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Mitigating Thermal Breakthrough in Enhanced Geothermal Systems Using Nanofluids

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ABSTRACT

Early thermal breakthrough in Enhanced Geothermal Systems (EGS) significantly limits heat extraction efficiency, particularly due to preferential flow channels. While previous studies focused primarily on circulation rate adjustments, this paper demonstrates the superior effectiveness of nanofluids in mitigating thermal breakthroughs. Through a transient thermal-hydraulic coupled model, we evaluated CuO, Al_2O_3, and Cu nanofluids, finding that Cu-nanofluid with 5% volume fraction achieved optimal performance. This configuration extended thermal breakthrough time from 35 to 59 years and elevated production temperature by 26.32°C after 100 years of operation. Our analysis revealed a direct correlation between nanoparticle concentration and performance improvement, with temperature gains increasing from 6°C to 27°C as volume fraction rose from 1% to 5%, though showing diminishing returns at higher concentrations. System performance was further optimized through reduced injection velocity and temperature, which extended fluid residence time and enhanced thermal gradients. These findings establish nanofluids as a promising solution for improving EGS efficiency, offering practical insights for future geothermal energy development.

1. INTRODUCTION

The Enhanced Geothermal System (EGS) is an advanced technology designed specifically for the large-scale development of geothermal resources in hot dry rock formations (Li et al. 2022). Its core objective is to enhance the permeability of HDR through hydraulic fracturing or other reservoir stimulation techniques, thereby enabling efficient heat extraction (Liu et al. 2024; Liu et al. 2023) However, in practical operations, these reservoir stimulation methods inevitably create preferential flow pathways between injection and production wells. The injected working fluid tends to flow rapidly along these pathways, reaching the production wells without sufficient heat absorption and leading to the issue of thermal breakthrough (Zhang et al. 2023a; Zhang et al. 2024; Zhang et al. 2023b). For instance, in Japan's Hijiori geothermal project, the presence of preferential flow pathways caused the production well temperature to drop sharply from 260°C to 140°C in less than one year, significantly impairing the system's heat energy recovery capacity (Tenma et al. 2008). Therefore, developing effective strategies to delay thermal breakthrough and enhance the overall efficiency of EGS has become a critical direction for EGS's development.

Optimizing the thermal and physical properties of working fluids represents a promising strategy to enhance heat transfer efficiency in fractures, thereby significantly improving the thermal energy extraction efficiency of EGS. In recent years, the application of nanotechnology in renewable energy has achieved remarkable progress. The addition of nanoscale particles to base fluids has proven effective in substantially improving the heat transfer characteristics and thermophysical properties of working fluids. Kapıcıoğlu et al. (2020) investigated the heat transfer performance of Al_2O_3-ethylene glycol/water nanofluids in U-shaped and helical geothermal heat exchangers (GHEs). Their findings revealed that with an Al_2O_3 mass fraction of 0.1 %, the heat transfer efficiency per meter of the heat exchanger increased by 19 % compared to the base fluid. Du et al. (2020) experimentally studied the impact of CuO nanofluids on the heat extraction performance of coaxial geothermal heat exchanger, reporting a 39.84 % increase in heat transfer rates when using nanofluids. In a complementary numerical study, Du et al.(2020b) demonstrated that spherical CuO/water nanofluids achieved 8.55 % higher heat extraction efficiency than rod-shaped counterparts. Chappidi et al.(2023) employed numerical simulations to evaluate the efficiency of mono and hybrid nanofluids in geothermal energy extraction from abandoned oil and gas wells. Their findings indicated that adding 4 % CuO and Al_2O_3 nanoparticles to water increased the outlet fluid temperature by 16.5 % and 9.7 %, respectively. Jamshidi et al. (2018) explored the application of nanofluids in conical spiral geothermal heat exchangers and observed that a nanofluid concentration of 0.5 % increased the heat flux on the pipe wall by 18 %. Additionally, Javadi et al. (2021) demonstrated that employing a 15 % volume fraction of Ag-MgO/water hybrid nanofluids in a 2-meter-long U-tube heat exchanger improved the coefficient of performance by approximately 67 % compared to water.

