Development module of a geothermal reservoir in sedimentary rocks in Taiwan

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ABSTRACT

The purpose of this study is to build up a geothermal development module for the geothermal reservoir in sedimentary rocks in Taiwan. The sedimentary geothermal reservoir we targeted is a saline aquifer with a formation temperature above 147℃ in Taiwan's sedimentary basins. The geothermal gradient of the sedimentary basin in western Taiwan is above 3.5℃/100m. This makes the formation temperature higher than 130℃ at a depth of 3500 meters.

The reservoir simulation method is used in this study. We build up a natural-state geothermal reservoir model and then give a specific well design by considering the well replacement, well completion, production and injection rates, and the total simulation time. The basic design of the geothermal development module is using two horizontal production wells and one horizontal injection well with a horizontal section length longer than 1000 meters. The injection well is placed in the middle between them. The numerical calculation is conducted by the simulator STARS developed by CMG.

The efficiency of the geothermal development module is analyzed based on the running capacity calculation. The spatial distribution of the reservoir pressure, fluid flow, and temperature are analyzed. We use the pressure front to define the effective volume of the geothermal development module with specific well replacement and well completion designs. The injected water front is used to analyze the recirculation efficiency of the geothermal fluid. The cold front is used to define the optimal distance between the injection and production wells within an operation time period.

1. INTRODUCTION

The world currently relies heavily on fossil fuels for energy use. Fossil fuels are non-renewable, that means it is a finite energy resource. Most important, fossil fuel energy is not a clean energy resource and has environmental damaging. In contrast, renewable energy resources will never run out and is a clean source of energy. Renewable energy has a much lower environmental impact than the conventional fossil fuel energy.

Most renewable energy comes either directly or indirectly from the sun, such as solar, wind and biomass energies. Geothermal energy is different; it taps the Earth's internal heat. Geothermal energy is not intermittent like solar and wind power, this benefit makes geothermal energy can be used at any time and makes it fairly reliable to allows its use as a baseload power provider to the electrical grid. Besides electric power production, geothermal can be used for district heating, industrial heating and heat pumps. The use of geothermal energy is variety.

Taiwan is located at collision zone of the tectonic plate and belongs to the Pacific Fire Belt. Abundant geothermal energy is stored in the volcanic area in northern Taiwan and the metamorphic rock area in eastern Taiwan.

Currently, Taiwan possesses an approximate geothermal electrical capacity of 5 MW, predominantly situated within metamorphic rock geothermal areas. In the context of geothermal development in metamorphic rock areas, the presence of fault or fracture networks is of paramount importance.

In contrast, Taiwan's volcanic rock geothermal areas boast higher geothermal fluid temperatures compared to metamorphic rock regions. However, a prevailing drawback is the pronounced acidity of most geothermal fluids in these areas. This extreme acidity necessitates the usage of acid-resistant piping materials, incurring significant material costs that consequently dampen development efficacy. Recent initiatives have explored small-scale direct steam extraction for geothermal utilization. Nevertheless, the adoption of steam-based geothermal development remains relatively low, and the realization of scalable and widespread resource exploitation necessitates further validation over time.

The western Taiwan is mainly composed of sedimentary rocks which contain natural gas reservoirs. Taiwan has oil and gas development and drilled many oil and gas production wells in the western sedimentary rock area.

These wells are up to 3,000 meters to 5,000 meters long and have encountered formation temperatures of more than 120 degrees Celsius. The heat extracted from this low-enthalpy geothermal source, through flash-type geothermal power generators, could potentially become a valuable source of electricity generation.

This study draws upon the sedimentary rock geothermal development project conducted by DEEP, a prominent Canadian geothermal company positioned as a leading large-scale geothermal power producer in Canada. Within an area encompassing 39,120 hectares (approximately 100,000 acres), DEEP holds geothermal rights with an estimated geothermal power potential of 200 MW (DEEP Corp,2022). In the winter of 2019, DEEP successfully executed a production and injection cycle between producer and injector wells. Following the success of this loop test, DEEP drilled Canada's first-ever horizontal geothermal well, which reached a depth of 3,500 meters and extended horizontally for 2,000 meters (DEEP Corp,2022). This well was utilized to conduct a larger flow-rate loop test. The data obtained from this loop test were utilized to finalize reservoir information required for the feasibility report, as well as the

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ultimate design parameters for Canada's inaugural geothermal power plant.

