermal heat exchanger. The results showed that using the nanofluid improved thermal performance by 9% compared to a basic fluid. Daneshipour and Rafee [29] numerically simulated the heat transfer performance of copper oxide water and aluminum oxide water nanofluids when applied to geothermal well heat exchangers. Their results showed that the copper oxide nanofluid had a better convective heat transfer rate than the aluminum oxide nanofluid, and thus could extract more heat. Kapıcıoğlu and Esen [30] experimentally studied the heat transfer enhancement brought about by alumina nanofluids and ethylene glycol–water solutions. The research explored the heat transfer characteristics of two U-shaped ground heat exchangers: horizontal and helical. Their results showed that using alumina nanoparticles with a volume concentration of 0.1%, compared to EG–water, increased the output temperature by 19% and 22%, respectively, in the two types of pipes. Chappidi et al. [31] used nanofluids as the heat transfer medium to extract geothermal energy. They studied the influence of aluminum oxide–copper/water-mixed nanofluids on the performance of the system through numerical simulation methods. Their results showed that adding 4% of copper nanoparticles to water increased the outlet fluid temperature by 25%. Shariati and Rafee [32] conducted three-dimensional model simulations of steady flow in a heat exchanger. They simulated the heat extraction performance of different volume fractions of Al_2O_3 , SiO_2 , and a mix of 50% Al_2O_3 and 50% SiO_2 nanoparticles when used for geothermal well heat exchange. The convective heat transfer coefficients of the Al_2O_3 , mixed $\text{Al}_2\text{O}_3 + \text{SiO}_2$, and SiO_2 nanoparticles increased by 8.5%, 5%, and 1.6%, respectively.

Besides the aforementioned research on heat transfer performance inside heat exchange tubes, the geological conditions and geological heat conduction properties in geothermal well heat transfer systems also have a significant influence [33,34]. Ghasemi-Fare and Basu [35] used finite difference to study the heat conduction of circulating fluid and soil to simulate heat transfer. Their research results show that the initial temperature difference, the thermal conductivity, and the size of the circulating pipe are the most significant parameters affecting the geothermal performance. The study of the heat conduction properties within the soil enables the calculation of porous medium heat conduction, which is currently mostly calculated using artificial intelligence [36], which can also be considered in subsequent geothermal simulations. In addition, the important influences of ground conditions, soil moisture portion, and groundwater flow have also been studied in order to better exploit geothermal resources [37,38].

Despite these advancements, several research gaps persist. Most prior numerical studies on nanofluids in GHEs have focused on shallow systems or simplified homogeneous geology. There is a lack of comprehensive evaluation of the long-term performance of different nanofluids in mid-deep coaxial GHEs under realistic, heterogeneous geological conditions. Furthermore, systematic comparisons between common nanoparticles (like Al_2O_3 and SiO_2) and analyses of key operational parameters like inlet temperature are limited. To address these gaps, this study presents a validated numerical model for a 2 km-deep coaxial GHE. The primary objectives are: (1) to compare the heat extraction performance of water, water- Al_2O_3 , and water- SiO_2 nanofluids and (2) to quantitatively investigate the impact of inlet fluid temperature on system performance. This work aims to provide actionable guidance for fluid selection and operational optimization in practical mid-deep geothermal projects.

2. Model Description

2.1. Physical Model

A schematic diagram of a coaxial geothermal heat exchanger is presented in Figure 1. This heat exchanger contains two concentric tubes, with the diameter of the outer tube being 177 mm and the diameter of the inner tube being 110 mm. The outer tube is formed by an installed steel sleeve with a thickness of 9.2 mm, and the inner tube is composed of a polyethylene tube with a wall thickness of 10 mm [39]. A backfill layer is constructed between the outer tube and the geological rock layer, and the backfill material used is a heat-conductive material, which facilitates the rapid transfer of heat. Working medium flows downward from the outer tube into the heat exchanger and transfers heat with the geological layer during its journey, extracting geothermal energy. When the working medium reaches the bottom of the outer tube, it turns to flow upward into the inner tube. During this process, it exchanges heat with the working medium in the outer tube. Finally, the working fluid releases heat to the ground working system, completing the entire geothermal extraction process.

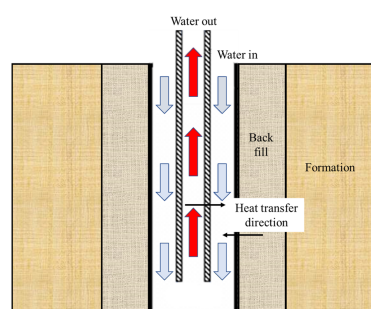


Figure 1. Schematic diagram of heat exchange in coaxial geothermal heat exchanger.

2.2. Geometry Parameters

The deep geothermal well under study is located in Xining City, Qinghai Province. The thermal zoning in this area is a severely cold region, with a significant demand for winter heating in buildings. After exploration, it was found that the underlying bedrock at the location of this geothermal well is ancient Proterozoic metamorphic rock, with a burial depth of approximately 950 m. The main strata are the Cretaceous strata, the Tertiary strata, and the Quaternary strata. The Cretaceous strata are between 450 and 950 m underground, the Tertiary strata are between 50 and 450 m underground, and the Quaternary strata are located between 0 and 50 m. The Cretaceous strata mainly consist of sand–gravel rock, sandstone and mud–sandstone interlayers, as well as mudstone, while the Tertiary strata consist of sandstone and sand–gravel rock, and the Quaternary strata are composed of loose sediments. Figure 2 shows that the total depth is 2013 m, the rock properties are divided into eight layers, and presents the geothermal gradient. Table 1 shows the thermal conductivity and depth of every layer. The average temperature gradient above 750 m is 3.5 °C/100 m and 2.4 °C/100 m when lower than 750 m.