These studies collectively underscore the potential of nanofluids as advanced working fluids to significantly enhance the thermal energy extraction efficiency of geothermal systems. However, most existing research has concentrated on wellbore heat exchangers in ground-source heat pump systems, while the application of nanofluids in HDR geothermal reservoirs remains underexplored. HDR resources, characterized by their abundant reserves and higher thermal energy potential at depth, offer substantial development opportunities. Consequently, investigating the feasibility of using nanofluids in EGS is of paramount importance. This research area demands further exploration to bridge the current knowledge gaps and accelerate the efficient exploitation of HDR geothermal resources.

In this study, we investigate the enhancement of thermal breakthrough and heat extraction efficiency in EGS using nanofluids through numerical simulations. The structure of this paper is as follows: In section 2, we introduce the mathematical model and develop a numerical model of an EGS system with thermal breakthrough. In section 3, the constructed model is employed to analyze the impact of different types and concentrations of nanofluids on the heat extraction efficiency of EGS.

2. METHODOLOGY

2.1 Mathematical Model

The Darcy velocity tensor u, describing fluid seepage in the reservoir rock, is expressed as:

$$\mathbf{u} = -\frac{k_{\mathrm{m}}}{\mu_{\mathrm{f}}}\left(\nabla p - \rho_{\mathrm{f}}\mathbf{g}\nabla z\right), \tag{1}$$

where k_{m} is the reservoir matrix permeability in μm^2. μ_{f} and ρ_{f} are fluid viscosity in Pa·s and density in kg/m^3, respectively. p is the pore pressure of the reservoir matrix in Pa. $\boldsymbol{g}$ is the gravitational acceleration in m/s^2.

The mass conservation in the reservoir matrix is represented as

$$\frac{\partial\left(\phi_{\mathrm{m}}\rho_{\mathrm{f}}\right)}{\partial t} + \nabla\cdot\left(\rho_{\mathrm{f}}\mathbf{u}\right) = 0, \tag{2}$$

where $\O_{\mathrm{m}}$ is the reservoir matrix porosity.

The Dracy velocity in fracture flow can be calculated as

$$\mathbf{u}_{\mathrm{f}} = -\frac{k_{\mathrm{f}}}{\mu_{\mathrm{f}}}\left(\nabla_{\mathrm{T}} p + \rho_{\mathrm{f}}\mathbf{g}\nabla_{\mathrm{T}} z\right), \tag{3}$$

where k_{f} is the fracture permeability in μm^2.

The mass conservation in the fracture can be represented as

$$\nabla_{\mathrm{T}}\cdot\left(d_{\mathrm{f}}\rho_{\mathrm{f}}\mathbf{u}_{\mathrm{f}}\right) + d_{\mathrm{f}}\frac{\partial}{\partial t}\left(\phi_{\mathrm{f}}\rho_{\mathrm{f}}\right) = 0, \tag{4}$$

where d_{f} represents the fracture aperture in m.

The energy conservation equation in the HDR is

$$\left(\rho c\right)_{\mathrm{eff}}\frac{\partial T}{\partial t} + \rho_{\mathrm{f}} c_{\mathrm{f}}\mathbf{u}\cdot\nabla T - \nabla\cdot\left(\lambda_{\mathrm{eff}}\nabla T\right) = 0, \tag{5}$$

where T is the HDR temperature in K. c_{f} is the fluid thermal capacity in J/(kg·K). λ_{eff} in this equation can be calculated as

$$\lambda_{\mathrm{eff}} = \phi_{\mathrm{m}}\lambda_{\mathrm{f}} + \left(1-\phi_{\mathrm{m}}\right)\lambda_{\mathrm{s}}, \tag{6}$$

where λ_{s} and λ_{f} are the thermal conductivities of rock and circulation fluid in W/(m·K), respectively. $(\rho c)_{\mathrm{eff}}$ in the energy conservation equation can be calculated as

$$\left(\rho c\right)_{\mathrm{eff}} = \phi_{\mathrm{m}}\rho_{\mathrm{f}} c_{\mathrm{f}} + \left(1-\phi_{\mathrm{m}}\right)\rho_{\mathrm{s}} c_{\mathrm{s}}, \tag{7}$$

where c_{s} is the thermal capacity of the HDR in J/(kg·K). ρ_{s} is the density of HDR in kg/m^3.

