Evaluation of Rock Temperature Evolution in the Lahendong Geothermal Reservoir, North Sulawesi, Indonesia

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Introduction

Understanding the long-term efficiency of geothermal energy production is essential for efficient management and sustainable utilization. The reinjection of the colder water into the geothermal reservoir will cause the thermal drawdown, pressure drawdown, land subsidence, etc. Therefore, a three-dimensional (3D) numerical model was utilized to guide the optimum application of geothermal resource exploitation. Using the finite element method, a fully coupled simulation of rock mass deformation, heat transfer, and fluid flow was carried out at each realization. Finally, the simulation results were compared with the field observation data in order to validate the established numerical model.

Methods

In order to describe the heat transfer, fluid flow, and rock mass deformation in the geothermal field, the governing equations need to be defined. The equations for the rock matrix and discrete fractures flow can be described as,

$$S\frac{\partial p}{\partial t}+\nabla\left(-\frac{\kappa}{\mu}(\nabla p+\rho_w g\nabla z)\right)=-\frac{\partial e}{\partial t}+Q \quad (1)$$

$$d_f S_f\frac{\partial p}{\partial t}+\nabla_\tau\left(-d_f\frac{\kappa_f}{\mu}(\nabla_\tau p+\rho_w g\nabla_\tau z)\right)=-d_f\frac{\partial e_f}{\partial t}+Q_f \quad (2)$$

where S is the rock matrix storage coefficient [1/Pa], p is the pore pressure [Pa], t is the time [s], κ is the rock matrix permeability [m^2], μ is the dynamic fluid viscosity [Pa·s], ρ_w is the fluid density [kg/m^3], g is the gravitation [m/s^2], e is the volumetric strain of the rock matrix [-], Q is the source-sink term of the seepage process [s^{-1}], d_f is the discrete fracture thickness [m], S_f is the fracture storage coefficient [1/Pa], κ_f is the discrete fracture permeability [m^2], e_f is the volumetric strain of the fracture [-], and Q_f is the flow exchange between the rock matrix and the fractures [s^{-1}] where expressed by $Q_f=-\frac{\kappa_f}{\mu}\frac{\partial p}{\partial_n}$.

The heat transfer in the rock matrix and discrete fractures can be described as,

$$\rho C_s\frac{\partial T_s}{\partial t}+\nabla\cdot(-\lambda\nabla T_s)=0 \quad (3)$$

$$d_f\rho_w C_w\frac{\partial T_f}{\partial t}+d_f\rho_w C_w\cdot u_f\nabla_\tau T_f=\nabla_\tau\cdot\left(d_f\lambda_f\nabla_\tau T_f\right)+h(T_s-T_f) \quad (4)$$

where ρ is the rock density [kg/m^3], C_s is the specific heat capacity of rock matrix [J/kg/K], T_s is the rock temperature [°C], λ is the thermal conductivity of rock [W/m/K], C_w is the specific heat capacity of fluid [J/kg/K], T_f is the water temperature in the discrete fracture [°C], u_f is the fluid flow velocity in the discrete fracture, λ_f is the thermal conductivity of fluid [W/m/K], h is the convection efficiency [W/m^2/K].

The rock mass deformation in the rock matrix and discrete fractures are expressed as,

$$\frac{E}{2(1+v)}u_{i,jj}+\frac{E}{2(1+v)(1-2v)}u_{j,ji}-\alpha_B p_{,i}-\alpha_T\frac{E}{(1-2v)}T_{s,i}+F_i=0 \quad (5)$$

$$u_{fn}=\frac{\sigma_n'}{k_n},\ u_{fs1}=\frac{\sigma_{s1}'}{k_s},u_{fs2}=\frac{\sigma_{s2}'}{k_s} \quad (6)$$

$$\sigma_n'=\sigma_n-\alpha_B p,\sigma_{s1}'=\sigma_{s1},\sigma_{s2}'=\sigma_{s2} \quad (7)$$

where E is the elastic modulus [Pa], v is the Poisson's ratio [-], u is the displacement [mm], α_B is the Biot-Willis coefficient [-], and α_T is the thermal expansion coefficient [1/K], F_i is the body force per unit volume in the x, y, z coordinate in 3D, u_f is the displacement of the fractures [mm], σ' is the effective stress of the fractures [Pa], and k is the fracture stiffness [Pa/m]. Subscripts n and s refer to the normal and tangential directions, respectively.

A geothermal field study is carried out based on the published data from the Lahendong geothermal field in Tomohon, North Sulawesi, Indonesia. Detailed locations of the research area are shown in **Figure 1**. **Figure 2** shows the geometry of the computational model in COMSOL Multiphysics. The initial temperature on the surface and eastside boundaries is 28 ºC and 25 ºC, respectively. At the other boundaries, no heat or mass was coming into the reservoir. The temperature gradient is 90 ºC/km, and there is a heat source with temperature ranging from 290ºC to 320ºC beneath the wells LHD-1 and LHD-4, respectively. The cold-water was injected into the injection well at the temperature of 40 ºC, and the production rate of 12 kg/s was assumed for each production well. The model was run until the 30 years of circulation time. Details on the parameters used in this study can be found in (Silitonga, Siahaan and Suroso, 2005; Yani, 2006; Maluegha, 2010; Permana, Mulyanto and Hartanto, 2015).

