

Performance Prediction of Two-Phase Geothermal Reservoir using Lumped Parameter Model

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Abstract. Many studies have been conducted to simulate performance of low-temperature geothermal reservoirs using lumped parameter method. Limited work had been done on applying non-isothermal lumped parameter models to higher temperature geothermal reservoirs. In this study, the lumped parameter method was applied to high-temperature two phase geothermal reservoirs. The model couples both energy and mass balance equations thus can predict temperature, pressure and fluid saturation changes in the reservoir as a result of production, re-injection of water, and/or natural recharge. This method was validated using reservoir simulation results of TOUGH2. As the results, the two phase lumped parameter model simulation without recharge shows good matching, however reservoir model with recharge condition show quite good conformity.

1. Introduction

Geothermal reservoir simulation is conducted to predict a geothermal field reservoir behavior for a certain time. Traditionally, reservoir simulation is needed, especially in the early stage geothermal field development and performance monitoring stage. But in early stage development, geothermal reservoir simulation process constrained by incomprehensive and limited data. While distributed parameter numerical model that commonly used requires a comprehensive data to perform simulations. This reservoir numerical modeling requires long run-times especially when the model becomes more complex. The history-matching process or the model calibration process take time because it needs to be run many times for adjustment parameters of reservoir. Lumped parameter model is an alternative method to reservoir simulation due to less parameters involved and shorter run-times.

Researches on lumped parameters to simulate geothermal reservoirs have been widely applied. Several examples include use lumped parameter models to simulate the pressure response of the reservoir [1]; conducted a reservoir simulation for a low temperature geothermal systems [6]; used a lumped parameter model for reservoir applications of low temperature liquid-dominated geothermal system [4]; conducted a study on high temperature geothermal reservoirs [8]; and studied a lumped parameter model for a liquid dominated low temperature reservoir containing carbon dioxide [3]. Many researches has been done for single-phase low-temperature geothermal system but only a few for high-temperature.



In this paper, the lumped parameter method is described for two-phase high-temperature geothermal reservoirs model. The model couples both energy and mass balance equations thus can predict temperature, pressure and fluid saturation changes. The basic flow equations are formulated with the lumped-parameter method. Example cases of simulation are presented to illustrate the capabilities of the model developed based on this approach.

2. Non-Isothermal Lumped Parameter Model

The lumped parameter model of non-isothermal system can predict changes of pressure and temperature. Pressure and temperature change occur because of production, mass will be reduced, pressure will drop and therefore internal energy will decline as well and causing a slight drop in temperature value. Temperature reservoir is a function of reservoir volume, production rate, injection rate and injection temperature, natural recharge rate and recharge temperature [4].

This study was used a single tank lumped parameter model with a non-isothermal system. The single tank model represents a geothermal system where there are reservoir, production, injection, and recharge. Reservoir in the model is a two-phase high-temperature reservoir which there are steam, hot water, and rock. Production mass are steam and water while for injection is only water. Lumped parameter model as illustrated in Figure 1.

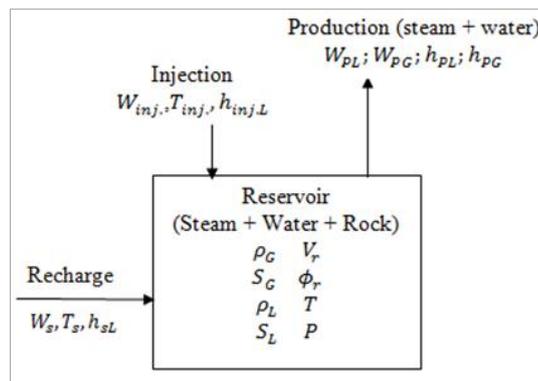


Figure 1. Single tank two-phase high-temperature lumped parameter model.

In single tank reservoir model there are density and saturation of steam, (ρ_V, S_V) ; density and saturation of water, (ρ_L, S_L) ; and rock. This two-phase reservoir has pressure, P and temperature T . Reservoir is produced with steam production rate, $W_{pV}(kg/s)$ and water production rate, $W_{pL}(kg/s)$. At the reservoir also injected water with injection rate, $W_{inj}(kg/s)$. Net production rate is the difference of total production rate with total injection rate. Mathematically, it can be written as follows:

$$W = W_{pL}(t) + W_{pV}(t) - W_{inj}(t) \quad (1)$$

Recharge mass flow rate can be approximated by [1][4]:

$$W_s = \alpha_s(P_i - P(t)) \quad (2)$$

Where $\alpha_s(kg/bar \cdot s)$ is an index recharge, $P_i(bar)$ is the initial pressure and $P(t)(bar)$ is the pressure of reservoir as a function of time. While recharge index value based on the equation of the relationship with permeability, fluid viscosity, fluid density, length of reservoir, and width and height of reservoir [2]. Equation (3) shows water recharge index $(\alpha_{s,L})$ and steam recharge index $(\alpha_{s,V})$.