For heat transfer in fractures, the energy conservation equation can be expressed as

$$d_{\mathrm{f}}\left(\rho c\right)_{\mathrm{eff}}\frac{\partial T}{\partial t} + d_{\mathrm{f}}\rho_{\mathrm{f}} c_{\mathrm{f}}\mathbf{u}\cdot\nabla_{\mathrm{T}} T - \nabla_{\mathrm{T}}\cdot\left(d_{\mathrm{f}}\lambda_{\mathrm{eff}}\nabla_{\mathrm{T}} T\right) = 0. \tag{8}$$

2.2 Numerical Implementation

This study investigates the potential benefits of using nanofluids as working fluids to improve the heat extraction efficiency of EGS through numerical simulations. A geological model has been constructed to simulate the development of EGS based on the mathematical model described in the previous section. As shown in Figure 1, the model dimensions are 600 m × 600 m, with an injection well and a production well placed 500 m apart within the reservoir. The reservoir consists of fracture network and rock matrix, with a dominant flow channel specifically designed between the injection and production wells to more realistically simulate the occurrence of thermal breakthrough and the principles of heat transfer. The boundary conditions are set to be impermeable and insulated around the reservoir. The injection well is assigned a flow rate boundary condition, while the production well is assigned a pressure boundary condition. The specific parameters used in the simulation, including reservoir characteristics and operating conditions, are listed in Table 1.

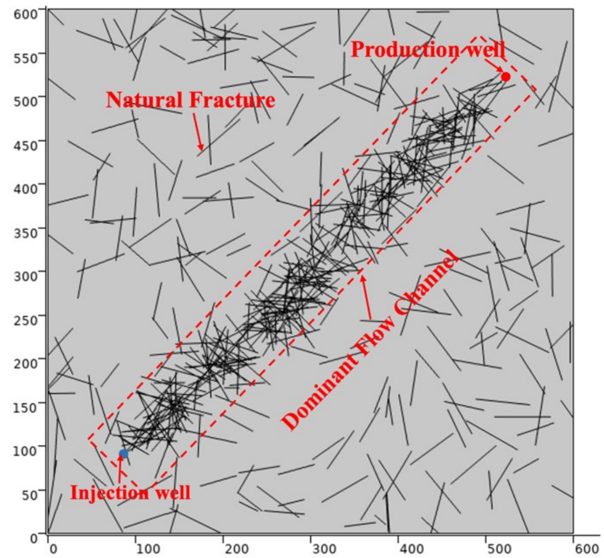

Figure 1: Schematic diagram of the computational model.

Table 1: Parameters used for the simulation.

Parameters	Value	Unit
Density of HDR	2700	kg/m^3
Thermal conductivity of HDR	3.5	W/(m·K)
Specific thermal capacity of HDR	900	J/(kg·K)
Initial porosity of the reservoir	0.1	-
Permeability of the reservoir	5×10^{-15}	m^2
Thickness of the fractures in dominant flow channel	5	mm
Permeability of the fractures in dominant flow channel	5×10^{-10}	m^2
Thickness of the natural fractures	1	mm
Permeability of the natural fractures	1×10^{-11}	m^2
Total injection rate	5	kg/s
Injection temperature	40	℃
Reservoir initial temperature	200	℃

The properties of nanofluids, such as specific heat capacity, viscosity, density, and thermal conductivity, depend on parameters like the characteristics of nanoparticles and their concentration. The properties of water-based nanofluids are calculated using methods from existing literature (Diglio et al. 2018). The properties of different nanoparticles are listed in Table 2.