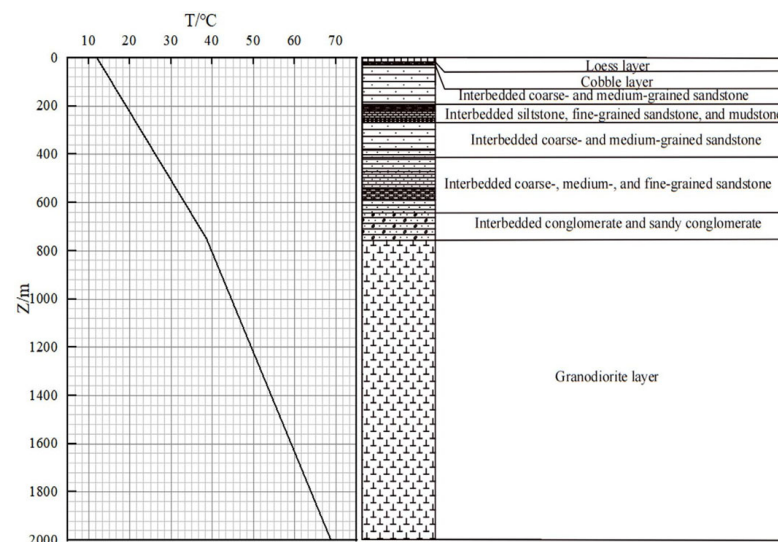


Figure 2. Geological distribution map of researched geothermal well [39].

Table 1. Description of the lithological classification of strata [39].

Stratum Type	Depth (m)	Thermal Conductivity (W/(m·K))
Loess layer	16.8	0.8
Cobble layer	15.5	2.2
Interbedded coarse- and medium-grained sandstone	158.9	2.8
Interbedded siltstone, fine-grained sandstone, and mudstone	75.0	2.2
Interbedded coarse- and medium-grained sandstone	147.3	2.6
Interbedded coarse-, medium-, and fine-grained sandstone	225.1	2.8
Interbedded conglomerate and sandy conglomerate	115.8	3.0
Granodiorite layer	1258.8	3.3

2.3. Governing Equations

Physical modeling in the problem of fluid flow and heat transfer in pipes is simplified from a three-dimensional flow into a one-dimensional problem [40]. The main problem of pipe flow is to solve the momentum and mass conservation equations [41], which mainly

involve the following two equations, and the governing equations are presented in their general vector form for conciseness:

$$\rho_f \frac{\partial \mathbf{u}}{\partial t} = -\nabla p - f_D \frac{\rho_f}{2d_h} \mathbf{u} |\mathbf{u}| \quad (1)$$

$$\nabla \cdot (A_{pi} \mathbf{u}) = 0 \quad (2)$$

where ρ_f is the fluid density (kg/m^3), $\mathbf{u}$ is the velocity vector (m/s), p is the pressure (Pa), f_D is the Darcy friction factor (dimensionless), d_h is the hydraulic diameter (m), and A_{pi} is the pipe cross-sectional area (m^2). The second term on the right side of Equation (1) is caused by the pressure drop, which contains the gravity force. The Darcy friction coefficient in Equation (1) takes into account the continuous pressure drop generated by the viscous shear of the pipeline. This term can be determined by the Reynolds number Re , as well as the ratio of surface roughness to the hydraulic diameter e/d_h . Churchill proposed the following correlation [42]:

$$f_D = 8 \left[\left(\frac{8}{Re} \right)^{12} + (C_A + C_B)^{-1.5} \right]^{1/12} \quad (3)$$

C_A and C_B can be written as

$$C_A = \left[-2.457 \ln \left(\frac{7}{Re} \right)^{0.9} + 0.27 (e/d_h) \right]^{16} \quad (4)$$

$$C_B = \left(\frac{37530}{Re} \right)^{16} \quad (5)$$

Among the variables, e represents the surface roughness of the pipeline. Re is the Reynolds number (dimensionless), and d_h is the hydraulic diameter (m). This correlation was chosen because it provides a universally applicable formula for the friction factor across all Reynolds number regimes (laminar and turbulent) and for both smooth and rough pipes, which is suitable for the wide range of flow conditions potentially encountered in the wellbore.

For the calculation of the internal flow of a geothermal well, the internal heat transfer controlled by the energy equation is also an important aspect.

$$\rho_f A_{pi} c_{pf} \frac{\partial T}{\partial t} + \rho_f A_{pi} c_{pf} \mathbf{u} \cdot \nabla T = \nabla \cdot A_{pi} k_f \nabla T + f_D \frac{\rho_f A_{pi}}{2d_h} |\mathbf{u}|^3 + q'_{wall} \quad (6)$$

where c_{pf} is the specific heat capacity of the fluid at constant pressure ($\text{J}/(\text{kg} \cdot \text{K})$), T is the temperature (K), k_f is the thermal conductivity of the fluid ($\text{W}/(\text{m} \cdot \text{K})$), and q'_{wall} is the heat source term from the pipe wall (W/m). For convective heat exchange during the flow process with geological rock layers, the calculation is as follows

$$q'_{wall} = (hZ)_{eff} (T_{ext} - T) \quad (7)$$

where $(hZ)_{eff}$ is the effective overall heat transfer coefficient per unit length ($\text{W}/(\text{m} \cdot \text{K})$), and T_{ext} is the external temperature outside the pipe (K). The effective convective heat transfer coefficient during the flow process can be predicted by the internal film resistance, the overall heat transfer coefficient, and the wall thermal resistance together [39].

