Numerical simulation of thermo-hydro-mechanical coupling effect in mining fault-mode hot dry rock geothermal energy

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Introduction

Introduction

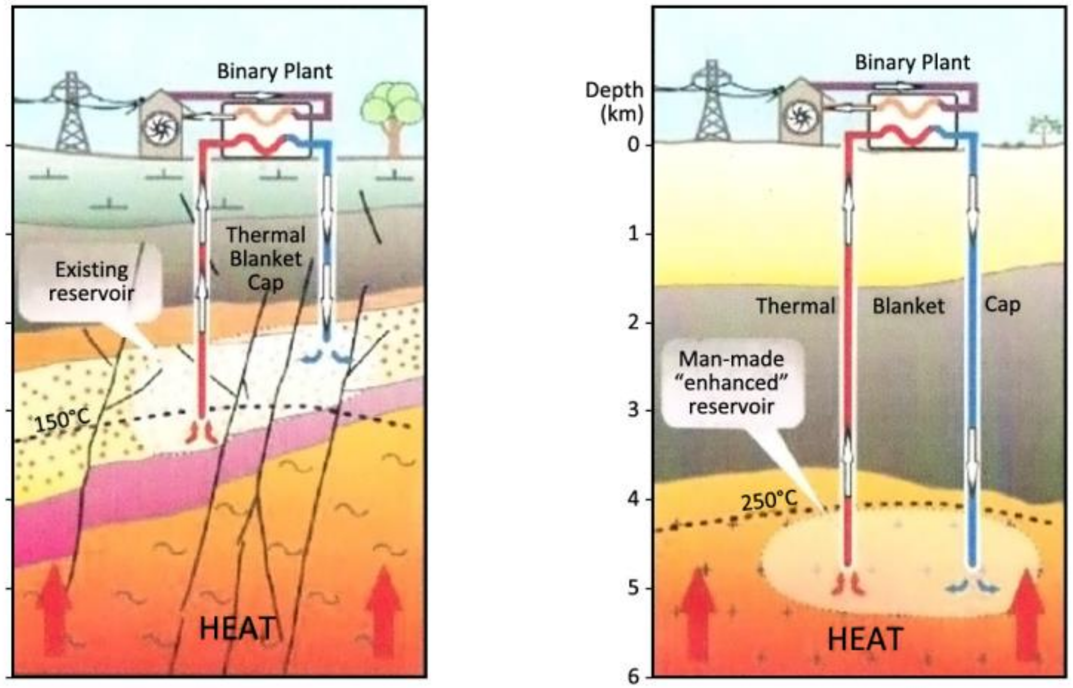
a) Hot dry rock geothermal energy is a type of renewable energy with great development prospects in deep strata. However, it is quite difficult to construct an artificial reservoir.

b) In this paper, deep large-dip-angle fault zone in the Yangbajing geothermal field in Tibet of China is used as a natural reservoir, and a set of hot dry rock heat extraction schemes for such fault modes is proposed.

c) A three-dimensional thermo-hydro-mechanical coupling model is established for the scheme to study the distributions of temperature, stress and seepage during the process of mining fault-mode hot dry rock geothermal energy.

Geothermal resource types

Hydrothermal | **Petrothermal**



Heat carrier (steam/hot water) at depth is locally present
→ rather rare

Heat carrier must be artificially circulated to extract heat
→ in principle ubiquitous

HDR geothermal reservoir

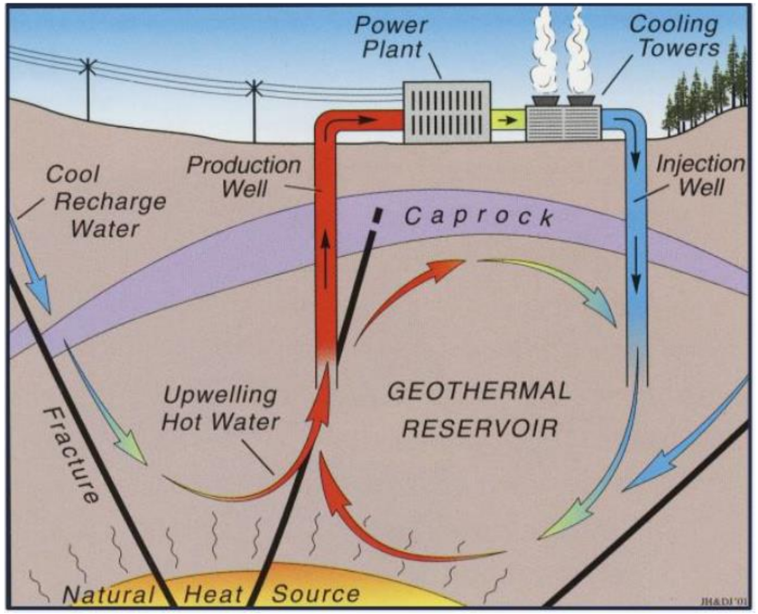
✓ Fractures play a significant role in the storage of geothermal fluids and dominate the fluid flow.

Rybach et al., 2014

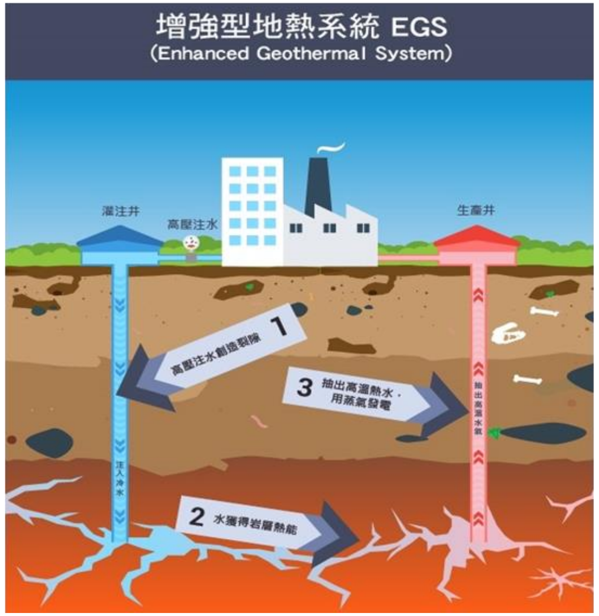
CGS & EGS

- Conventional geothermal system (CGS)
- Enhanced geothermal system (EGS)

▶ CGS



▶ EGS



◆ A certain rock-fracturing technology such as hydraulic stimulation is used to create an artificial heat reservoir, and then heat transmission fluids are circulated through the aperture networks to extract heat for earth-surface thermal and power generation utilizations.