$$\alpha_{s,L} = 8 \frac{wz}{L_x} \frac{k}{\mu_L} \rho_L, \quad \alpha_{s,V} = 8 \frac{wz}{L_x} \frac{k}{\mu_V} \rho_V \quad (3)$$

Based on these assumptions the mass conservation equation can be written as follows:

$$V_r \frac{d}{dt} [\rho_L S_L \phi_r + \rho_V S_V \phi_r] - \alpha_{s,L} (P_i - P(t)) - \alpha_{s,V} (P_i - P(t)) + W_{pL}(t) + W_{pV}(t) - W_{inj}(t) = 0 \quad (4)$$

Where V_r is volume reservoir and ϕ_r is reservoir porosity. The mass conservation equation encompasses mass accumulation in the reservoir, mass flow rate from recharge source, and net production rate.

There are two kinds of heat transfer in geothermal system; convection and conduction. Temperature changes occur by the fluid movement such as production, injection, or natural recharge. Therefore, convection is more dominant in system, in this model conduction and heat loss is negligible. The energy conservation encompasses energy accumulation in the reservoir, heat flow from injection fluid, heat flow from recharge, and heat flow as a result of production.

Energy conservation equation can be written as follows:

$$\frac{d}{dt} [(1 - \phi_r) V_r \rho_m C_m T + V_r \phi_r (\rho_L S_L u_L + \rho_V S_V u_V)] - W_{inj}(t) h_{inj,L}(t) - \alpha_{s,L} (P_i - P(t)) h_{s,L}(t) - \alpha_{s,V} (P_i - P(t)) h_{s,V}(t) + W_{pL}(t) h_{pL}(t) + W_{pV}(t) h_{pV}(t) = 0 \quad (5)$$

Where $\rho_m, C_m, T, u_L, u_V, h_{inj,L}, h_{s,L}, h_{pL}, h_{pV}$ respectively are density of rock matrix, specific heat capacity of rock matrix, temperature of reservoir, specific internal energy of water, specific internal energy of steam, specific enthalpy of injected water, specific enthalpy of recharge water, specific enthalpy of production water, and specific enthalpy of production steam.

In this model, porosity changes depend on pressure and temperature as in the following equation [4]:

$$\phi_r(P, T) = \phi_i [1 + c_r (P - P_i) - \beta (T - T_i)] \quad (6)$$

Where c_r, β, ϕ_i, T_i respectively are compressibility of porosity at constant temperature, thermal expansion coefficient of porosity at constant pressure, initial porosity at initial pressure and temperature, and initial temperature of reservoir.

Mass and energy conservation equation are non-linear differential equation. The solution of couple equation is solved by using Newton-Raphson method. A finite difference discretization scheme is used for the terms involving the derivative of the time.

3. Example Synthetic Application

In this section, we provide a few synthetic applications of the non-isothermal two-phase model. The lumped parameter models is validated to the reservoir simulation results of TOUGH2.

Two-phase condition occurs when pressure and temperature value are on the saturation line. Temperature value is temperature saturation of the pressure. In this study, the initial temperature is set as temperature saturation of the initial pressure ($T_i = T_{sat}@P_i$).

The simulation two-phase model is performed in two case conditions: first, there are no fluid flow from the recharge source; and second, the recharge source contribute to system. Several reservoir properties that used in this model are shown in Table 1.

Table 1. Properties and initial condition of lumped parameter two-phase model.

Parameters	Symbol	Value	Units
Compressibility	β	0	1/°C
Initial porosity	ϕ_i	0.2	fraksi
Thermal expansion	c_r	1.33×10^{-4}	1/bar
Initial pressure	p_i	50	bar
Initial temperature	T_i	263.91	°C
Injection temperature	T_{inj}	60	°C
Density of rock matrix	ρ_m	2650	kg/m ³

Specific heat capacity of rock matrix	C_m	1000	$J/kg^{\circ}C$
Volume reservoir	V_r	1.0×10^7	m^3
Permeability	k	2.719×10^{-14}	m^2

Parameter values such as; density, internal energy, enthalpy of recharge, enthalpy of injection, enthalpy of production are obtained from the calculation of steam table [7]. Density and internal energy are calculated based on pressure in the solution of the equation, while enthalpy production is calculated based on pressure and temperature of production. The enthalpy of recharge is calculated based on initial pressure and temperature, while enthalpy of injection is based on initial pressure and temperature of injection.

