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# Non-Isothermal Lumped Parameter Model for Two Phase High Temperature Geothermal Reservoirs

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## ABSTRACT

Extensive work have been done on the simulation of behavior of low-temperature geothermal reservoirs using lumped-parameter. However, there have not been much effort placed on using lumped parameter methods for high temperature – two phase geothermal reservoirs.

In this paper, the lumped parameter method was applied to a high-temperature two phase geothermal system. To account for this system, a lumped parameter model was developed using Matlab software to provide a flexible means for assessing the behavior of the reservoir. The model couples both energy and mass conservation equations thus can predict both temperature/enthalpy and pressure changes in the reservoir resulting from production, re-injection of a low temperature water into the system, and/or natural recharge. This method was validated using reservoir simulation results and high enthalpy geothermal field data. A computer program will be then used to perform sensitivity studies on reservoir size, porosity, aquifer recharge, and temperature of recharge fluid.

## 1. INTRODUCTION

Modeling of a geothermal system is usually performed to estimate the behavior of a geothermal system in a field in the future. Each modeling method is unique compared to others. The model has been validated can be used to predict future performance of the geothermal field.

In modeling of geothermal systems, there are several methods that have been used, these include, decline curve and trend analysis method, numerical modeling, and lumped parameter models. Decline curve and trend analysis method is a method that involves matching a logarithmic, harmonic, and exponential functions with data such as pressure or enthalpy but not based on a conceptual model of the reservoir. Numerical modeling is modeling with grids involving many cells to represent the reservoir by considering the properties of each grid. The use of this model requires a lot of data and a long time to run the models. Before performing any prediction, these models needs to undergo a history-matching process that also requires quite a long time. Reservoir behavior can be difficult to predict because of the dynamic nature of many properties. Modeling can also be hard to use for a field that has a small amount of data, especially for new fields. Lumped parameter models is a simple model to describe the geothermal system as a homogeneous block. This model does not require as much time as numerical modeling. A lumped parameter model that has been history-matched, can be used to predict changes in temperature and pressure for a number of production and injection scenarios. This model can be used for the new field and developed where there is not as much data.

Research on lumped parameters to simulate geothermal reservoirs have been widely applied. Several examples include Gudni Axelsson (1989) using lumped parameter models to simulate the pressure response of the reservoir; Sarak, et al. (2003) conducted a reservoir simulation for a low temperature geothermal systems; Onur, et al. (2008) used a lumped parameter model for reservoir applications of low temperature liquid-dominated geothermal system; Sveinbjörnsson (2011) conducted a study for high temperature geothermal reservoirs; and Hosgor, et al. (2013) studied a lumped parameter model for a liquid dominated low temperature reservoir containing carbon dioxide.

For the use of a lumped parameter model in a low temperature geothermal system, not many studies have used these simple techniques such as the lumped parameter method in the field of a high temperature reservoir. In this study, the method that was applied to a lumped parameter model of a two phases high temperature geothermal system. This model is expected to show the reservoir behavior and predict reservoir behavior in the future.

## 2. LUMPED PARAMETER MODEL

The focus of this paper is to study the two-phase high temperature reservoir of liquid (water) and gas (steam). This lumped parameter study is for a two-phase reservoir model that is based on mass and energy conservation equations. Onur, et al (2008) have conducted research lumped parameter model for the low temperature liquid dominated geothermal reservoirs. While in this paper described the lumped parameter model for two-phase high temperature geothermal reservoir which is a development of research Onur, et al (2008).

The system acts as a non-isothermal although the reservoir is closed. In a closed reservoir, when there is only production, the pressure decreases and the energy also decreases causing a slight decline temperature. This paper used a single tank of non-isothermal lumped parameter model shown in Figure 1.