Introduction

- Objective

In 2012, Zhao and Feng proposed “The geothermal development of the HDR in fault mode” scheme and a specific implementation plan for the HDR geothermal field in Yangbajing, Tibet, China. The core of the scheme is to use the natural fault zone commonly found in the surrounding rock of HDR geothermal reservoirs for geothermal development, which is regarded as one of the most attractive new technical schemes for HDR geothermal development.

In this study, a three-dimensional THM coupling model is established to simulate the extraction of HDR geothermal energy in a fault mode.

Methodology

Assumptions

- To grasp the core scientific patterns of the geothermal development of HDR and make calculations as simple as possible, the following basic assumptions are proposed to establish the mathematical model in this study.

1. The rock mass structure is composed of rock mass with faults and a matrix rock block without faults.
2. Compared with those of rock masses with faults, the water storage and water permeability of matrix rock blocks are very weak; thus, these factors can be neglected in the mathematical model.

Assumptions

3. The seepage of water in faults complies with Darcy's pattern.
4. Under high-temperature and high-pressure conditions, it is assumed that the water does not evaporate; that is, the rock mass is saturated with single-phase water.
5. Both the rock mass with faults and the matrix rock without faults comply with the thermoelastic constitutive pattern.
6. Water density is a function of temperature and pressure.
7. Rock masses transfer heat through both conduction and convection, and radiative heat transfer is ignored.

Mathematical model

- Governing equations

Based on the abovementioned assumptions, the mathematical model of THM coupling is established as follows:

✓ Rock mass solid deformation equation:

$$(\lambda+\mu)U_{j,ji}+\mu U_{i,jj}+F_i-\beta_r T_{,i}=0$$

U Solid displacement
F_i Applied to rock mass body force
β_r Rock linear thermal expansion

✓ Matrix rock block temperature field equation:

$$c_r\rho_r\frac{\partial T}{\partial t}=\lambda_r\nabla^2 T+W$$

c_r Specific heat of the rock
ρ_r Density of rock
λ_r Heat conductivity

Mathematical model

- Governing equations
  - ✓ Rock mass with fault temperature field equation:

$$c_r \rho_r \frac{\partial T}{\partial t} = \lambda_r \nabla^2 T - c_w \left(\rho_w k_{fi} h_{,i} T \right)_{,i}$$

ρ_w density of water

c_w specific heat of water

  - ✓ Rock mass with fault water seepage equation:

$$\mathrm{div}(\rho_w q_i) + \varphi \beta_w \rho_w \frac{\partial h}{\partial t} = 0 \qquad q_i = -k_{fi} \frac{\partial h}{\partial s_i}$$

ϕ fault porosity

β_w water compressibility

Table 2
Physical parameters of the rock mass.

Parameter	Unit	Matrix rock block	Fault rock mass	Water
Storage	–	1.0×10^{-8}	1.0×10^{-7}	–
Density	kg m^{-3}	2.4×10^{3}	2.4×10^{3}	1.0×10^{3}
Young's modulus	MPa	1.0×10^{4}	1.0×10^{4}	–
Poisson's ratio	–	0.3	0.3	–
Heat conductivity	W m^{-1} $°C^{-1}$	3.2	3.2	2.58
Heat capacity	J kg^{-1} $°C^{-1}$	1.08×10^{3}	1.08×10^{3}	4.05×10^{3}
Thermal expansion Coefficient	$°C^{-1}$	1.0×10^{-6}	1.0×10^{-6}	–
Permeability	m s^{-1}	5.0×10^{-12}	The horizontal direction: 0.005 exp $(-0.025\|\Theta\|)$ The vertical direction: 5.0×10^{-7} exp $(-0.025\|\Theta\|)\Theta$ represents volume stress, MPa	–

Model setting

Geometry

- The model is simplified as a 3 km × 15 km × 15 km cubic model.
- The upper boundary of the model is the ground, the fault thickness is 1.5 km, and the fault dip angle is 18°.
- The coordinates are (0 m, 7500 m, 5500-15000 m), (0 m, 3000 m, 7000-15000 m) and (0 m, 4500 m, 6500-15000 m) for the injection well, #1 production well and #2 production well, respectively.

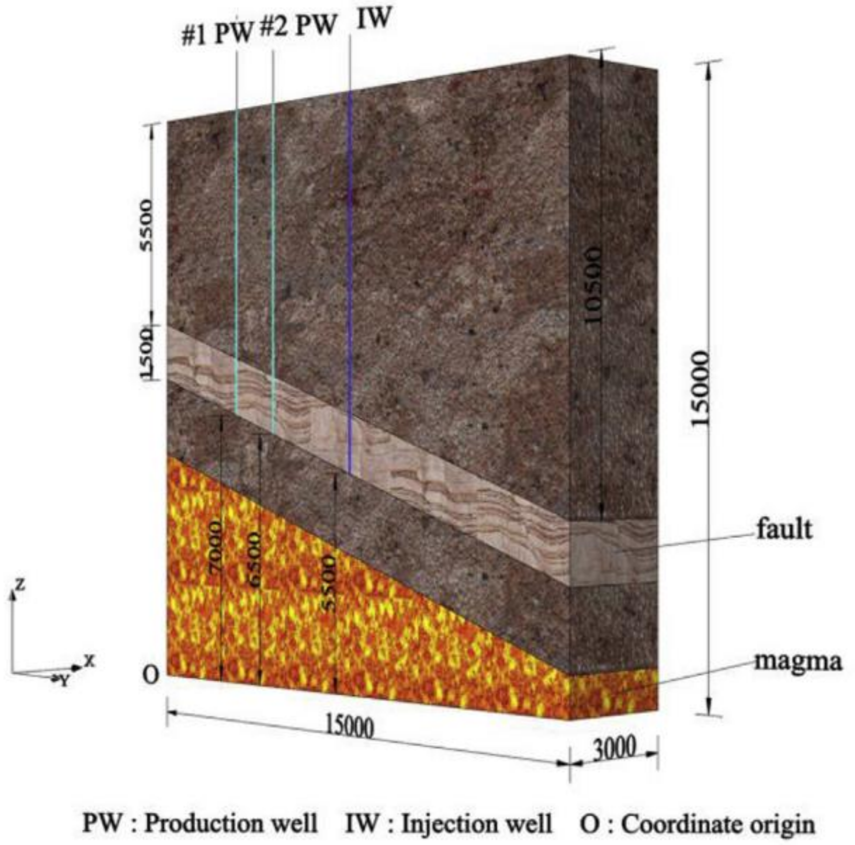


Fig. 3. Simplified three-dimensional model dimensions and coordinates of the HDR geothermal energy extraction system in the fault model.