There are about 400 of natural gas wells had drilled in western Taiwan. We believe that sedimentary rock from western Taiwan can provide heat and not oil for energy use. The geothermal gradient of the sedimentary basin in western Taiwan is above 3.5℃/100m. This makes the formation temperature higher than 147 ℃ at a depth of 3500 meters.

The purpose of this study is to build up a geothermal development module for the geothermal reservoir in sedimentary rocks in Taiwan. The sedimentary geothermal reservoir we targeted is a saline aquifer with a formation temperature above 130℃ in Taiwan's sedimentary basins.

2. METHODOLOGY

Geothermal reservoir development entails a complex engineering endeavor that necessitates consideration of intricate geological conditions, fluid flow phenomena within the reservoir, and dynamic variations induced during the development process. Given this complexity, geothermal numerical simulation methods have been employed since 1970 to comprehensively account for the collective impact of various physical, chemical, thermal, and flow properties within the geothermal system. These simulations are utilized to design or evaluate optimal development and production approaches.

Numerical simulation or reservoir simulation has evolved into an effective assessment tool for geothermal resource development and management. Geothermal numerical simulation primarily comprises two components: the mathematical model and the solution scheme (also known as the numerical scheme). In the mathematical model, a set of partial differential equations is constructed to describe fluid flow and energy transfer within the reservoir by utilizing principles of mass conservation, energy conservation, Darcy's law for fluid motion, equation of state, and related auxiliary equations. Appropriate boundary and initial conditions are applied to complete this model formulation.

Within the solution scheme (or numerical scheme), the partial differential equations describing fluid flow within the reservoir are discretized in both time and space. Spatial discretization involves partitioning the study area into grids, while time discretization involves segmenting the study period into time steps. The sizes of the grids and time steps are determined based on the research objectives.

In this study, the finite difference method was employed to establish a set of finite difference equations for pressure and temperature between grid nodes, which serves as a discretized approximation of the original partial differential equations. Subsequently, these finite difference equations were linearized. By incorporating the boundary conditions and initial conditions into the linear algebraic equations, an iterative approach was employed to solve for the solutions of the equations. This iterative process led to the determination of pressure and temperature distributions and their variations at different grid nodes and time intervals.

In the aspect of simulator utilization, this study employed the Steam Thermal Adaptive Reservoir Simulator (STARS) developed by Computer Modelling Group Ltd. (CMG) for conducting simulation investigations. The STARS simulator is designed to simulate multiphase fluid flow, heat conduction, geochemistry, and rock mechanics reactions within geothermal reservoirs. It comprehensively assesses the mass and heat transfer behaviors of geothermal reservoirs and is capable of simulating various production and injection scenarios for engineering design(CMG.2023b).

3. MODEL CONSTRUCTION

The process of constructing the numerical simulation model involves two main procedures. Firstly, under the geological conditions of the mining area, grid design is performed, and within each grid, various parameters of the geological formations, fluid phase properties, fluid-rock interactions, initial temperature and pressure conditions, are sequentially input to establish the geological model of the reservoir. Secondly, considering the positioning of geothermal production and reinjection wells, drilling patterns, determination of perforation depths and lengths, specifying production and injection rates, the numerical simulation model utilized in this study is finalized through the design of production and injection engineering scenarios.

The foundational model case of this study consists of a uniformly thick, homogeneous, and isotropic sandstone layer, with the top and bottom boundaries assumed to be impermeable shale layers with no flow. In terms of grid formulation, to facilitate a clearer observation of the interactive effects between wells in the J-direction, the number of grid cells in the J-direction is higher compared to the other two axes. The grid configuration is 40×99×5 (i×j×k), totaling 19,800 grid cells (Figure 1.).