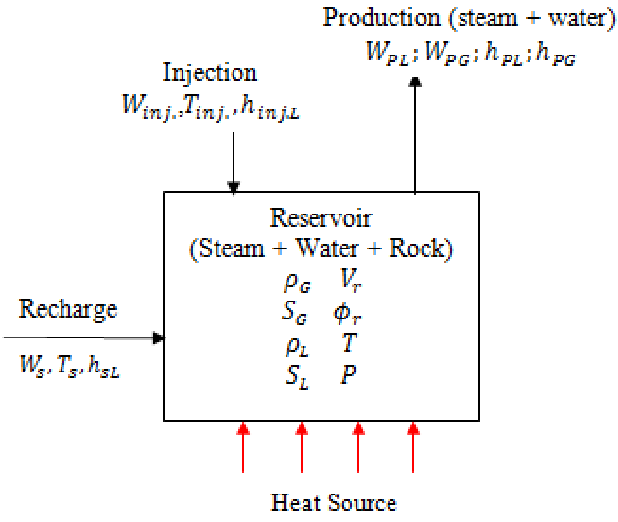


**Figure 1: Single tank lumped parameter model**

This model represents a single tank geothermal system which includes a reservoir, production, injection, and recharge source. The reservoir in the model is a two-phase high-temperature reservoir. Mass produced is in the form of steam and water while for injection and recharge it is just water. With time, the reservoir will remain continuously heated by a heat source underneath. Net production rate is the difference between the total production rate and the total injection rate. Mathematically it can be written as follows:

$$W = W_{pL}(t) + W_{pG}(T) - W_{inj}(t) \tag{1}$$

Total production for the steam represented by $W_{pG}(kg/s)$ and for water is $W_{pL}(kg/s)$. While $W_{inj}(kg/s)$ represents the total injection rate. According to Axellson (1989), Sarak, et al. (2005) and Onur, et al. (2008), the mass flow rate of recharge can be approximated by:

$$W_s = \alpha_s\big(p_i - p(t)\big) \tag{2}$$

Where $\alpha_s(kg/(bar.s))$ is an index recharge, $p_i(bar)$ is the initial pressure, and $p(t)(bar)$ is the pressure of the reservoir as a function of time. Based on these assumptions the mass conservation equation can be written as follows:

$$V_r\frac{d}{dt}[\rho_L S_L \phi_r + \rho_G S_G \phi_r] - \alpha_s\big(p_i - p(t)\big) + W_{pL}(t) + W_{pG}(T) - W_{inj}(t) = 0 \tag{3}$$

Where $V_r$ is the bulk volume; $\phi_r$ is the porosity of the reservoir; $\rho_L, S_L$ is the density and saturation of water; and $\rho_G, S_G$ is the density and saturation of steam.

The mass conservation equations include the mass accumulation in the reservoir, the mass flow rate of the source of recharge, and the net production rate. The energy conservation equation is written as shown in equation (4). In geothermal systems, there are heat transfer processes of conduction and convection. Temperature changes occur largely due to the presence of fluid motion such as production, injection or recharge. So that the convection heat transfer process dominates in this model system and the conduction heat transfer and heat loss is negligible. The energy conservation equation consists of the energy accumulated in the reservoir, the flow of heat from the fluid injection, the heat flow from the recharge, and the heat flow due to fluid production.

$$\frac{d}{dt}[(1-\phi_r)V_r\rho_m C_m T + V_r\phi_r(\rho_L S_L u_L + \rho_G S_G u_G)] - W_{inj}(t)h_{inj,L}(t) - \alpha_s\big(p_i - p(t)\big)h_{s,L}(t) + W_{pL}(t)h_{pL}(t) + W_{pG}(t)h_{pG}(t) = 0 \tag{4}$$

Where $\rho_m, C_m, T, u_L, u_G, h_{inj,L}, h_{s,L}, h_{pL}, h_{pG}$ are the density of rock matrix, spesific heat capacity of rock matrix, temperature, specific internal energy of water, specific internal energy of steam, specific enthalpy of injected water, specific enthalpy of water from recharge source, specific enthalpy of produced water, specific enthalpy of produced steam respectively.

In this model, change in the porosity depend on the pressure and temperature as shown in the following equation (Onur, et al. 2008):

$$\phi_r(P,T) = \phi_i[1 + c_r(p - p_i) - \beta(T - T_i)] \tag{5}$$

Where $c_r, \beta, \phi_i, T_i$ are the compressibility of porosity at constant temperature, thermal expansion coefficient of porosity at constant temperature, initial porosity and the initial temperature of reservoir respectively.

The mass and energy conservation equations are non-linear differential equations. To solve these non-linear equations, a forward finite difference and Newton-Raphson method are used. Pressure and temperature values are then plotted against time so that it can be seen the behavior of the reservoir within a certain time.