Boundary & Initial conditions

- Solid stress field
  - ✓ Among the six boundaries, the surface boundary is considered a free boundary, while the remaining boundaries are specified as displacement constraints.
- Temperature field
  - ✓ The temperature of the magma sac is fixed at 550 °C, the temperature of the ground is fixed at 10 °C, the temperature of the injection well is fixed at 10 °C.
  - ✓ The four surrounding boundaries are set as adiabatic boundaries.

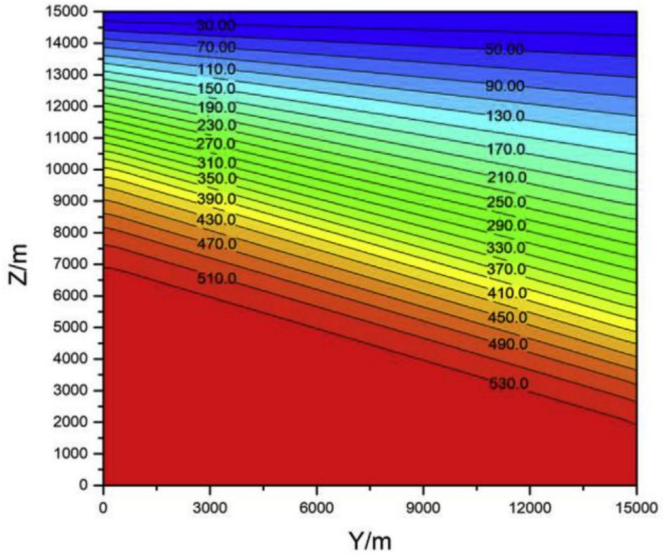


Fig. 4. Initial temperature field of the formation.

Boundary & Initial conditions

- Seepage field
  - ✓ The initial formation pressure is 0.1 MPa, the injection well pressure is fixed at 250 MPa, the production well pressure is fixed at 10 MPa.
  - ✓ The four surrounding boundaries are set as impervious boundaries.

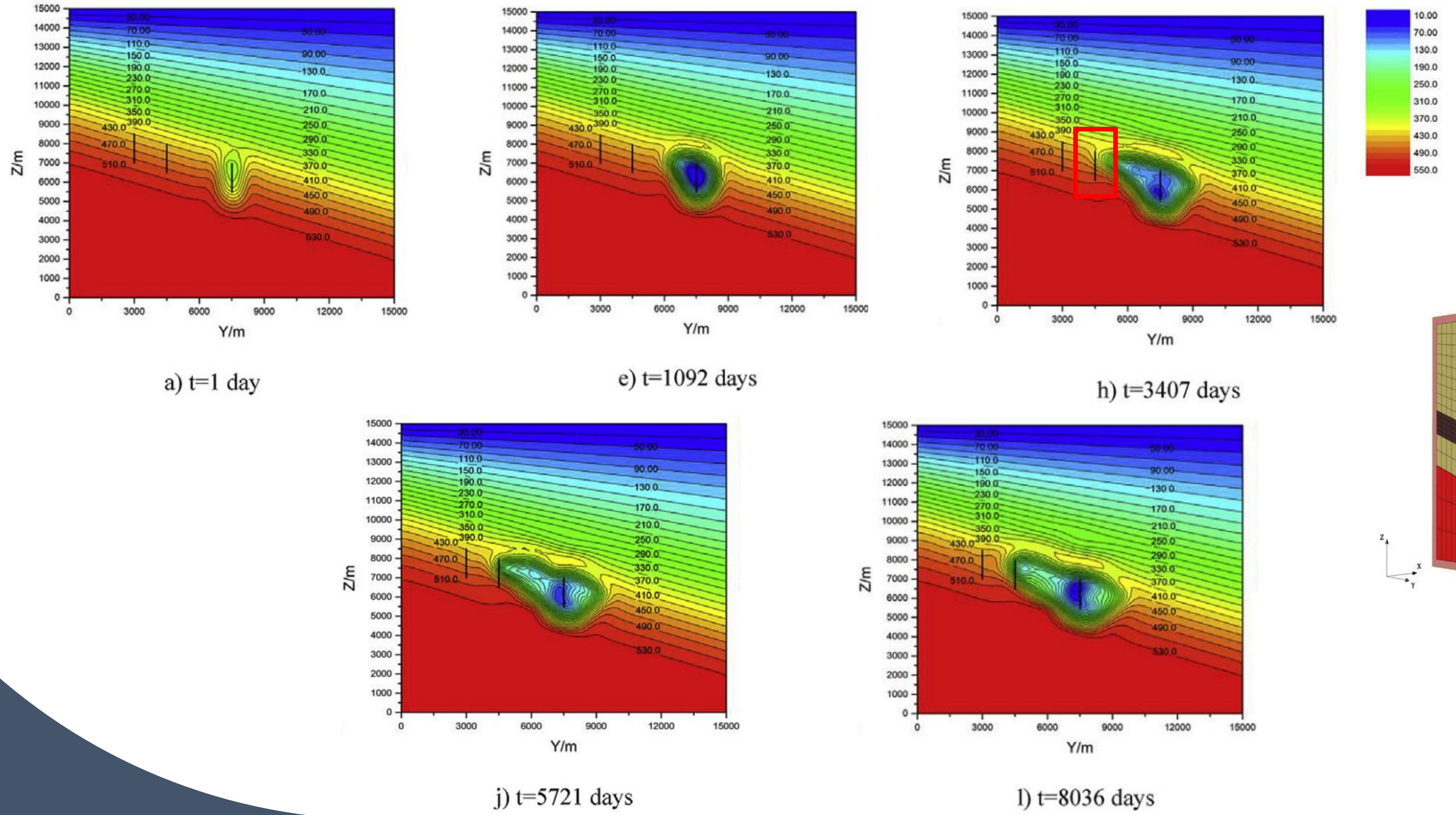
Table 1
Boundary and initial conditions of the computing model.