To accommodate the lengths of the horizontal well segments adequately, the total length in the i-direction of the model is set to 4000 meters. In the j-direction, it is adjusted to accommodate the spacing between three wells, resulting in a total length of 4950 meters. For the k-direction of the model, corresponding to the overall thickness of the reservoir, a continuous sequence of 20-meter sandstone layers is defined.

In the sandstone layers, this study references domestic sedimentary rock core analyses to set the porosity of the sandstone layer at 20%. The permeability values are assumed to be 50 mD in all three directions due to the homogeneous and isotropic nature of the reservoir, based on the setting of the storage layer.

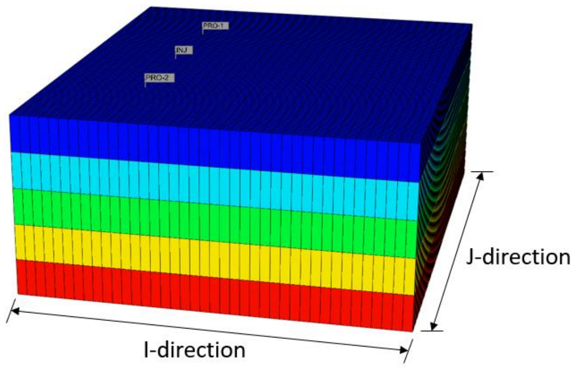


Figure 1: Model schematic diagram

The length of the horizontal well segment is set at 2000 meters. With the total length of the horizontal well not exceeding 6000 meters, the depth primarily ranges from 3000 meters to 4000 meters. Among these depths, 3500 meters is used as the top depth for the baseline case model.

The reservoir temperature is primarily governed by the geothermal gradient. Under the premise of a surface temperature of 25°C, the typical geothermal gradient for sedimentary rocks in Taiwan is approximately 3 to 3.5°C per 100 meters. In this study, the optimal value of 3.5°C per 100 meters was selected. With a model top depth of 3500 meters, the reservoir temperature is estimated to be approximately 147°C in Celsius.

In this study, the reservoir is assumed to be at a water saturation of 100%. The reservoir pressure is set to hydrostatic pressure, calculated at a rate of 1000 kPa per 100 meters. Therefore, at a model top depth of 3500 meters, the hydrostatic pressure in the model top is 35000 kPa.

The fluid within the reservoir is primarily formation water. Under normal temperature and pressure conditions, water has a viscosity of approximately 1 cP. However, in geothermal environments, elevated temperatures and pressures can lead to a reduction in fluid viscosity. In this study, the viscosity of the fluid, which is water, is set to 0.2 cP in the design, considering the high-temperature and high-pressure conditions.

Despite the elevated temperature and pressure conditions in geothermal environments, at a temperature of 150°C and a pressure of 35000 kPa, liquid water does not reach the vaporization point to become steam. Therefore, in terms of phase behavior, the water within the reservoir remains in the liquid state. The fluid compressibility of liquid water is set to 3×10^{-6} (1/kPa) in this study.

Table 1 *Initial Geological State Parameter Table of Base case*

Parameter	*units*	*Value*
Formation Top	m	3500
Thickness	m	20
Porosity		
Sand	frac	0.2
Permeability	mD	
Sand i-direction	mD	50
Sand j-direction	mD	50
Sand k-direction	mD	50
Formation initial pressure	kPa	35080
@ 3508m		
Formation temperature	°C	147.78
Water saturation	%	100
viscosity	cP	0.2

Moving on to wellbore design, this study employs a case of two producers and one injector. The injector well is positioned between the two producer wells, allowing the increased pressure from the injected water to simultaneously support the pressure depletion caused by pumping in the producer wells. The length of the horizontal wellbore segment is set at 2000 meters, with a spacing of 1200 meters between the wells. All three horizontal wells extend along the i-direction of the model, and their wellbore depths are centered within the reservoir.