Table 2: Properties of nanoparticles

Nanoparticle	Thermal conductivity	Specific thermal capacity	Density
Al_2O_3	40	775	3970
CuO	32.9	525	6500
Cu	401	385	8933

Adding nanoparticles to water increases the density of the mixture. According to the mass balance of the mixing theory, the density of the nanofluid can be effectively calculated using Equation (9)

$$\rho_{\mathrm{nf}} = (1-\alpha)\rho_{\mathrm{w}} + \alpha\rho_{\mathrm{np}} , \tag{9}$$

where α is the volume fraction of nanoparticles, ρ_{w} is the density of water, ρ_{np} is the density of nanoparticles, and ρ_{nf} is the density of nanofluid.

Xuan et al. (2000) proposed Equation (10) to calculate the specific heat capacity of nanofluids, which is calculated as

$$C_{p,\mathrm{nf}} = \frac{(1-\alpha)\rho_{\mathrm{w}} C_{p,\mathrm{w}} + \alpha\rho_{\mathrm{np}} C_{p,np}}{\rho_{\mathrm{nf}}} , \tag{10}$$

where $C_{p,\mathrm{nf}}$ is the specific thermal capacity of the nanofluid, $C_{p,\mathrm{w}}$ is the specific heat capacity of water, and $C_{p,\mathrm{np}}$ is the specific heat capacity of the nanoparticles.

Brinkman (1952) introduced an equation to estimate the viscosity of nanofluids, which can be calculated as

$$\mu_{\mathrm{nf}} = \frac{1}{(1-\alpha)^{2.5}} \mu_{\mathrm{w}} , \tag{11}$$

where μ_{nf} is the viscosity of the nanofluid and μ_{w} is the viscosity of water.

The thermal conductivity of the nanofluid is calculated as

$$k_{\mathrm{nf}} = \frac{k_{\mathrm{np}} + 2k_{\mathrm{w}} - 2(k_{\mathrm{np}} - k_w)\alpha}{k_{\mathrm{np}} + 2k_{\mathrm{w}} - (k_{\mathrm{np}} - k_w)\alpha} k_w , \tag{12}$$

where k_{nf} is the thermal conductivity of the nanofluid, k_{w} is the thermal conductivity of water, and k_{np} is the thermal conductivity of the nanoparticles.

In this study, COMSOL software was used for numerical simulation. Since COMSOL employs the finite element method to discretize the governing equations, it is necessary to first perform mesh generation for the computational domain. To enhance computational efficiency and accuracy, the mesh was refined in the vicinity of the fractures. The final mesh consists of a total of 163530 elements, and a schematic representation of the mesh distribution is shown in Figure 2.

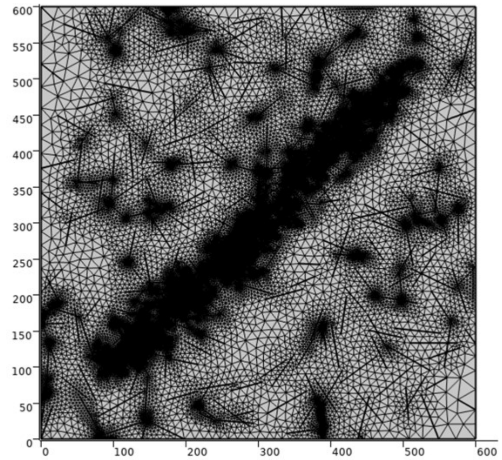

Figure 2: Mesh scheme for the simulation model.

3. RESULTS AND DISCUSSIONS

3.1 Effect of nanoparticle type

Incorporating various types of nanoparticles into water can significantly enhance the heat extraction efficiency of EGS. To systematically examine this effect, this section investigates the specific impacts of Al_2O_3, CuO, and Cu nanoparticles on system performance, with the volume concentration of all nanoparticles fixed at 5%. Figure 3 illustrates the changes in production temperature for different cases. The results reveal that the addition of nanoparticles effectively delays the thermal breakthrough time of EGS. For instance, using Cu-nanofluid as the working fluid extends the thermal breakthrough time from 35 years to 59 years. Furthermore, nanofluids markedly improve the production temperature of EGS. After 100 years of operation, the production temperature of Cu-nanofluid reaches 146.53 °C, which is 26.32 °C higher than that of water case.