Items	Boundary	Boundary and initial conditions
Solid deformation	Z = 0 bottom surface	Uz = 0 first-type boundary
	Z = 15000 m roof surface	free boundary with zero stress
	X = 0 before surface	Ux = 0 first-type boundary
	X = 3000 m behind surface	Ux = 0 first-type boundary
	Y = 0 left surface	Uy = 0 first-type boundary
	Y = 15000 m right surface	Uy = 0 first-type boundary
	All points	$\sigma_z(t) = \gamma h$, $\sigma_x(t) = \sigma_y(t) = \nu/(1-\nu)\gamma(15000-z)$, t = 0
Temperature	All points	As shown in Fig. 4
	Injection well	T(t) = 10 °C, $0 \le t < \infty$
	Magma sac	T(t) = 550 °C, $0 \le t < \infty$
	Ground	T(t) = 10 °C, $0 \le t < \infty$
	X = 0 before surface	q(t) = 0 adiabatic, $0 \le t < \infty$
	X = 3000 m behind surface	q(t) = 0 adiabatic, $0 \le t < \infty$
	Y = 0 left surface	q(t) = 0 adiabatic, $0 \le t < \infty$
	Y = 15000 m right surface	q(t) = 0 adiabatic, $0 \le t < \infty$
Seepage	All of the points	p(t) = 0.1 MPa, t = 0
	Injection well	p(t) = 250 MPa, $0 \le t < \infty$
	Production well	p(t) = 10 MPa, $0 \le t < \infty$
	X = 0 before surface	q(t) = 0 impervious, $0 \le t < \infty$
	X = 3000 m behind surface	q(t) = 0 impervious, $0 \le t < \infty$
	Y = 0 left surface	q(t) = 0 impervious, $0 \le t < \infty$
	Y = 15000 m right surface	q(t) = 0 impervious, $0 \le t < \infty$

Results

◆ Variation of temperature field

Fig. 8. Temperature (unit: °C) distribution on the vertical profile of X = 50 m.



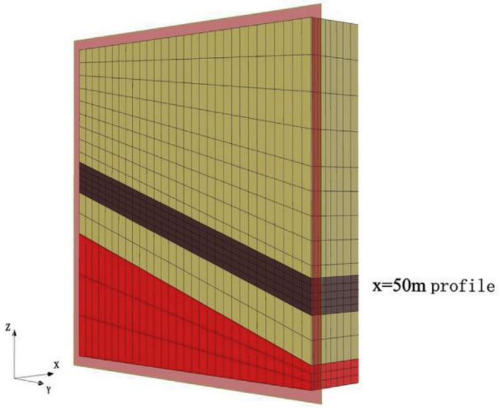


Fig. 6. X = 50 m profile diagram.

◆ Variation of temperature field

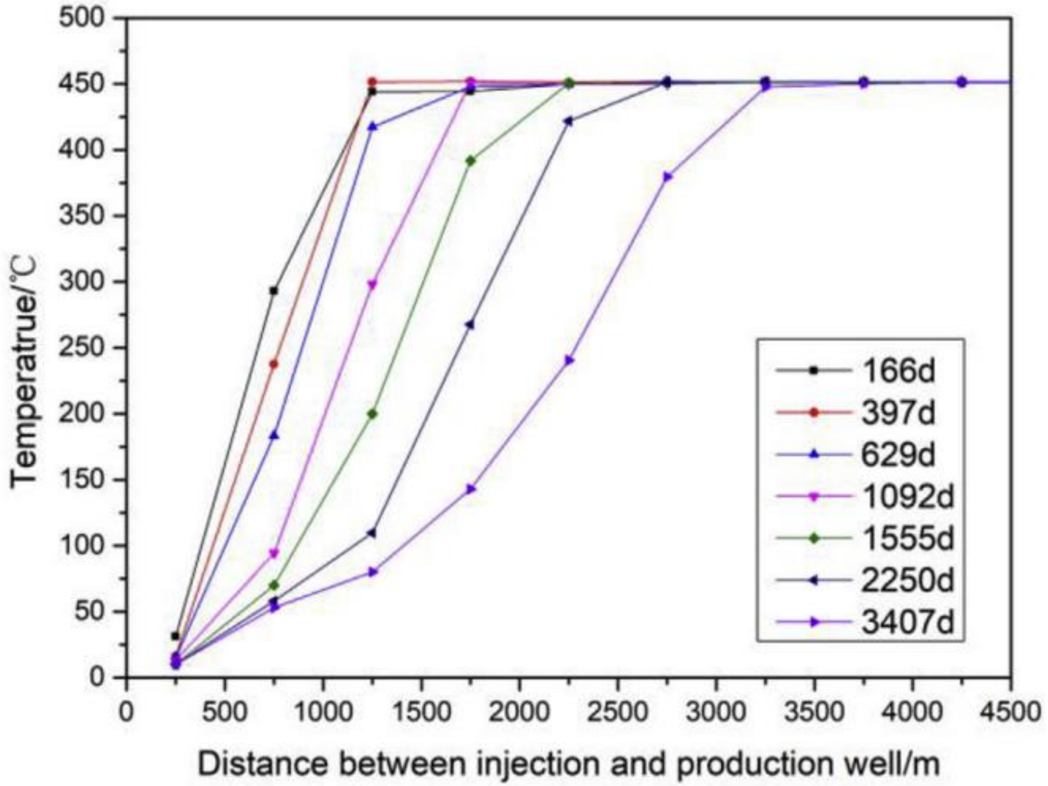


Fig. 9. Variation in temperature between drilling wells.