The two producer wells have equal production rates, both operating at 4000 m3/day, while the injector well has an injection rate of 8000 m3/day. The temperature of the injected water decreases due to power generation, and thus the injection temperature is set at 75°C.

According to Taiwanese regulations, the operating lifespan of a geothermal power plant is 20 years. Therefore, the simulation covers a total period of 20 years, with data generated daily during the initial month and subsequently on a monthly basis.

4. RESULTS

Figure 2 illustrates the variations in production rates over time for the two producer wells and the injector well. In conventional oil and gas production processes, pressure decline often leads to a reduction in production rates. However, the horizontal wellbore segments in horizontal wells effectively mitigate pressure changes caused by significant water extraction and injection. Therefore, it can be observed that over the 20-year power generation period, production rates remain stable under the condition of minimal pressure fluctuations.

Figures 2 (a)(b) display the variations in bottomhole pressures over the 20-year production period for the producer wells and injector well. Notably, in Figure 3, it is evident that in the case of the producer wells, rapid pressure decline occurs initially due to the substantial fluid extraction, before the pressure support from the injector well has fully propagated. However, subsequent to the pressure augmentation from injection, a gradual equilibrium between the two pressures is achieved, marking the onset of a stable production phase.

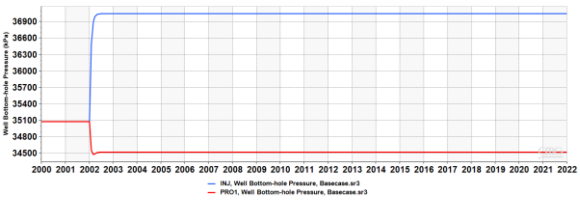
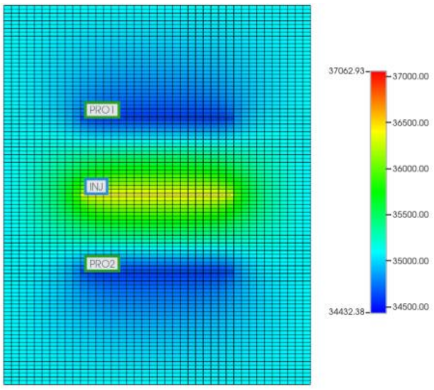
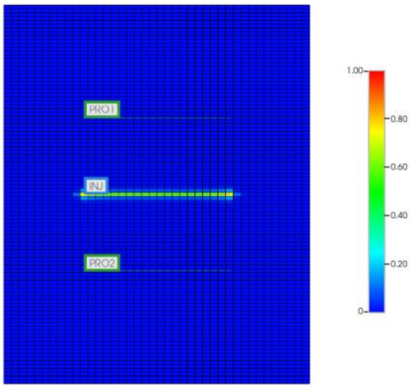


Figure 2: (a) Injection & Production Well's Bottomhole Pressure vs. Time

To delineate the modular scope more comprehensively, this study examines horizontal well production and injection behaviors from three distinct perspectives regarding the propagation speeds of pressure peaks, water peaks, and temperature peaks. The results, as depicted in Figure 2, illustrate the distribution scenarios. Figures 3(a)(b)(c) present the distribution after one month of production initiation. Among the three factors, pressure peaks exhibit the fastest propagation speed, followed by water peaks, while temperature peaks display the slowest progression. On the other hand, Figures 3(d)(e)(f) showcase the distribution one year into production. As indicated by Figures 2, due to the relatively swift pressure equilibrium between producer and injector wells, there is no significant alteration in pressure distribution over time. Meanwhile, the influence of water and temperature peaks gradually expands outward with time. However, in terms of propagation, the order remains consistent: pressure peaks propagate the fastest, followed by water peaks, and temperature peaks propagate the slowest.