## 3. VERIFICATION MODEL

Lumped parameter model is verified based on research with Onur, et al. (2008). Modeling is done to monitor reservoir changes within 30 days. The rate of production in the first 10 days is equal to 20 kg/s with injection rate of 15 kg/s. At 10 days later, all wells shut-in so there is no mass and no mass produced injected. In the last 10 days of production and injection processes performed by the same amount in the first 10 days. Paper Onur, et al. (2008) focused on low temperature liquid dominated reservoirs so that the value $S_L = 1$ and $S_G = 0$.

Lumped parameter models are verified with two conditions. The first condition is that the system is a closed system and there is no flow from the recharge source. So that the recharge value index is 0 kg/(s-bar). The second condition is a condition where there is a recharge source of fluid flow into the system. Recharge value index in the second condition is 1 kg/(s-bar). Temperature recharge source is assumed to be equal to the initial temperature of the reservoir is 140°C.

Lumped parameter model developed in this paper has been adapted to the verification of data and the processing has been done by Onur, et al. (2008) resulted in the same graphical form.

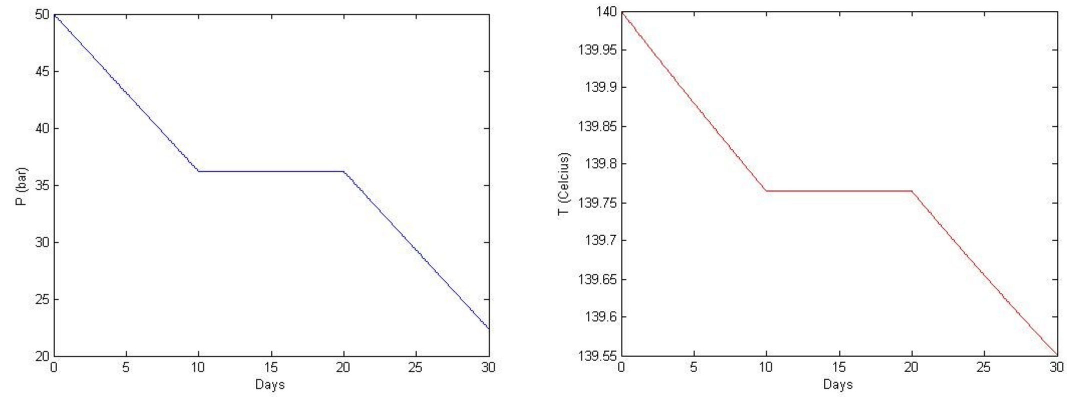


**Figure 2: Pressure (left) and temperature (right) behavior verification with no recharge**

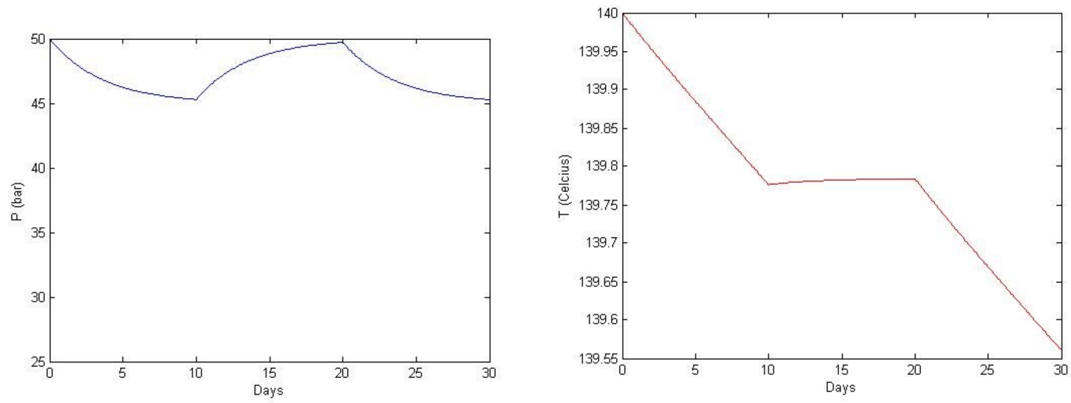


**Figure 3: Pressure (left) and temperature (right) behavior verification with recharge**

## 4. EXAMPLE SYNTHETIC APPLICATION

Applications lumped parameter method in this paper uses some synthetic data. The single tank model is expected to show the behavior of a reservoir for a two phase high temperature geothermal system, since the data is derived from a two phase high-temperature geothermal field in Indonesia. In this synthetic example, there are two conditions that will be reviewed; a condition where there is no fluid flow from the recharge source and the conditions where recharge source contributing to system. Several reservoir properties used in this model are shown in Table 1. The total production rate is assumed to be 92.1 kg/s with 40.5 kg/s as steam and 51.6 kg/s as water. While the injection rate is assumed to be 50 kg/s, the production rate and the injection rate are assumed to be constant over the lifetime. In this model the initial temperature is set to be 280°C and a pressure of 200 bar while the initial injection temperature was at 180°C.