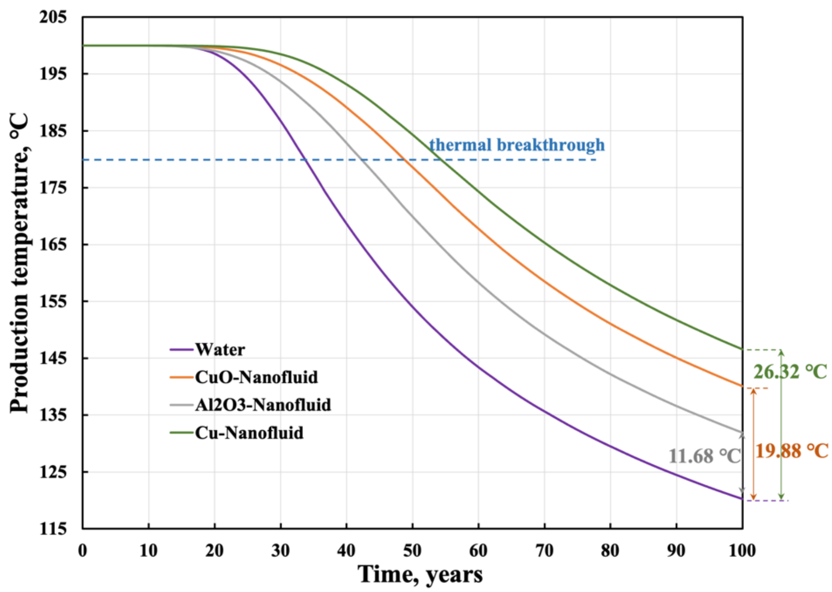

Figure 3: Effect of nanoparticle type on production temperature.

Among the three types of nanoparticles, Cu nanoparticles demonstrate the most superior performance, primarily due to copper's high thermal conductivity. To quantitatively assess the influence of nanoparticles on the heat transfer properties of the working fluid, the Mouromtseff number (*Mo*) is introduced (Timofeeva et al. 2011). A higher *Mo* value indicates superior heat transfer characteristics. The *Mo* is a function of the nanofluid's viscosity, specific thermal capacity, thermal conductivity, and density, which is calculated as follows:

$$Mo = \frac{\rho^{0.8} k^{0.67} C_p^{0.33}}{\mu^{0.47}} \quad (13)$$

The normalized Mouromtseff number (*Mo**) represents the ratio of the nanofluid's *Mo* to that of water, which can be calculated as follows:

$$M_o^* = \frac{(Mo)_{\mathrm{nf}}}{(Mo)_{\mathrm{w}}} \tag{14}$$

Figure 4 compares the Mo* values of different nanofluids. The results show that Cu-nanofluid achieves the highest Mo* value of 9.5, indicating that the addition of copper nanoparticles increases the fluid's heat transfer coefficient nearly tenfold. This finding further underscores the remarkable advantages of Cu-nanofluids in enhancing heat transfer efficiency.

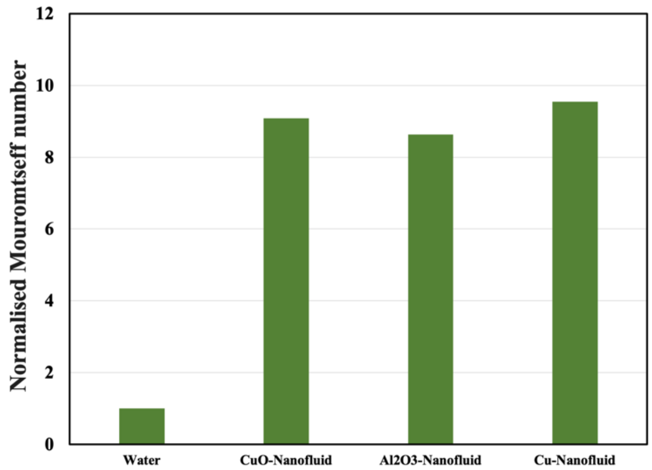

Figure 4: The normalized Mouromtseff number for different nanofluids.