(a)



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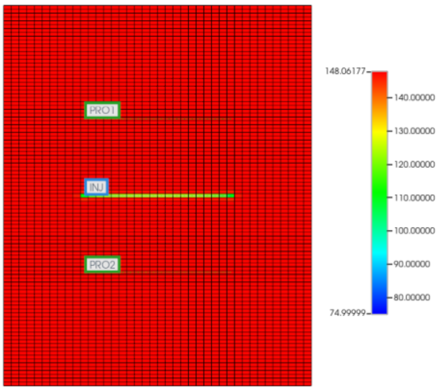
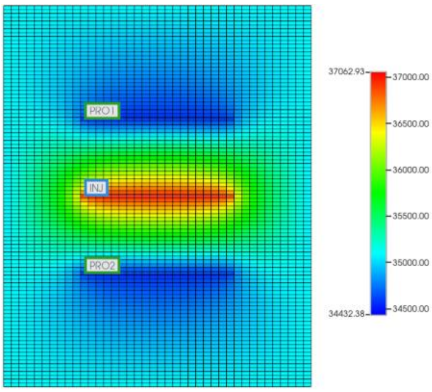
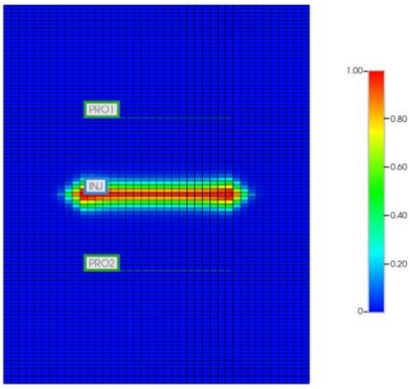


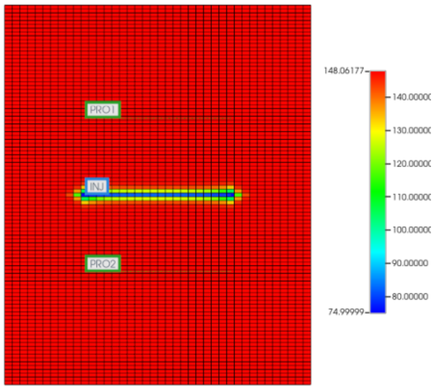
(c)



(d)



(e)



(f)

Figure 3: (a) Pressure front (For a Month) (b) Water front (For a month) (c) Thermal front (For a month) (d) Pressure front (For a year) (e) Water front (For a year) (f) Thermal front (For a year)

In terms of facility capacity, this case follows a dual-production and single-injection well configuration. Given that the production rates from the two producer wells are equal, the formula for the facility capacity of a single producer well is as follows:

$$W = \dot{m} \cdot h \cdot \eta \cdot \frac{1}{3600} \quad (1)$$

Where, W represents the facility capacity (MW); $\dot{m}$ denotes the production rate (m^3/hr); h signifies the fluid enthalpy (kJ/kg); and η represents the energy conversion efficiency (assumed to be 10% in this study).

By utilizing Equation (1) for computation, the facility capacity of a single producer well is determined to be 2.4 MW. Under the configuration of dual-production and single-injection wells, the total achievable facility capacity amounts to 4.8 MW.

5. DISCUSSION

Permeability refers to the capacity of rocks or rock formations to allow fluid flow. In the context of geothermal production and injection operations, permeability plays a crucial role in determining changes in reservoir pressure. As evident from the table 2, regardless of the magnitude of permeability, the trajectory of the temperature peak remains consistent with the baseline case. The key differences lie in the pressure variations of the injection and production wells. Given the configuration of dual-production and single-injection wells, the focus primarily shifts to the pressure changes in the injection well. Excessive pressure variations can lead to rock fracturing, thus evaluating the reservoir's ability to withstand pressure changes becomes a critical aspect of stable production.

This study sets limitations on the pressure changes that the reservoir can tolerate and still maintain stable production. Specifically, the cold-water peak cannot surpass the production well, and the pressure change at the injection well over the 20-year span cannot exceed 20%. The table above indicates that permeability does not directly impact the progression of temperature peaks. Consequently, it does not exert a direct influence on facility capacity. However, in cases of excessively low permeability within the reservoir, rapid pressure accumulation can occur, thereby affecting the stability of production.