$$(hZ)_{eff} = \frac{2\pi}{\frac{2}{d_{pi} h_{int}} + \frac{\ln(d_{po}/d_{pi})}{k_p}} \quad (8)$$

where h_{int} is the internal film heat transfer coefficient ($\text{W}/(\text{m}^2 \cdot \text{K})$), d_p is the pipe diameter (m), with d_{pi} and d_{po} representing the inner and outer pipe diameters (m), respectively, and k_p is the thermal conductivity of the pipe material ($\text{W}/(\text{m} \cdot \text{K})$). The internal film thermal resistance is calculated based on the characteristic constant Nu number

$$h_{\text{int}} = \text{Nu} \frac{k_f}{d_h} \quad (9)$$

where Nu is the Nusselt number (dimensionless), k_f is the thermal conductivity of the fluid ($\text{W}/(\text{m} \cdot \text{K})$), and d_h is the hydraulic diameter (m). The calculation of the Nu number adopts the model proposed by Gnielinski [43],

$$\text{Nu} = \frac{(f_D/8)(\text{Re} - 1000)\text{Pr}}{1 + 12.7(f_D/8)^{1/2}(\text{Pr}^{2/3} - 1)}, \quad 0.5 < \text{Pr} < 2000, \quad 3000 < \text{Re} < 6,000,000 \quad (10)$$

where Pr is the Prandtl number of the fluid (dimensionless). After fluid flow within the pipe is completed, the calculation results are transferred to the surrounding rock layers through mapping relationships, and then three-dimensional heat conduction and heat transfer calculations are carried out in the surrounding rock layers. Furthermore, the temperature evolution within the geological rock layers develops according to the following:

$$(\rho c_p)_{\text{eff}} \frac{\partial T}{\partial t} + \nabla \cdot (-\mathbf{k}_{\text{eff}} \nabla T) = q \quad (11)$$

Among these terms, q represents the heat dissipation from deeper layers to the geothermal reservoir (W/m^3), and $\mathbf{k}_{\text{eff}}$ and $(\rho c_p)_{\text{eff}}$ are the effective thermal conductivity ($\text{W}/(\text{m} \cdot \text{K})$) and specific heat capacity ($\text{J}/(\text{m}^3 \cdot \text{K})$). This is because the rock layers also contain some water. Using the effective thermal conductivity and thermal specific heat capacity can more accurately describe the heat transfer within rock layers. After obtaining the percentage of water content φ in the rock layers, they are calculated by the following formula:

$$(\rho c_p)_{\text{eff}} = (1 - \varphi)(\rho c_p)_s + \varphi(\rho c_p)_l \quad (12)$$

$$(\mathbf{k})_{\text{eff}} = (1 - \varphi)(\mathbf{k})_s + \varphi(\mathbf{k})_l \quad (13)$$

where φ is the volume fraction of water in the rock layers (dimensionless), and the subscripts s and l denote the solid rock and liquid (water) phases, respectively. $(\rho c_p)_s$ and $(\rho c_p)_l$ are the volumetric heat capacities of solid rock and water ($\text{J}/(\text{m}^3 \cdot \text{K})$), and $(\mathbf{k})_s$ and $(\mathbf{k})_l$ are their thermal conductivities ($\text{W}/(\text{m} \cdot \text{K})$). It is worth noting that for the coaxial casing geothermal wells covered by this study, both the inner and outer pipes adopt the pipe-inflow calculation method based on their line elements, and there is heat exchange between the two pipes.

In this study, nanofluids are used as the working medium, and the physical property parameters of nanofluids are of great significance in the calculation process. The determination of the physical property parameters of mixed substances, such as nanofluids, usually includes their thermal conductivity, specific heat capacity, viscosity, and density. Among them, the determination of specific heat capacity follows [44]:

$$c_{p, \text{nf}} = \frac{(1 - \xi)\rho_f c_{p, f} + \xi\rho_n c_{p, n}}{\rho_{\text{nf}}} \quad (14)$$

where the subscript f represents fluid, the subscript n represents the nanoparticles, and the subscript nf represents the nanofluid. ξ is the volume fraction of nanoparticles (dimensionless). Nanofluid density is determined as $\rho_{\text{nf}} = (1 - \xi)\rho_f + \xi\rho_n$. ρ_f and ρ_n are the densities of the base fluid and nanoparticles (kg/m^3), respectively. The thermal conduc-

tivity of nanofluids is determined by the combination of the thermal conductivity of the nanoparticles and that of the fluid.

$$k_{nf} = \frac{k_n + 2k_f - 2\zeta(k_f - k_n)}{k_n + 2k_f + \zeta(k_f - k_n)} k_f \quad (15)$$

where subscript n, f, and nf mean the nanoparticle, basic fluid, and nanofluid. k_{nf} , k_f , and k_n are the thermal conductivities of the nanofluid, base fluid, and nanoparticles (W/(m·K)), respectively. ζ is the volume fraction of the nanoparticles (dimensionless).

The viscosity of a nanofluid can be determined by the fluid viscosity and the percentage of nanoparticle content in the mixture [32],

$$\mu_{nf} = (1 + 2.5\zeta + 6.2\zeta^2)\mu_f \quad (16)$$

where μ_{nf} and μ_f are the dynamic viscosities of the nanofluid and base fluid (Pa·s), respectively. The fluid was water, and the added nanoparticles were Al₂O₃ and SiO₂. The corresponding physical property parameters are presented in Table 2.

Table 2. Physical properties of Al₂O₃, SiO₂ and water [45,46].

Material	μ (Pa·s)	ρ (kg/m ³)	k (W/(m K))	c_p (J/(kg K))
Water	0.001	995.4	0.6	4183
SiO ₂	-	2220	1.3	603.46
Al ₂ O ₃	-	3970	36	718.7

2.4. Simulation Configuration

The numerical calculations in this study were carried out using Fluent 2022. For the numerical simulation process, the initial state is set following the entire geological reservoir based on the geothermal gradient. The geological distribution and temperature gradient are described in Section 2.2, and the geothermal gradient can be summarized by the following equation.

$$T = \begin{cases} 12.02 - 0.035 \times Z & 0 \text{ m} > Z \geq -750 \text{ m} \\ 38.6 - 0.025 \times (Z + 750) & -750 \text{ m} > Z \geq -2063 \text{ m} \end{cases} \quad (17)$$

where T is the temperature (°C), and Z is the depth (m), with $Z = 0$ at the surface and negative values indicating depth below the surface.