3.2 Effect of nanoparticle volume fraction

The above study confirms the effectiveness of Cu-nanofluids in enhancing production performance of EGS. Therefore, it is necessary to further explore the specific impact of different volume concentrations on system performance. As shown in Figure 5, the temperature enhancement effect of EGS increases significantly with the rise in Cu nanoparticle volume concentration. For instance, when the volume concentration is 1%, the temperature increases by only 5.86 °C, whereas at a volume concentration of 5 %, the temperature increase markedly rises to 26.87 °C. However, further analysis reveals that the incremental temperature increase diminishes as the volume concentration continues to rise. Specifically, when the volume concentration increases from 1 % to 2 %, the temperature rises by 5.75 °C, but when the concentration increases from 4 % to 5 %, the temperature increase is only 3.88 °C. This trend indicates the need to balance cost-effectiveness and efficiency in practical applications to optimize the additive concentration.

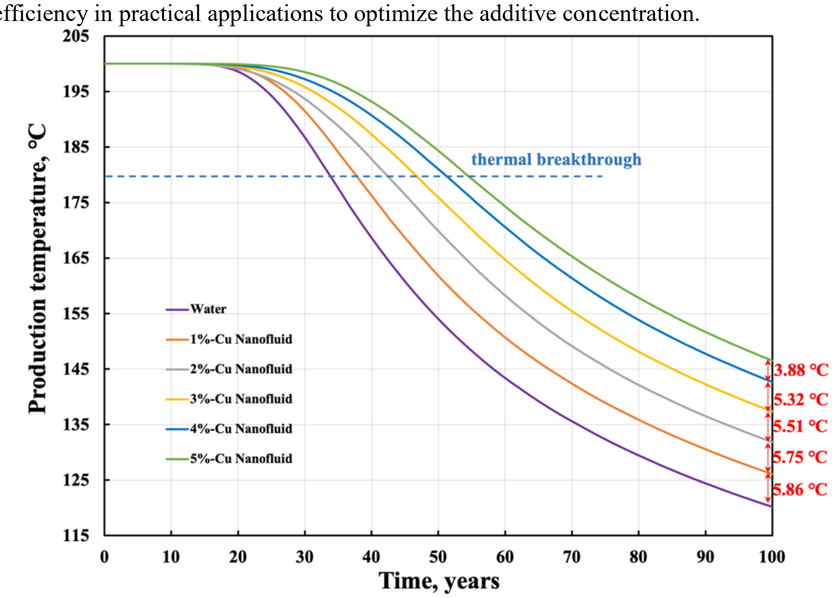

Figure 5: Effect of nanoparticle volume fraction on production temperature.

3.3 Effect of injection rate

Injection rate is a critical operational parameter affecting the performance of EGS. This section investigates the impact of nanofluids on system performance when the injection rate increases from 5 kg/s to 10 kg/s. In the study, the volumetric concentration of Cu nanoparticle is fixed at 3%. Figure 6 compares the production temperature variations of the system under different injection rates when using Cu-nanofluid and water as working fluid. The results indicate that Cu-nanofluid have a more pronounced effect on production temperature improvement at lower injection rates. For instance, when the injection rate is 10 kg/s, the production temperature increases by only 9.80 °C. However, when the injection rate decreases to 5 kg/s, the temperature increase reaches 17.12 °C. This difference is primarily attributed to the direct relationship between the injection rate and the residence time of the fluid in the thermal reservoir. At lower injection rates, the fluid remains in the reservoir for a longer period, allowing for more effective heat exchange with the rock formation and better utilization of the high thermal conductivity properties of the nanofluid.

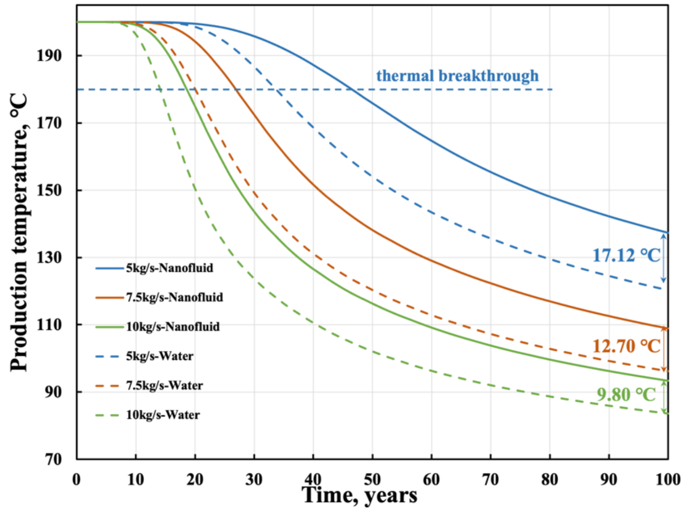

Figure 6: Effect of injection rate fraction on production temperature.