Table 1. Properties of reservoir

| | |
|---|---|
| $V_r$ ($m^3$) | 19 x $10^9$ |
| $S_L$ (fraction) | 0.56 |
| $S_G$ (fraction) | 0.44 |
| $\phi_i$ (fraction) | 0.1 |
| $\rho_m$ ($kg/m^3$) | 2700 |
| $C_m$ (J/kg.$^o$C) | 1000 |
| $c_r$ (1/bar) | 5 x $10^{-5}$ |
| $\beta$ (1/$^o$C) | 0 |

The first case are the closed models where there is no fluid flow coming from the recharge source. In these conditions the recharge value index is $\alpha_s$=0. So after the model is run, the results are as shown in Figure 4 and 5.

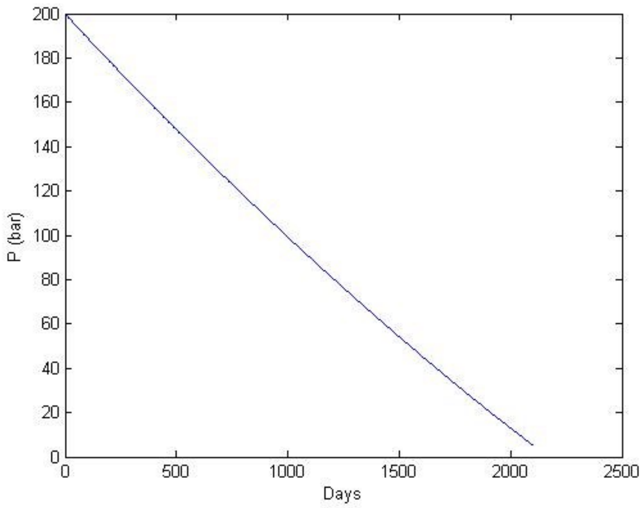


**Figure 4: Pressure behavior with no recharge**

Figure 4 shows that the pressure drop will occur continuously even going to reach a value of zero. This is due to the mass taken (production) continuously without replacement masses through recharge source. The pressure will continue to decrease until it reaches zero at day 2150 or around the year 6. Models stopped at day 2150 due to the model could not perform the calculation for the value of pressure down through the value zero. Pressure decreases and the energy decreases will cause a slight drop in temperature as shown in figure 5. Temperature on day 1 to day 2150 did not seem to have a significant decrease in temperature. The decrease in temperature from 280$^o$C to 279.57$^o$C occurred with a difference of 0.43$^o$C. On day 2000 reservoir temperature in the first case is 279.59$^o$C.

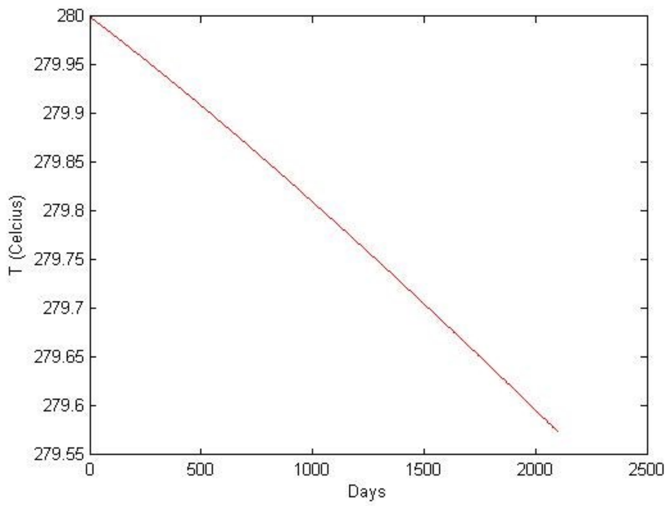


**Figure 5: Temperature behavior with no recharge**

The second case is where the flow of fluid into the system. Incoming fluid flow is derived from the recharge source. In these conditions the recharge value index $\alpha_s$=1. Changes in pressure and temperature of the lumped parameter model results are as shown in figure 6 and 7.