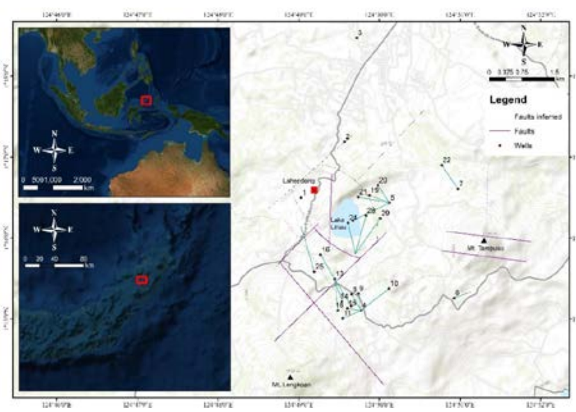


Figure 1: Location of the research area and wells at the Lahendong geothermal field.

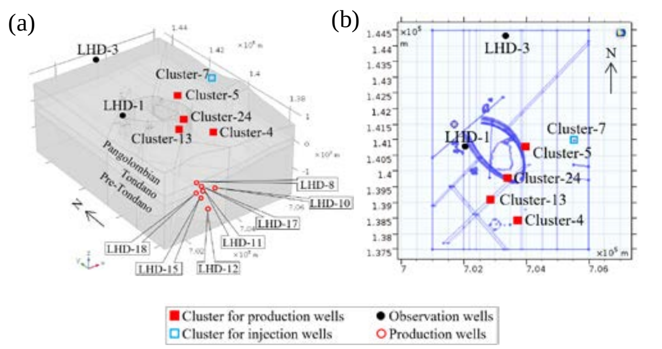
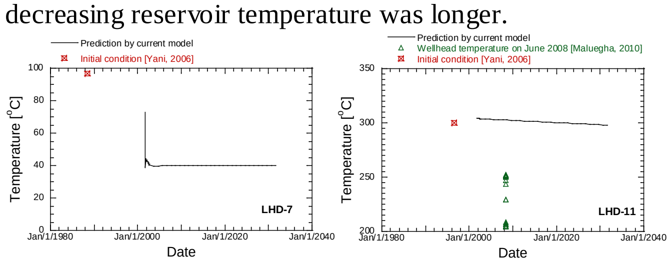


Figure 2: a) 3D model geometry, **b)** a cut plane at Z = 0 m

Results

Figure 3 shows the results of the rock temperature evolution between measurements and predictions by the current model. Four of the wells (LHD-7, LHD-11, LHD-12, and LHD-18) were explained as being representative of the other wells. Although several wells, such as wells LHD-7 and LHD-18, have a different initial temperature than the actual measured data, almost all of the predicted temperature values match closely with the actual measured data. After the cold-water injection was started in the injection well LHD-7, the well temperature began to decline. However, it was not significantly affected the temperature change in the production wells.

Regarding the well temperature results for production well LHD-11, the temperature was seen to decrease from 304 °C to 298 °C over the 30-year period. While the temperature in production well LHD-12 was seen to a constant temperature of 320 °C. After six years of simulation time, the production well LHD-18 was started to production. The results for the well temperature in the production well LHD-18 began at 313 °C and decreased to around 311 °C in 24 years. Based on the temperature evolution simulations, it can be concluded that fluid migration and heat transfer should be important processes for these simulations. The well positions located farther from the injection well and closer to the heat source make the time required for the process of decreasing reservoir temperature was longer.



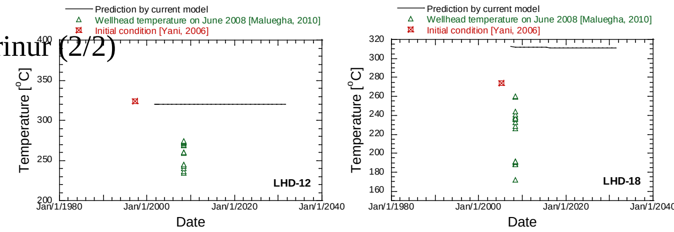


Figure 3: Comparison of evolution temperature between measurements and predictions.

As shown in **Figure 4**, the prediction by the current model was compared to the actual measured data in the production well LHD-11. The simulation results showed a trend that was close to CO_2/H_2 gas geothermometer calculations. The temperature of the production well LHD-11 fluctuated at around 300 °C over the given period. Therefore, the numerical simulation model was validated, and it can be concluded there was no significant change in temperature in this geothermal reservoir during 30-year production period.

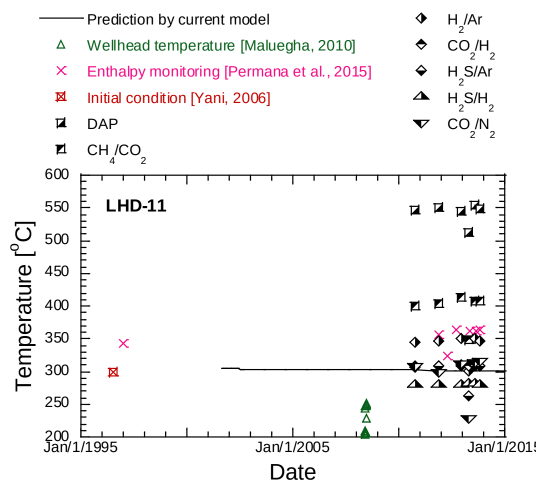


Figure 4: Comparison of evolution temperature in LHD-11 among initial condition, wellhead temperature, enthalpy monitoring, gas geothermometer data, and predictions.

Conclusion

A three-dimensional (3D) numerical model for the combined action of rock mass deformation, heat transfer, and fluid flow in the geothermal field has been developed. The evolution of the reservoir temperature for long-term production (30 years) was simulated, and no significant changes were seen. The results obtained in this simulation are important to further analyze reservoir conditions in terms of development and increase production. Furthermore, the effects of the chemical processes were not considered in this numerical simulation but should be considered in future work.

References

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