3.4 Effect of injection temperature

Injection temperature is another key operational parameter that affects the performance of EGS. This section investigates the impact of Cu-nanofluid on system performance as the injection temperature increases from 40 °C to 45 °C. In this study, the volume concentration of Cu nanoparticle is maintained at 3 %. Figure 7 shows the variation in production temperature under different injection temperatures when using nanofluids and water as working fluids. The results indicate that at lower injection temperatures, nanofluids can significantly improve production temperature. For example, when the injection temperature is 40 °C, the production temperature increases by approximately 17.12 °C; however, when the injection temperature rises to 50 °C, the increase drops to 16.05 °C. This phenomenon can be attributed to the fact that lower injection temperatures result in a larger temperature difference between the injected fluid and the geothermal reservoir, creating a stronger thermal gradient. In this scenario, nanofluids can enhance the formation and maintenance of the thermal gradient, thereby improving the efficiency of heat transfer and optimizing the performance of EGS.

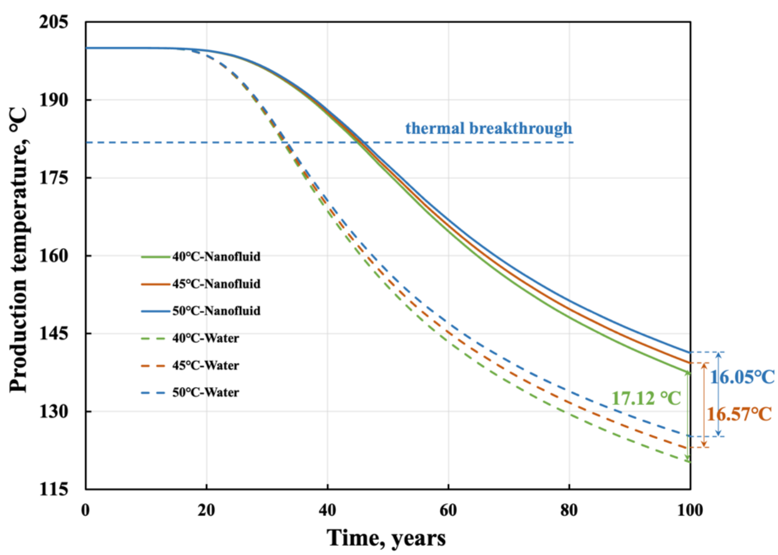

Figure 7: Effect of injection temperature fraction on production temperature.

4. CONCLUSION

This study investigates the effects of nanofluids on delaying thermal breakthrough and enhancing thermal extraction efficiency in EGS through numerical simulations. The following quantitative findings were obtained: adding different types of nanoparticles significantly improves the system's thermal extraction efficiency, with copper nanofluids showing the best performance. Due to their high thermal conductivity, copper nanofluids increase the heat transfer coefficient by nearly tenfold, extend the thermal breakthrough time from 35 years to 59 years, and raise the production temperature by approximately 26.32°C. When the nanoparticle volume fraction increases from 1% to 5%, the temperature gain rises from 5.86°C to 26.87°C, although the incremental benefit diminishes with further increases. Lower injection rates and lower injection temperatures further optimize system performance by extending residence time and strengthening the thermal gradient. At an injection rate of 5 kg/s, the temperature gain reaches 17.12°C, while at an injection temperature of 40°C, the temperature gain is approximately 17.12°C. These results demonstrate that the rational selection and optimization of nanoparticle types and concentrations can significantly enhance the thermal energy utilization efficiency of EGS, providing strong guidance for practical applications.

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