For the fluid inlet in the pipeline, the fluid inlet temperature and inlet flow rate are, respectively, set at 22 °C and 21 m³/h. After obtaining the flow rate, the fluid velocity inside the pipe can be determined based on the interface area. Additionally, the pressure of the fluid at the pipe inlet is set to standard atmospheric pressure. For the fluid outlet of the pipeline, the outlet velocity is obtained by iteratively calculating according to mass conservation. Heat transfer at the outlet only considers flow direction, and heat transfer perpendicular to the flow direction and radiation heat transfer are ignored. In this study, the annular pipe heat exchange well has the ring pipe's internal flow outlet connected to the inner pipe, maintaining continuity of the two flows. This setting is carried out through the generalized stretching operator, which complies with

$$\begin{cases} T_{c,i}(r, z, t) = T_{\text{outer}}(r', z', t') \\ T_{c,o}(r, z, t) = T_{\text{inner}}(r'', z'', t'') \end{cases} \quad (18)$$

Among these terms, (r, z) represents the coordinate system of the target point (m), while (r', z') and (r'', z'') represent the relationships between two interrelated coordinate sys-

tems and the target point (m). $T_{c,i}$ is the temperature at the connection interface (K or °C), T_{outer} is the temperature of the outer pipe (K or °C), and t and t' represent time (s). The function G representing the mapping relationship is implicit in the coordinate transformation.

2.5. Solution Setting

For the differential equations, the finite element method is used for discretization, and the second-order Lagrange elements method was used. For the nonlinear terms in the equations, the following was employed.

$$X^{(n+1)} = X^n - J^{-1}(X^n)F(X^n) \quad (19)$$

The second-order implicit Backward Differentiation method was employed for the discretization of the time term. To ensure the convergence, the relative tolerance was set to 0.001, and the iterative calculation was considered to have converged when the convergence residual of each time step was less than 10^{-3} .

2.6. Analysis Methods

During the continuous heat exchanging process of the geothermal well heat exchanger, heat exchanging efficiency decreases gradually as the geological reservoir temperature declines. Therefore, analyzing heat exchange effectiveness can reflect the strength of its heat exchange capacity. Generally, the heat exchange effectiveness of a well is defined as the ratio of its actual heat exchange quantity to the theoretical heat exchange quantity.

$$E = \frac{Q_{act}}{Q_{the}} = \frac{\rho c_p q_v (T_{out} - T_{in})}{\rho c_p q_v (T_{the} - T_{in})} \quad (20)$$

where the subscript act represents the actual operating condition parameters during the actual operation process, while the subscript “the” represents the operating condition parameters used in theoretical calculations. The theoretical calculation temperature T_{the} is the result obtained by integrating and averaging the temperature gradient of the geothermal reservoir.

3. Verification of Model

3.1. Verification of Mesh Independence

To obtain more accurate calculation results, it is necessary to conduct dimensionless verification of the number of grids used, using multiple models, before conducting a large number of calculations. In this study, the outlet temperature was used as a comparison object, and a verification of grid independence was carried out by comparing the water temperatures at the outlet as calculated using different grid numbers. The results are presented in Table 3. As the number of grids gradually increases, the calculated water outlet temperature gradually decreases. When the number of grids exceeds 8123, the calculated water temperature approaches 16,500, and no longer shows significant changes. During the calculation process, more grids result in a larger amount of computation. However, 8123 grids can not only obtain a calculation result that is close to that of 16,500 grids but also save a considerable amount of computation. Therefore, in subsequent batch calculation research, the study will be conducted using a grid number of 8123.

Table 3. Comparison of the calculated outlet temperature under different meshes.

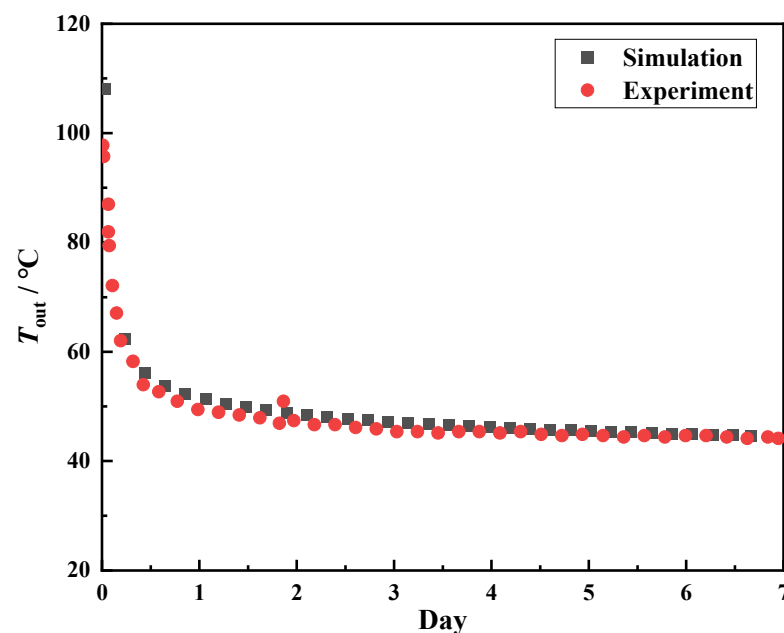
Meshes	Outlet Temperature (°C)	Relative Error (%)
3550	32.878	0.174
5836	32.860	0.119

Table 3. *Cont.*

Meshes	Outlet Temperature (°C)	Relative Error (%)
8123	32.838	0.052
13,450	32.824	0.009
16,500	32.821	