Simulations are conducted to observe historical pressure, temperature, and saturation for 30 days. There are three periods in production and injection scenario that used in this simulation. First and third 10 days conducted production and injection with production rate 20 kg/s and injection rate 15 kg/s. While in the second 10 days or second period, there are no mass produced and injected.

The results are compared with simulation results using numerical simulator TOUGH2 [5]. A model without recharge condition is described as a single grid block with volume $V_r = 1.0 \times 10^7 m^3$ and there are no fluid flow and heat flow from the surrounding (Figure 2a). Production and injection well are in the middle of reservoir.

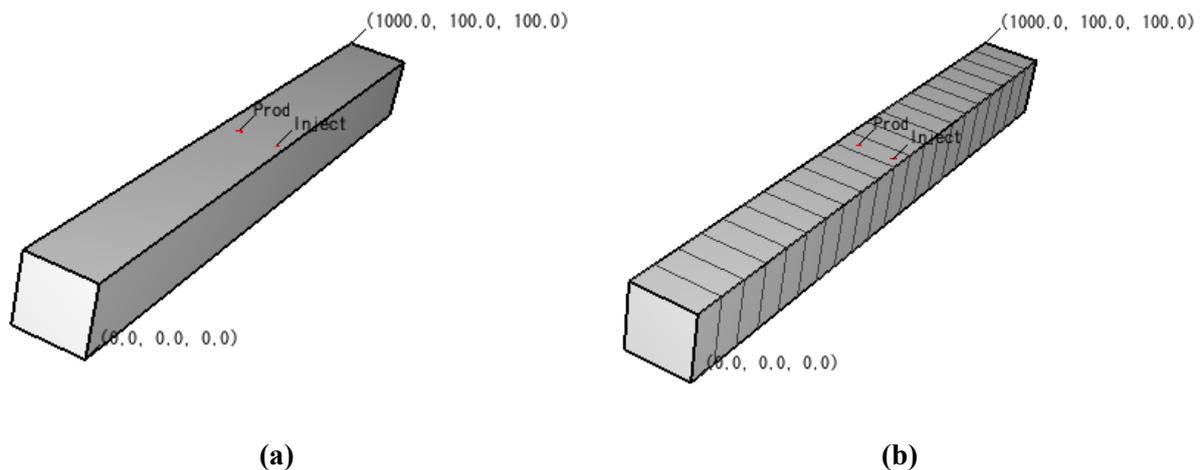


Figure 2. TOUGH2 model without (a) recharge and (b) with recharge.

For recharge condition model is described as a reservoir with 21 grid blocks with fixed pressure and temperature on the sides (see Figure 2b). To minimize discretization errors, the system consists of 21 grid blocks. This boundary condition allow the fluid flow from the boundary towards the well. Pressure and temperature value are compared to the average value of the whole blocks in the TOUGH2 model.

4. Simulation Results

4.1. Without recharge condition

In this two-phase simulation, the results that observed are pressure, temperature, water saturation, and steam saturation change. There is a decline for pressure and temperature in first 10 days or first period of production. In the second period pressure and temperature tend to be constant and there is decline again when in the third period. Figure 3a. shows that lumped parameter simulation result and TOUGH2 pressure curve are quite match and has a difference 0.15 bar. In temperature curve, simulation result of lumped parameter and TOUGH2 temperature curve also quite match as well with difference 0.2°C.

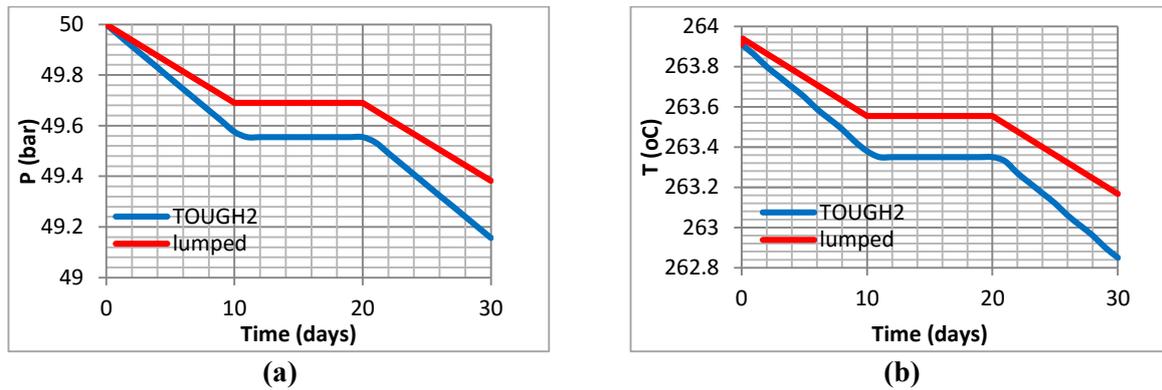


Figure 3. (a) Pressure change and **(b)** temperature change without recharge.