Table 2 *Permeability sensitivity analysis (after 20 years)*

	-50%	-25%	Base	25%	50%
k(mD)	25	37.5	50	62.5	75
Formation top(m)	3500	3500	3500	3500	3500
T(℃)	147.78	147.78	147.78	147.78	147.78
Thickness (m)	20	20	20	20	20
Porosity	0.2	0.2	0.2	0.2	0.2
Depth - Length(m)	3508-2000	3508-2000	3508-2000	3508-2000	3508-2000
Injection (m^3/day)	6800	8000	8000	8000	8000
ΔP(%)	20.0	15.8	12.0	9.6	8.0
Enthalpy (kJ/kg)	517.73	517.73	517.73	517.73	517.73
MW(total)	4.07	4.793	4.793	4.793	4.793
ΔMW(%)	-15.1	0.0	0.0	0.0	0.0

Reservoir thickness refers to the desired thickness of the target sandstone reservoir in geothermal development, with continuous sandstone often yielding the best results. As indicated in the table 3, under the same conditions (20-year span, temperature peak approaching the production well, and pressure variation not exceeding 20%), a thicker reservoir thickness can accommodate larger production rates and consequently lead to higher facility capacity. This parameter is a crucial aspect in the assessment of sedimentary rock geothermal systems and plays a significant role in determining their potential for optimal performance.

Table 3 *Thickness sensitivity analysis (after 20 years)*

	-50%	-25%	base	25%	50%
Thickness (m)	10	15	20	25	30
Formation top(m)	3500	3500	3500	3500	3500
T(℃)	147.78	147.78	147.78	147.78	147.78
k(mD)	50	50	50	50	50
Porosity	0.2	0.2	0.2	0.2	0.2
Depth-Length(m)	3508-2000	3508-2000	3508-2000	3508-2000	3508-2000
Injection (m^3/day)	4000	6000	8000	10000	12000
ΔP(%)	11.8	11.9	12.0	11.7	11.9
Enthalpy (kJ/kg)	517.13	517.43	517.73	518.03	518.34
MW(total)	2.394	3.593	4.793	5.995	7.199
ΔMW(%)	-50.1	-25.0	0.0	25.1	50.2

Reservoir temperature is closely related to the geothermal gradient of sedimentary rocks, and temperature directly impacts the magnitude of enthalpy contained within geothermal fluids. Interestingly, even if the reservoir temperature is elevated, it does not slow down the progression of thermal front. Therefore, it does not directly increase production rates. However, under the same conditions, a higher reservoir temperature naturally results in a higher facility capacity. Hence, reservoir temperature stands as a crucial geological parameter in geothermal development, as demonstrated in table 4.

Table 4 *Reservoir temperature sensitivity analysis (after 20 years)*

	-50%	-25%	base	25%	50%
T(℃)	86.39	117.08	147.78	178.48	209.17
Formation top(m)	3500	3500	3500	3500	3500
Thickness (m)	20	20	20	20	20
k(mD)	50	50	50	50	50
Porosity	0.2	0.2	0.2	0.2	0.2
Depth - Length(m)	3508-2000	3508-2000	3508-2000	3508-2000	3508-2000
Injection (m^3/day)	8000	8000	8000	8000	8000
ΔP(%)	11.8	11.9	12.0	12.0	11.9
Enthalpy (kJ/kg)	256.85	386.44	517.73	651.61	789.10
MW(total)	2.378	3.578	4.793	6.033	7.306
ΔMW(%)	-50.4	-25.3	0.0	25.9	52.4

Porosity is a measure of the proportion of void spaces within rocks or soils to the total volume. In the context of a fixed-rate injection well, the concept of water displacement is akin to filling all the available pores in its path before progressing further. The principle behind porosity is similar to that of reservoir thickness, both representing the potential capacity of the formation to accommodate water. Therefore, a higher porosity implies that each displacement takes longer (even if permeability represents the fluid's flow capacity). Despite a smaller permeability, under fixed injection conditions, the water displacement rate remains unhindered due to artificial pressure, enabling rapid displacement of a fixed water volume. However, lower flow capacity results in quicker pressure buildup. Consequently, the propagation of temperature peaks also slows down, allowing for the injection and extraction of greater volumes of water over the 20-year period. Such characteristics underscore the significance of porosity as a pivotal geological parameter in geothermal development, as exemplified in table 5.