3.2. Validation of Numerical Model

To verify the calculation accuracy of the established numerical model, this study used the established model to simulate the heat exchange process of a geothermal well located in Hawaii, USA. The depth of the geothermal well is 876.5 m, and the thermal conductivity of the stratum is 1.6 W/(m·K). Detailed parameters of this geothermal well's structure are presented in the literature. The working medium in the geothermal well is circulated through a pump with a head of 30 m. The inlet flow rate and fluid temperature in the geothermal well are 80 L/min and 30 °C, respectively. Through simulation calculations, the outlet temperature of the pipeline was compared with the experimental test results. Figure 3 shows the outlet temperature of this continuously operated geothermal well for 7 days. The results show that the numerical results and experimental results possess a consistent trend of change. As geothermal heat is gradually extracted, the outlet water temperature of the geothermal well gradually decreases and eventually stabilizes near 45 °C. The numerical simulation results are in excellent agreement with the experimental test results, proving the computational accuracy of the established model.

**Figure 3.** Verification of the numerical model [47].

4. Results and Discussion

4.1. Evolution of Geothermal Heat Exchange

4.1.1. The Temperature Distribution

Figure 4 shows a comparative illustration of the temperature distribution in the formation when operated for 500 h, 1250 h, and 2000 h, using water as the working medium. The figure shows that the temperature of the geothermal reservoir rises with increasing formation depth. The isothermal lines transform into an hourglass shape near the pipeline, which is caused by heat transfer. The hourglass shape becomes deeper as the formation depth gradually increases. This is because the temperature of the geothermal reservoir is

higher when closer to the bottom, and the stronger the heat transfer of the working fluid, the deeper the hourglass shape formed by the isothermal lines. It is worth noting that when the formation depth is above -600 m, the hourglass-shaped isothermal lines form upwards. Hourglass-shaped isothermal lines below -600 m form a concave shape downwards. This is because in a geothermal reservoir above -600 m, the temperature is lower, and the fluid, with an inlet temperature of $22\text{ }^{\circ}\text{C}$, first conducts heat to the geothermal reservoir, forming an upward, bulging, inverted hourglass shape. At the bottom of the well, the temperature of the geothermal reservoir reaches $70\text{ }^{\circ}\text{C}$, greatly heating the working fluid inside the pipeline, forming a downward, concave, hourglass-shaped isothermal line. This is also the location where the working fluid most greatly extracts heat. Moreover, when comparing the geothermal reservoir temperature distribution diagrams, using water as the working medium, at different operating times, the funnel-shaped isothermal lines formed near the heat transfer fluid pipeline become larger and larger over time. This is the result of the continuous extraction of heat from the formation by the heat transfer fluid, and also proves the continuous generation of heat in the geothermal well.

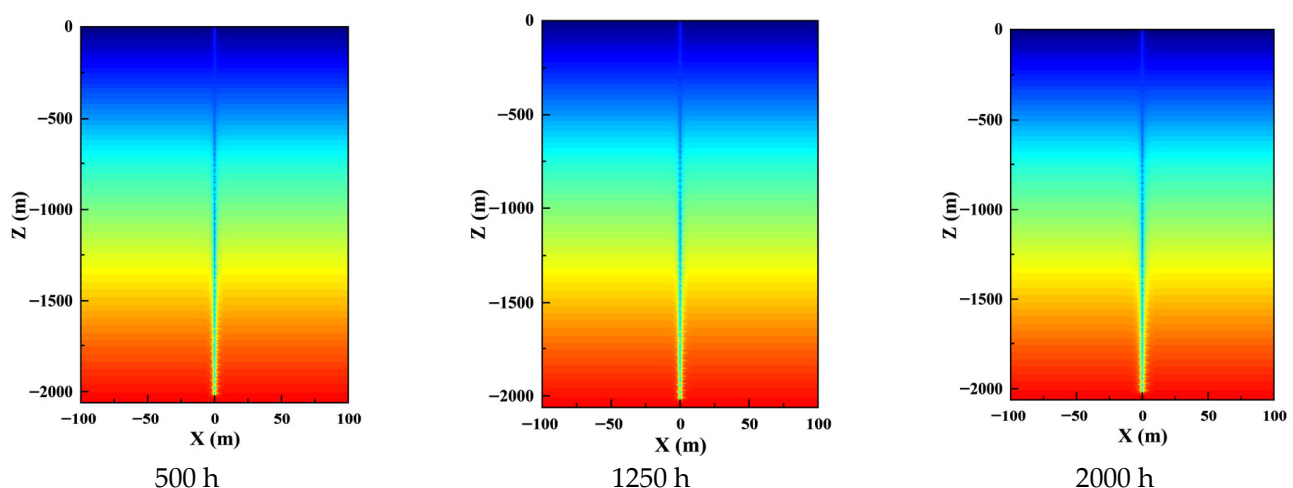


Figure 4. Display of the temperature evolution of the geothermal reservoir.

4.1.2. The Influence Radius

Figure 5 shows the influence radius generated by heat exchange in a geothermal well. This figure was drawn when the depth of the geothermal reservoir was 2000 m, and the operations lasted for 300 h, 900 h, and 1800 h. From the above figure, the temperature of the geothermal reservoir around the coaxial heat exchange well gradually decreases as the heat transfer progresses. However, due to the large size of the geothermal reservoir, the influence of the heat exchange is not obvious throughout the entire reservoir, and is thus difficult to compare. A thermal influence radius cloud map of the geothermal well can show the size of the influence radius produced by the coaxial heat exchange well, which reflects the heat disturbance able to be generated by the working medium, and also reflects the strength of heat exchange in the geothermal well's heat exchange process. From the figure, at 300 h, the thermal disturbance radius produced by the heat exchange pipeline is still small, less than 2 m. As the heat exchange gradually proceeds, the thermal disturbance radius produced by the heat exchange pipeline gradually increases, reaching 4 m at 900 h. With a continuous increase in heat exchange, the thermal disturbance radius also expands further, reaching 6 m at 1800 h. This figure also reflects the effect of the heat exchange pipeline on the geothermal reservoir as time progresses.