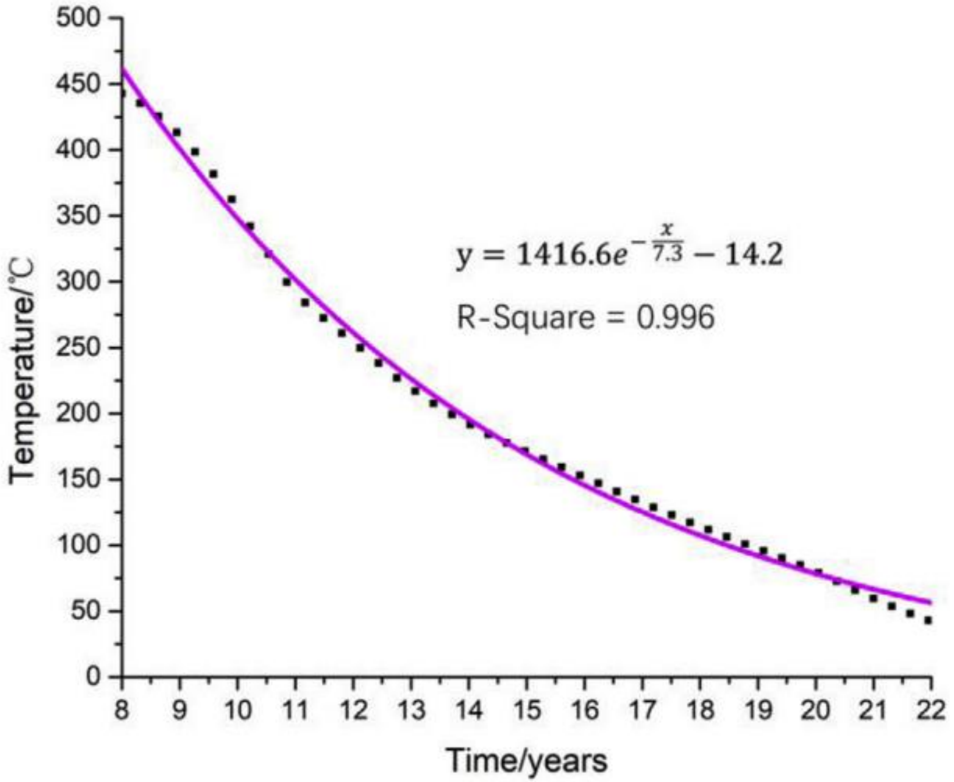
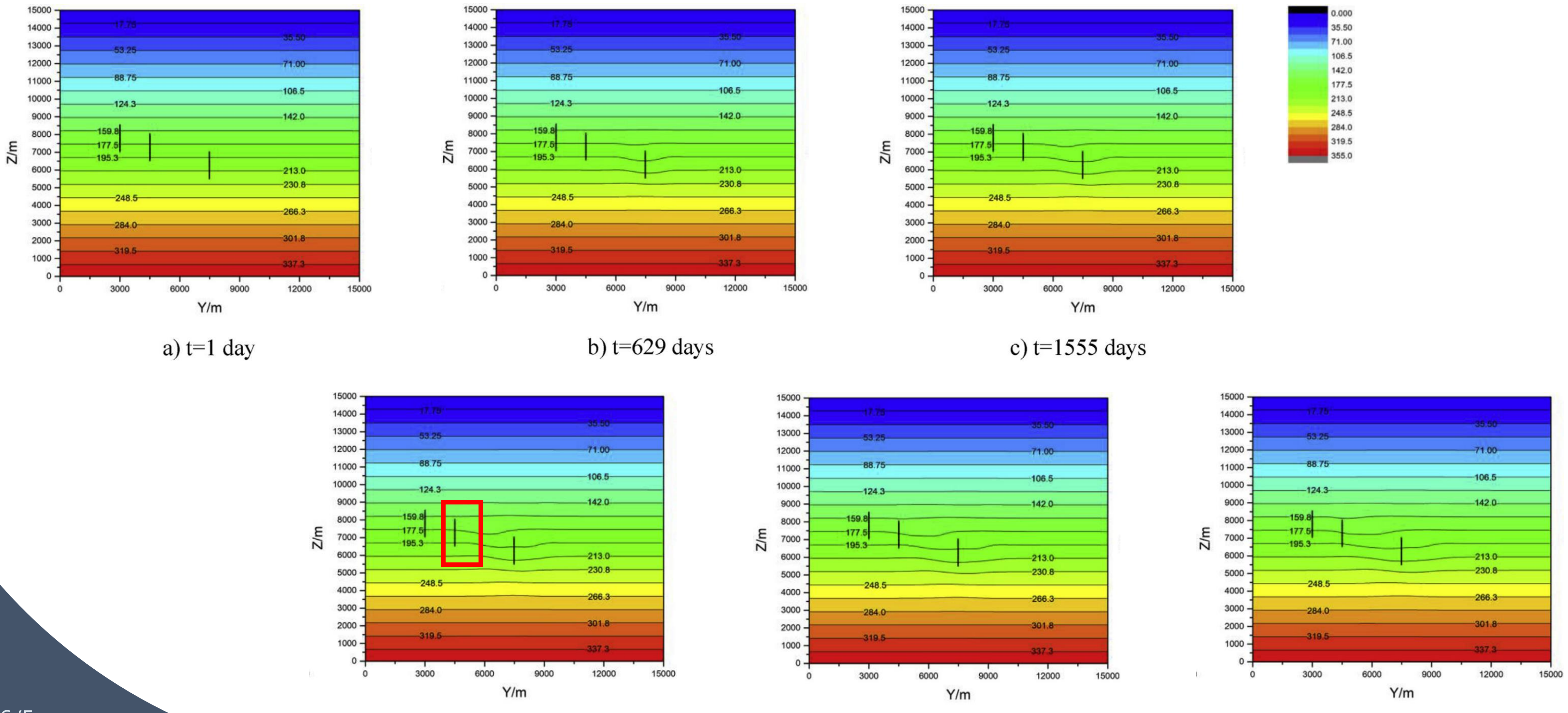


Fig. 10. Temperature variation in the #2 production well after 8 years.