Water saturation and steam saturation change can be seen in Figure 4. Water saturation curve indicate a decline in first and third period and a constant value during second period. While in steam saturation curve, there is an increase value when produced and tends to a constant when the well is shut-in then there is an increase when well is produced again. The increase of steam saturation represents the increasing steam phase in the reservoir. Lumped parameter simulation result and TOUGH2 water saturation curve are quite match and only has difference 0.0002. Lumped parameter simulation result and TOUGH2 steam saturation also has difference 0.0002 and quite match as shown in Figure 4b.

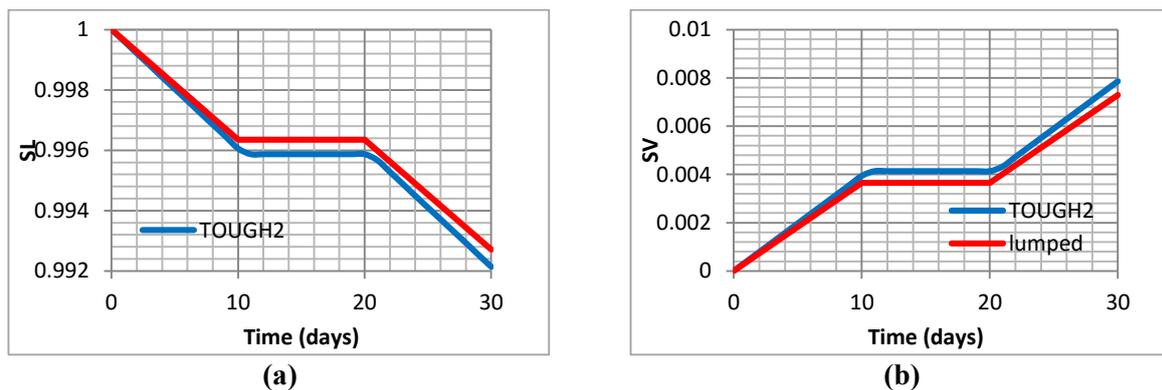


Figure 4. (a) Water saturation change and **(b)** steam saturation change without recharge.

Based on lumped parameter simulation result, the curve quite match, and the difference are very small. The lumped parameter models for two-phase condition without recharge has shown conformity and validated to be applied.

4.2. With recharge condition

In the two-phase lumped parameter model is also conducted a simulation with there is a fluid flow from recharge source into the reservoir. Figure 5a shows pressure change in system with recharge condition. Pressure curve in lumped parameter simulation result is decreased in first period, tends to be constant in second period and decreased again in third period. TOUGH2 simulation result pressure curve also decreased in first period but not as much lumped parameter. But in second period, the pressure curve is increase to the initial pressure and tends to be constant on day 13 to day 20. In third period, pressure is decreased again with the same gradient as in first period. Lumped parameter and TOUGH2 pressure curve has a difference 0.4 bar. In temperature curve, lumped parameter and TOUGH2 simulation result are quite match with the difference 0.15°C.

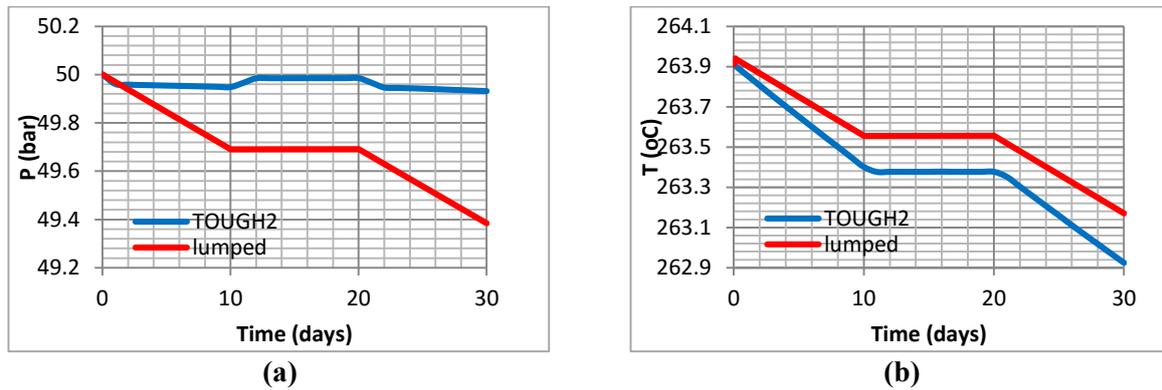


Figure 5. (a) Pressure change and (b) temperature change with recharge.