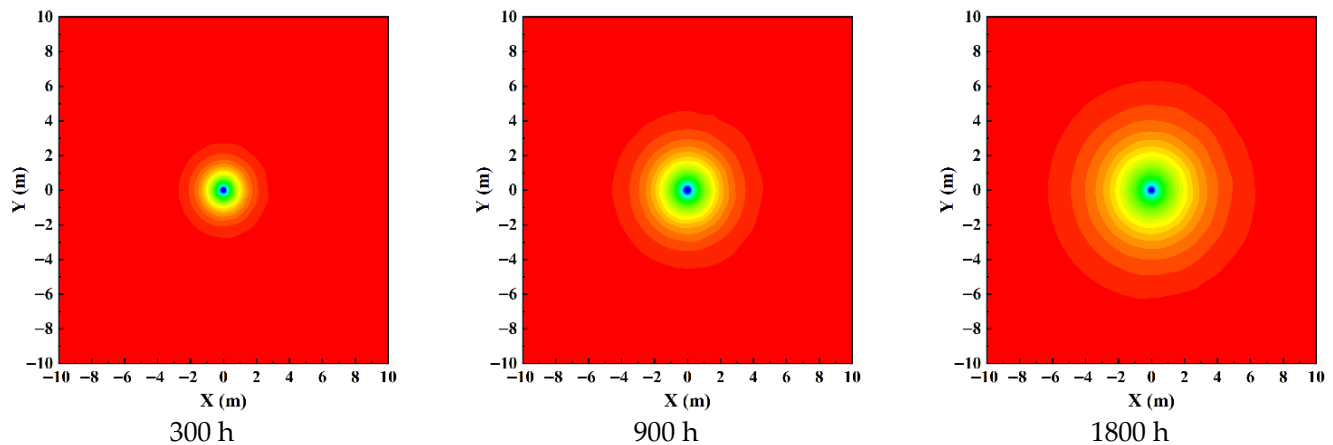


Figure 5. Display of the turbulence radius of the geothermal reservoir.

4.1.3. The Outlet Temperature

The outlet temperature after 2000 h of heat exchange in a concentric geothermal well is shown in Figure 6. From the figure, the water temperature at the well outlet can reach 40 °C at the beginning of the heat exchange, because at this time, the geothermal reservoir has a relatively high heat storage capacity. As the pipeline and geothermal reservoir gradually exchange heat, the water temperature at the outlet gradually decreases. Because the stratum near the pipeline has continuously taken heat and has already decreased in temperature to some extent, the heat resistance also gradually increases. The rate of the decrease in the water temperature first drops rapidly and then slowly. This is because the stratum temperature near the heat exchange pipeline becomes relatively low as heat exchange continues, which greatly increases the heat resistance of the heat exchange. After the geothermal well heat exchange reaches 746 h, the outlet temperature drops to 30 °C. However, the outlet temperature also enters a state of slow decrease, giving the outlet temperature a longer period of utilization value. As the process continues to 2000 h, although the outlet temperature has decreased somewhat, it can still be maintained at 29.2 °C, and thus still has a relatively high utilization value.

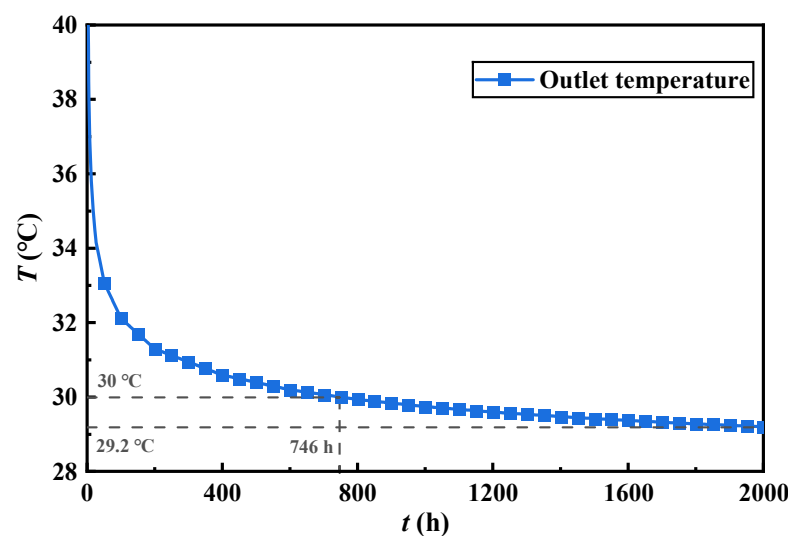


Figure 6. Display of the outlet temperature of the working fluid.

4.2. Influence of the Nanofluids

The results discussed in the previous section demonstrated the evolution characteristics of the geothermal well during the transient exchange process, which is very helpful for

understanding the heat exchange process of the geothermal well. This section conducts research on the application of nanofluids in geothermal well heat exchangers, comparing the effects of three working fluids, namely water, water + Al_2O_3 , and water + SiO_2 , on geothermal well heat exchange. This section mainly explores the working effects of these three working fluids, and therefore mainly focuses on research on parameters such as the outlet temperature and the heat exchange efficiency.