Table 5 *Porosity sensitivity analysis (after 20 years)*

	-50%	-25%	base	25%	50%
Porosity	0.1	0.15	0.2	0.25	0.3
Formation top(m)	3500	3500	3500	3500	3500
Thickness (m)	20	20	20	20	20
k(mD)	50	50	50	50	50
T(℃)	147.78	147.78	147.78	147.78	147.78
Depth-Length(m)	3508-2000	3508-2000	3508-2000	3508-2000	3508-2000
Injection (m^3/day)	7000	7500	8000	8500	9000
ΔP(%)	10.6	11.2	12.0.	12.7	13.4
Enthalpy (kJ/kg)	517.73	517.73	517.73	517.73	517.73
MW(total)	4.195	4.494	4.793	5.093	5.393
ΔMW(%)	-12.5	-8.8	0.0	6.3	12.5

The concept of wellbore length is analogous to that of reservoir temperature, differing in that depth determines temperature variations. Under a constant geothermal gradient conditions, deeper positions within the reservoir naturally receive higher geothermal fluid temperatures. This phenomenon contributes to the potential enhancement of power generation capacity, as illustrated in table 6. However, in current horizontal drilling techniques, longer wellbore lengths entail significant drilling costs and associated risks, thereby connecting wellbore length requirements and desired device capacity.

An interesting observation from this table is that in shallower depths, the same injection volume leads to varying changes in injection well pressure. This could be attributed to lower static water pressure in shallower formations. Consequently, in shallower formations, the pressure changes resulting from injecting the same volume of water are more pronounced. In contrast, in deeper formations, where higher static water pressure already exists, injecting the same volume of water may not yield such significant pressure variations. However, this also implies that for shallower geothermal development, the quantity of injected water needs to be re-evaluated, as it cannot be assumed to follow the same principles as deep sedimentary rock geothermal development.

Table 6 *Well depth & Well length sensitivity analysis (after 20 years)*

	-50%	-25%	base	25%	50%
Depth-Length(m)	1758-2000	2633-2000	3508-2000	4383-2000	5258-2000
Formation top(m)	1750	2625	3500	4375	5250
Thickness (m)	20	20	20	20	20
k(mD)	50	50	50	50	50
T(℃)	86.53	117.15	147.78	178.41	209.03
Porosity	0.2	0.2	0.2	0.2	0.2
Injection (m^3/day)	6400	8000	8000	8000	8000
ΔP(%)	20.0	16.3	12.0	11.6	11.5
Enthalpy (kJ/kg)	257.44	386.74	517.73	651.30	788.46
MW(total)	1.906	3.580	4.793	6.030	7.300
ΔMW(%)	-60.2	-25.3	0.0	25.8	52.3

6. CONCLUSION

1. This study employs a simple homogeneous and isotropic three-dimensional model to simulate the distribution of pressure peaks, water peaks, and temperature peaks during the production of sedimentary rock geothermal resources. The results reveal that the pressure peak propagates the fastest, followed by the water peak, with the temperature peak exhibiting the slowest progression.

2. Without considering costs, the geothermal potential of sedimentary rock may not necessarily be lower than that of traditional metamorphic rock geothermal resources.

3. For sedimentary rock geothermal resources, reservoir temperature and reservoir thickness are critical factors influencing power generation efficiency and the feasibility of geothermal power generation.

4. Permeability can lead to pressure accumulation issues in sedimentary rock geothermal development. While it may not have a direct impact on production rates, it is a crucial factor for engineering feasibility in this context.

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