◆ Variation of solid deformation field

Fig. 12. Stress (unit: MPa) distribution along the vertical profile of X = 50 m.



a) t=1 day

b) t=629 days

c) t=1555 days

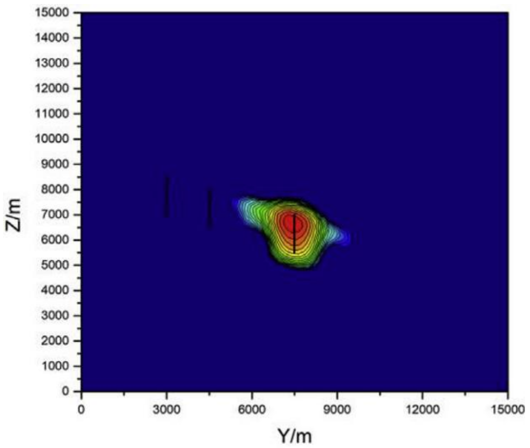
d) t=3407 days

e) t=5721 days

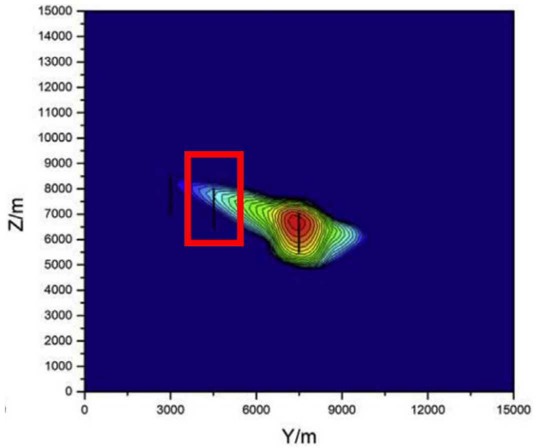
f) t=8036 days

◆ Variation of seepage field

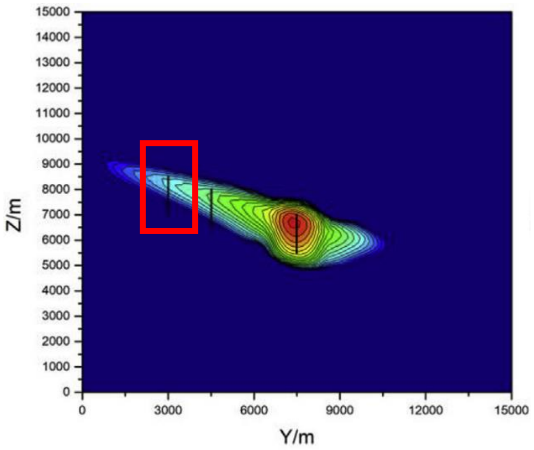
Fig. 15. Specific water flow (unit: $cm^3/cm^2/s$) distribution on the vertical profile of X = 50 m.