4.2.1. Comparison of Outlet Temperatures

The outlet water temperatures of water, water + Al_2O_3 , and water + SiO_2 fluids in the heat exchanger of a geothermal well are compared in Figure 7. This parameter is an important one in geothermal well applications and is also a key evaluation indicator in these applications. A comparison of the results in the figure shows that at any given transient moment, the outlet temperature of water is the lowest, while the outlet temperature of the water + SiO_2 nanofluid is the highest, and that of water + Al_2O_3 is in the middle. This is because adding Al_2O_3 and SiO_2 nanoparticles to water can significantly enhance its thermal conductivity, thereby increasing heat exchange performance. Moreover, adding SiO_2 nanoparticles to water results in a smaller increase in the thermal capacity of the nanofluid, which leads to the fastest increase in outlet water temperature for the composite fluid formed by water + SiO_2 nanoparticles, and the highest water temperature. The addition of SiO_2 nanoparticles resulted in the highest outlet temperature, approximately 0.2°C higher than pure water after 2000 h.

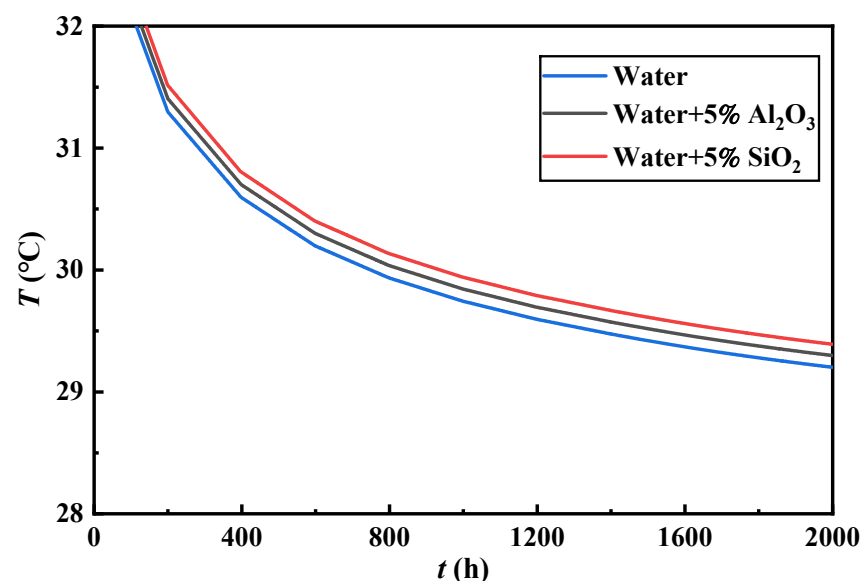


Figure 7. Comparison of outlet temperatures of three working fluids.

4.2.2. Comparison of Heat Exchange Effectiveness

From the comparison results in Figure 8, the heat exchange efficiency of the nanofluid composed of water and SiO_2 is the highest, while water as a heat transfer medium has the lowest heat exchange efficiency, and the composite nanofluid composed of water and Al_2O_3 has an intermediate heat exchange efficiency. This is attributable to the improved thermophysical properties of the nanofluids, particularly their increased effective thermal conductivity. This indicator also reflects that the nanoparticles of the nanofluid composed of water and SiO_2 have the best heat transfer efficiency, and that it has high applicability to the heat exchanger of this geothermal well. The heat transfer efficiency of water and SiO_2 is 2.75% higher than that of pure water.

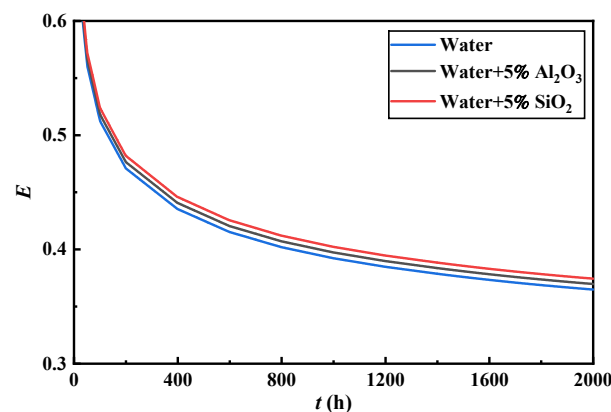


Figure 8. Comparison of heat transfer effectiveness of three working fluids.

4.3. Influence of the Inlet Temperature

The previous section compared and analyzed the heat extraction performance of different nanofluids in geothermal heat exchange wells. In this section, for the same nanofluid (Water + 5% SiO₂), its heat extraction performance in wells is compared and analyzed by selecting different inlet temperatures. A comparative analysis was conducted on the outlet water temperature and the heat output of nanofluid heat exchange at different inlet temperatures.

4.3.1. Comparison of Outlet Temperature

The outlet water temperature of the working fluid after heat exchange in the geothermal well at different inlet temperatures is compared in Figure 9. From the figure, as the inlet water temperature gradually increases, the outlet temperature also gradually increases. The outlet water temperature is at a relatively high level when the inlet temperature is also at a relatively high level. When the inlet temperature is 5 °C, the outlet temperature is the lowest, reaching 17.5 °C at 2000 h. When the inlet temperature is 25 °C, the outlet temperature is the highest, reaching approximately 33 °C at 2000 h, which is an increase of 88.57% compared to a Fa5 °C inlet temperature. The influence of inlet temperature is smaller in early of heat exchange and larger in later. After about 1600 h of heat exchange, the temperature difference in the outlet with different inlet water temperatures is approximately 10 °C.

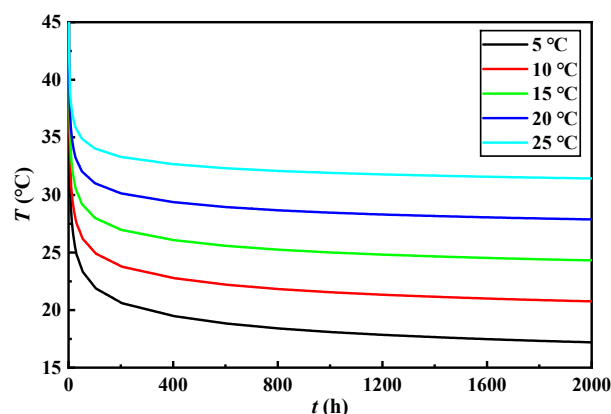


Figure 9. Comparison of the outlet temperature under different inlet temperatures.