There is an increase value of water saturation in lumped parameter simulation result during second period. This occurs because in the second period there is a fluid flow from recharge that into the reservoir. With no fluid produced and only water from recharge thus will increase the water phase and decrease the steam phase. TOUGH2 simulation results in water saturation curve relatively constant during second period and decreased in third period. Lumped parameter and TOUGH2 water saturation curve are quite match with difference 0.001. Figure 6b shows that there is a difference 0.001 between lumped parameter and TOUGH2 steam saturation curve.

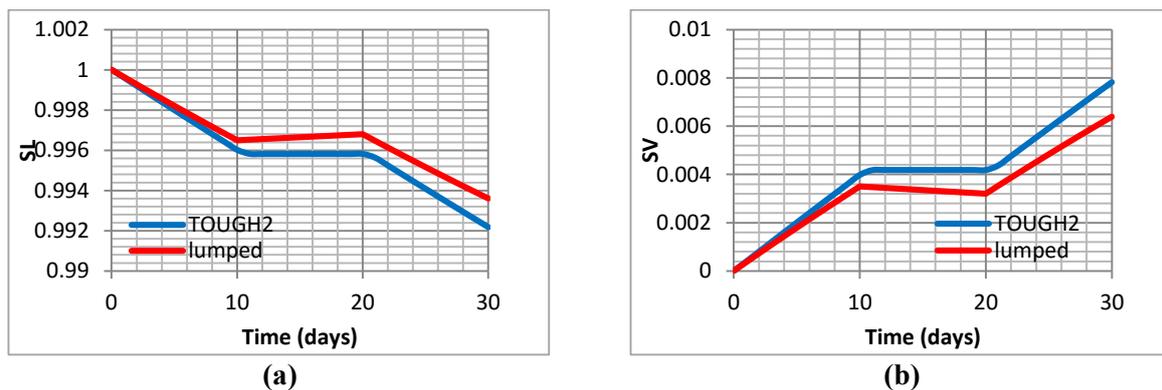


Figure 5. (a) Pressure change and (b) temperature change with recharge.

Lumped parameter model is model that based on mass and energy conservation equation so as TOUGH2 software. The difference between these two methods is the equation solving method. In lumped parameter, the equation is ordinary differential equations (ODE) and simpler to be solved because the dependent variable is only function of time. While in TOUGH2, it is a bit more complicated because the dependent variables are function of time and one or more spatial variable. Thus, the equation need to be solved for TOUGH2 is the partial differential equation (PDE). The differences equation solver method allows difference value on the simulation results but still rapprochement.

Reservoir simulation using the lumped parameter method has been developed for high-temperature reservoir. Reservoir simulation program with this method has been made and the results have been validated. This simulation program can be used in early stage of development where there are limited data available. The results of reservoir simulation by this method can predict the pressure and temperature reservoir condition where there are production and injection in the future. Lumped parameter reservoir simulation method is simpler and can be run in short time so it can quickly provide an estimate of reservoir pressure and temperature. The estimates of pressure and temperature is important to know at the early stage of development due to the construction of a power plant is

influenced by reservoir conditions. The estimates of pressure and temperature also can provide a reference criterion for separator, turbine, or other power plant equipment as well as pipes installation from well pad to power plant. If reservoir condition can be known with certainty, power plant capacity can be immediately determined.

5. Conclusions

Lumped parameter method has been developed and applied to two-phase high-temperature geothermal reservoir model. Mass and energy conservation equation are solved using Newton-Raphson method with pressure, temperature and saturation as the solution. Two-phase high-temperature reservoir simulation program with the lumped parameter method with and without recharge has been made and can predict the condition reservoir due to production and injection. The simulation results could be a reference to make a strategic plan in the early stage development of geothermal field. The result of two phase lumped parameter model simulation without recharge shows good matching, however the result is quite good conformity for reservoir model with recharge condition. The model has not been validated using actual data history. Therefore the next study will be validated with actual data so that lumped parameter model of the reservoir can get closer to the actual situation.

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