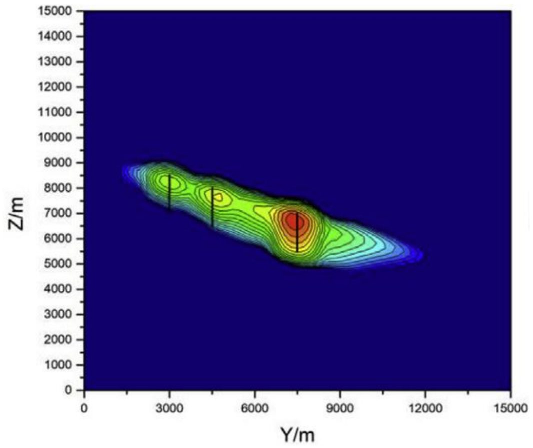
a) t=50 days



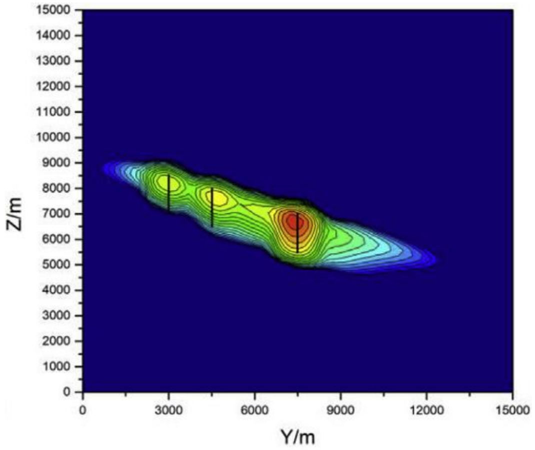
b) t=166 days



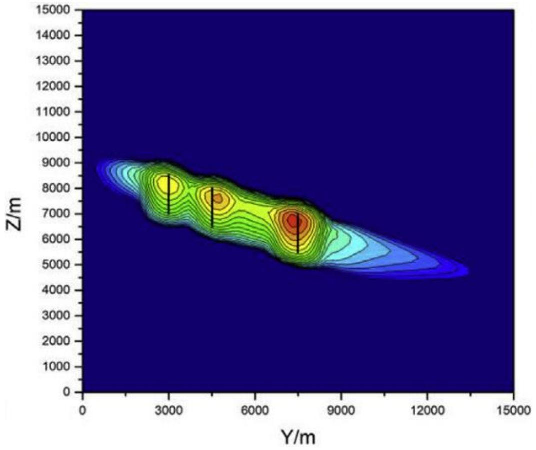
c) t=397 days



e) t=1555 days



f) t=3407 days



h) t=8036 days

◆ Output & Lifespan

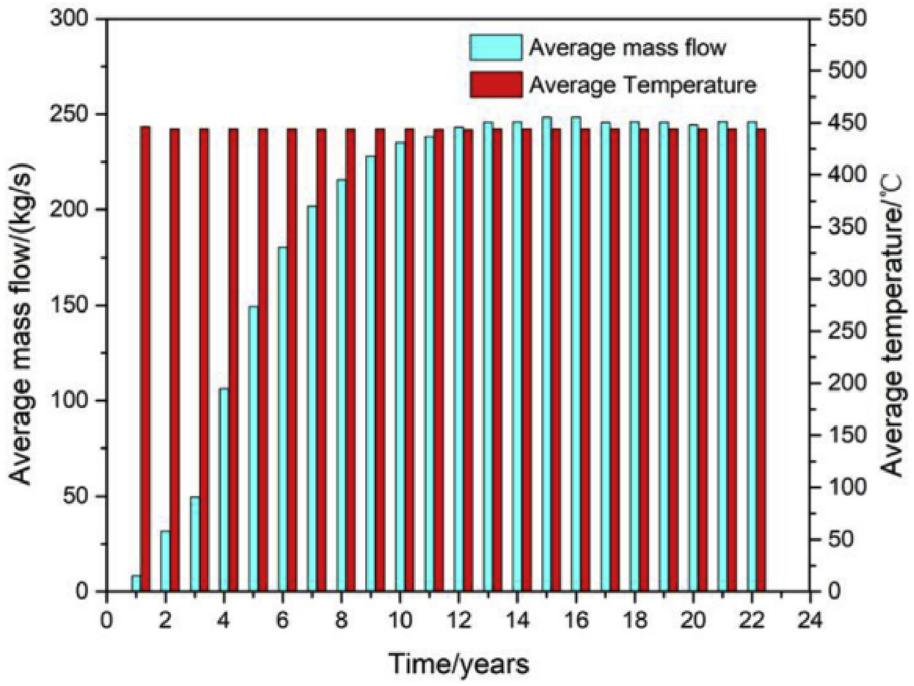


Fig. 23. Average mass flow and temperature of the change in the #1 production well over time.

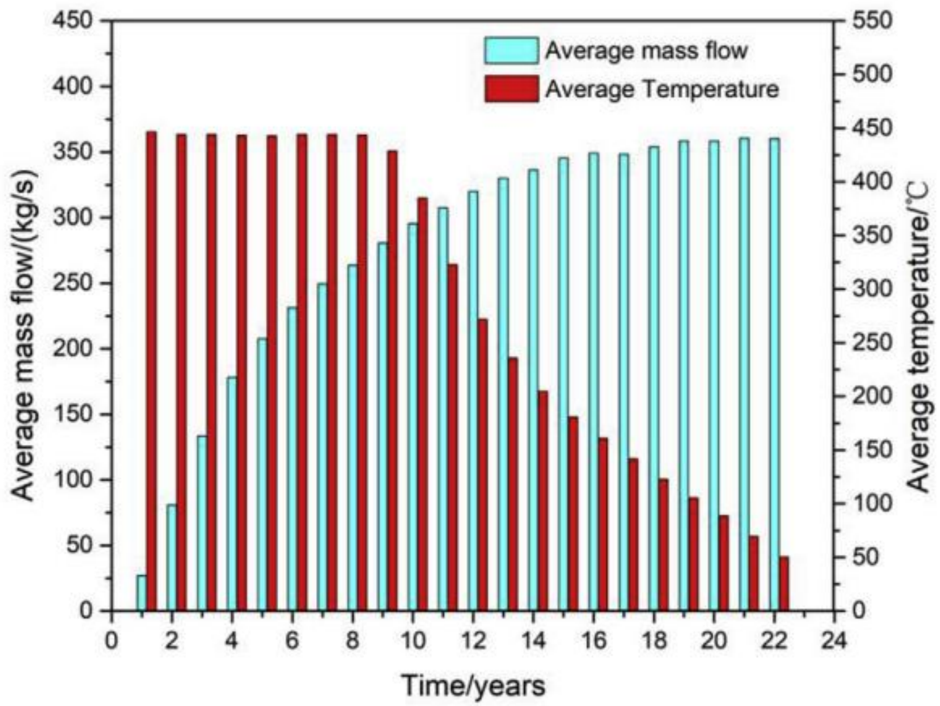


Fig. 24. Average mass flow and temperature of the change in #2 production well over time.

◆ Output & Lifespan

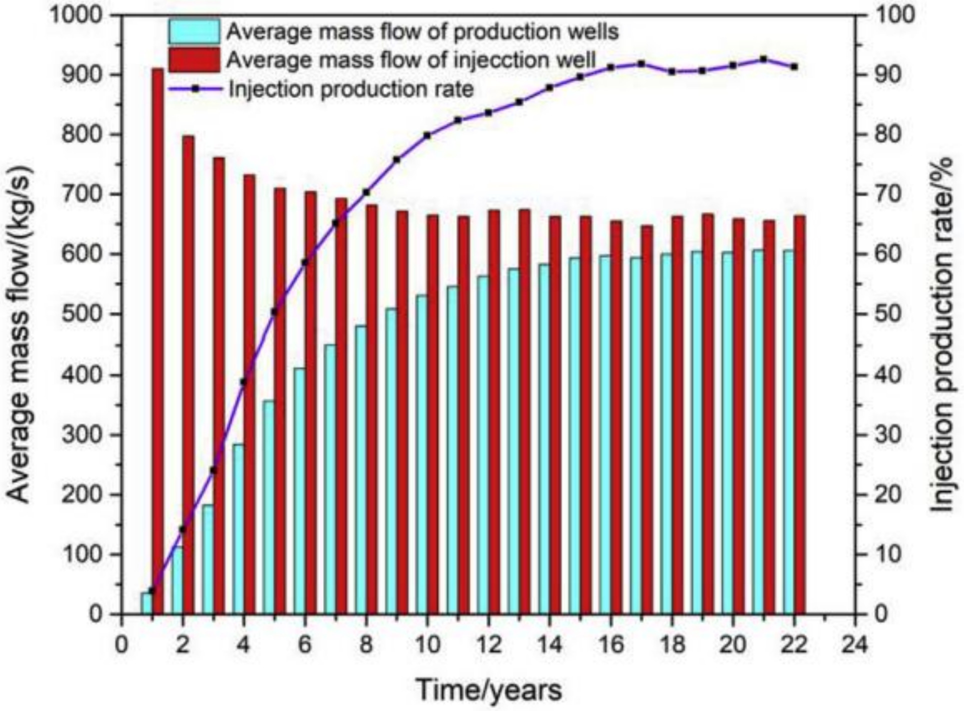


Fig. 25. Average mass flow rate of production and injection wells and injection-production rate change over time.