4.3.2. Comparison of Heat Extracted

Working fluids with different inlet water temperatures will reach different outlet temperatures after heat exchange in a geothermal well, which is not intuitive for the analysis

of their heat exchange capacity. Therefore, the heat extracted by the working fluid (water–SiO₂ nanofluid) with different inlet temperatures during operation is compared in Figure 10. The variation pattern of the extracted heat is exactly opposite to the variation pattern of the outlet temperature, mentioned above. Overall, the lower the inlet temperature, the higher the heat exchange capacity in a geothermal well, because when the inlet temperature is lower, fluid enters the geothermal reservoir with a larger temperature difference for heat exchange, which generates a larger heat exchange driving force, thereby extracting more heat. Therefore, when the heat exchange fluid is at a lower level, its heat extraction in the geological reservoir is higher.

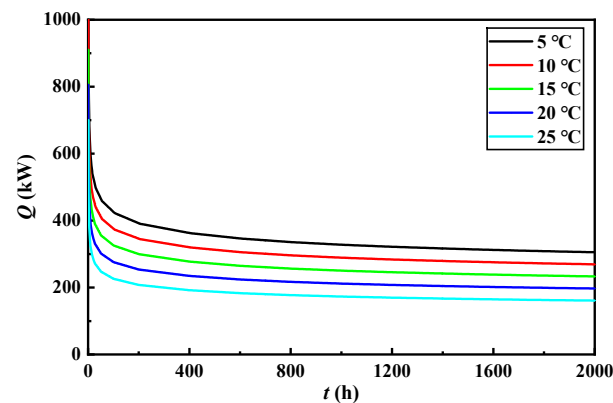


Figure 10. Comparison of the heat extracted under different inlet temperatures.

4.3.3. Comparison of Pipe Fluid Temperature

The magnitude of temperature change represents the heat transfer between the pipe and the geothermal reservoir. A comparison of the temperature changes within the pipe under five working conditions with temperatures of 5, 10, 15, 20, and 25 °C is shown in Figure 11. The overall trend of the fluid temperature within the pipe under these five conditions is that it gradually increases downward during flow and then gradually decreases upward during flow. As the aforementioned comparison results regarding the heat transfer magnitude show, the lower the temperature, the greater the heat transfer, and the wider the range of temperature changes. Among the five curves in the figure, the temperature change range within the pipe at a temperature of 5 °C is the widest, while that at a temperature of 25 °C is the narrowest. Moreover, the range of fluid temperatures within the pipe shows an overall decreasing trend as temperature increases. This also indicates that the heat transfer capacity of the working fluid gradually increases as the inlet temperature decreases.

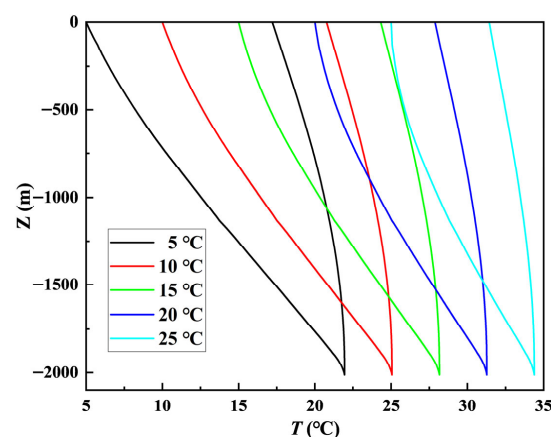


Figure 11. Comparison of the pipe fluid temperature under different inlet temperatures.

5. Conclusions

This study built and validated a comprehensive numerical model to evaluate the thermal performance of a deep coaxial geothermal well using water and nanofluid as working fluids. The main findings are summarized as follows:

1. The thermal influence radius of the heat exchanger expanded over time, from under 2 m at 300 h to approximately 6 m at 1800 h, indicating progressive heat depletion in the near-well region and underscoring the importance of long-term thermal management.
2. The outlet temperature of water declined to 30 °C after 746 h of operation and eventually stabilized at around 29.2 °C after 2000 h, demonstrating the system's ability to provide usable heat over extended periods despite a gradual decline.
3. The use of nanofluids significantly improves the heat extraction capability of geothermal systems. The addition of SiO₂ nanoparticles resulted in the highest outlet temperature, approximately 0.2 °C higher than pure water after 2000 h. The heat transfer efficiency of water and SiO₂ is 2.75% higher than that of pure water.
4. The inlet temperature critically influences system performance. When the inlet temperature decreased from 25 °C to 5 °C, heat extraction increased by 88.57%, although the outlet temperature was lower. This highlights a trade-off between extraction rate and output temperature for practical applications.

The findings highlight the potential of nanofluids, especially SiO₂-based nanofluids, to enhance geothermal energy extraction, and they provide a validated modeling framework for future system optimization. To provide broader guidance on the formation of nanoparticle concentrations, the concentrations of nanoparticles selected in this study were as high as 5%. This requires the development of methods for stabilizing high-concentration nanoparticles in fluid in the future. Future work can also explore the mixing of nanoparticles and hydraulic characteristics to further improve efficiency and sustainability.

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Nomenclature

c_p	Specific heat ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)
Pr	Prandtl number
Re	Reynolds number
t	Time (s)
T	Temperature (K)
$\vec{U}$	Velocity vector ($\text{m} \cdot \text{s}^{-1}$)
k	Thermal conductivity ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)
μ	Dynamic viscosity ($\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$)
ρ_f	Density of paraffin ($\text{kg} \cdot \text{m}^{-3}$)
ρ_{water}	Density of water ($\text{kg} \cdot \text{m}^{-3}$)

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