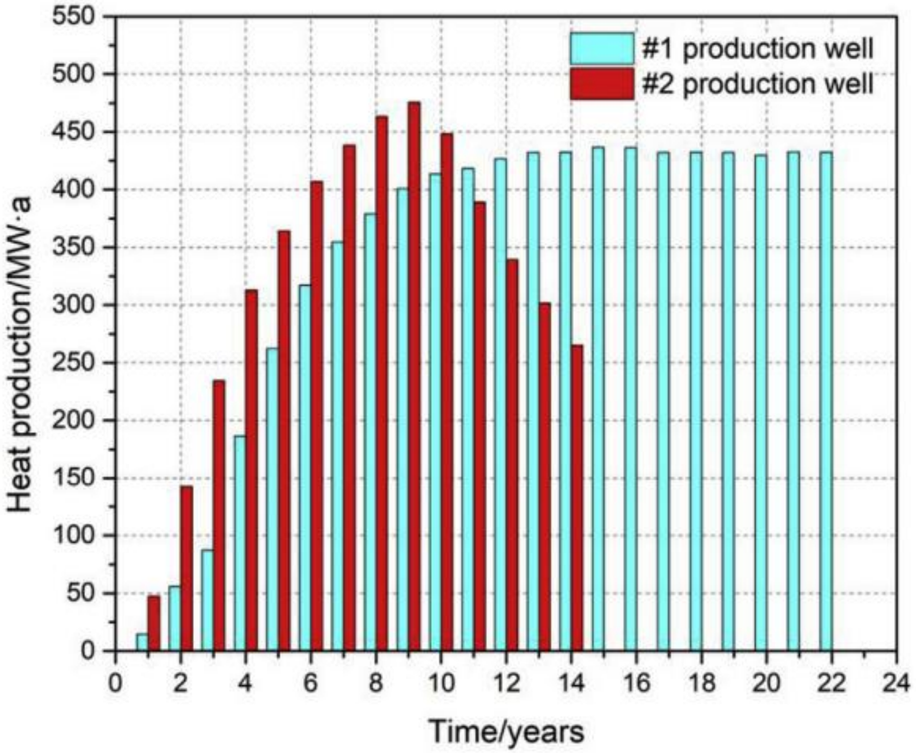


Fig. 26. Effective thermal output of the production wells.

After 22-year operation, the effective heat extraction can reach 13130 MWa, and the injection-production ratio is approximately 90% which indicates that the injected water is mostly heated and then mined.

Conclusions

Conclusions

A. The results of the temperature field distribution show that after the injection well is injected with low-temperature water, a low-temperature zone centred on the water injection well is formed. With the operation of the HDR geothermal extraction system, the low-temperature zone gradually expands to the production wells, resulting in an increase in the rate at which the water temperature in the fault zone gradually decreases.

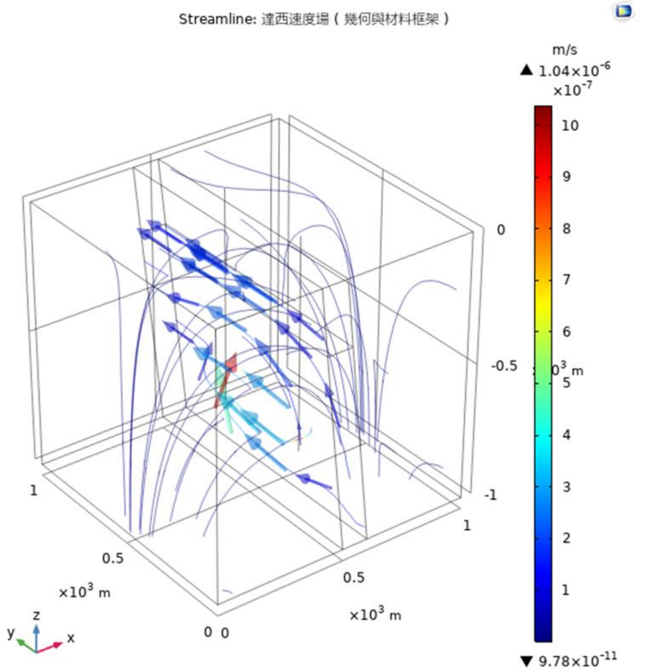
B. According to the seepage field simulation results, most of the injected water seeps into the production wells along the fault zone, and only a small part of the water seeps into the deeper rock mass or along the fault strike.

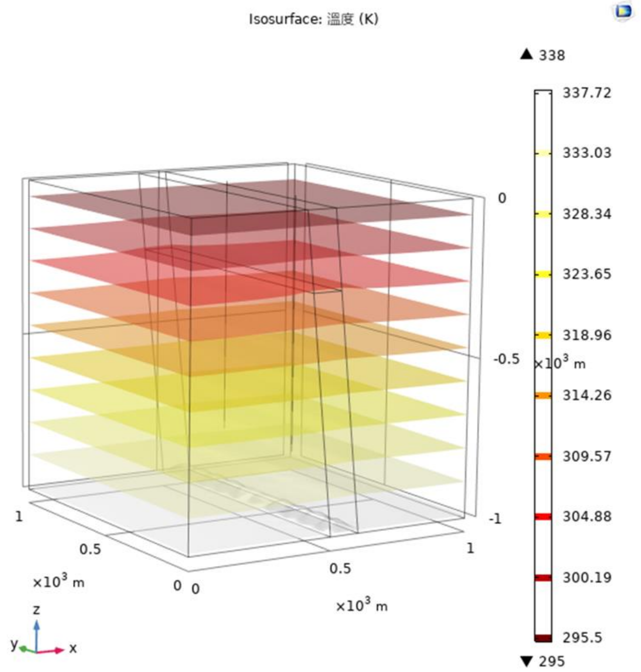
C. The highest average mass flow (above 200 °C) of the #1 and #2 production well reaches 245 kg/s and 335 kg/s, respectively. The average water temperature in the #2 production well decreased to 200 °C after 15-year operation. However, water temperature in the #1 well maintains high level which can make this system have longer lifespan.

Future work

Objective: Create a 3D THM coupling numerical model of Qingshui geothermal field

Software: COMSOL Multiphysics





Thank you for listening