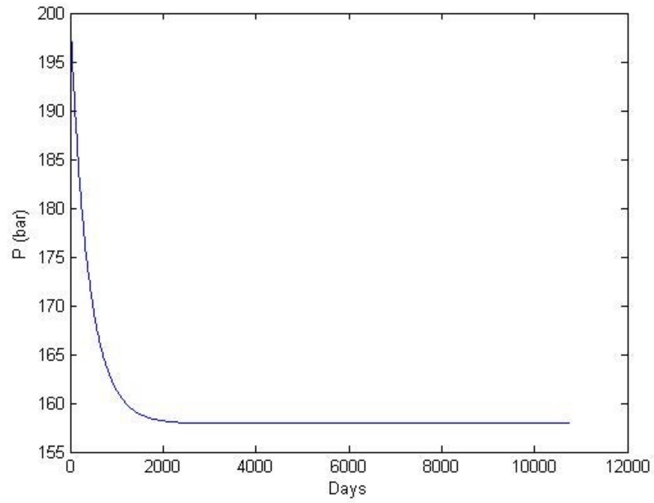


**Figure 6: Pressure behavior with recharge**

Changes in the value of the pressure in the reservoir with fluid flow recharge for 30 years shown in figure 6. Decline continued into until the day 2100 after the pressure became constant up to 10750 days. Pressure is at a constant value of 158 bar which occurs on year 6 (days in 2100) to 30 years (10750 days). In this condition, the model is still able to do the calculations due to the mass of fluid recharge so it can replace the incoming mass lost due to the production. The decrease in temperature as shown in Figure 7 occurs from 280$^o$C to 278$^o$C at 2$^o$C difference. On day 2000 for the second case the temperature is at a value 276.5$^o$C.

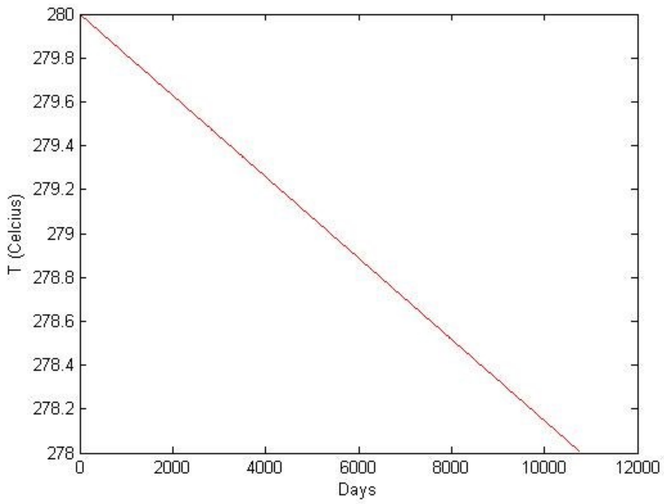


**Figure 7: Temperature behavior with recharge**

## 5. DISCUSSIONS

Applications of this lumped parameter model in this paper are divided into two conditions; without recharging reservoir conditions and reservoir conditions with flow recharge. The first case is where there is no fluid flow coming from the recharge source. Therefore, the first case can be referred to as closed models. Continuous production process is done but no mass is due to replace the missing mass production, resulting in a significant pressure drop. On year 6 or day 2150 the reservoir pressure has reached 0 bar and stopped counting models. If the model is continued, the model calculations become invalid because of the pressure value below zero or negative. Based on the first case the pressure drop is very noticeable that the presence of a continuous production process without recharging the geothermal system will not last long and unsustainable. While the ideal geothermal system is a system that is expected to be sustainable. The decrease in temperature in the first case does not occur significantly as the pressure drops. The decrease in temperature in year 6 only 0.43$^o$C.

The second case is where there is a system in the incoming fluid flow from the recharge source. In second cases a decrease in pressure up to 42 bar on year 6. Then the pressure became constant at 158 bar until on year 30. Mass lost as a result of the production process is replaced by the incoming mass of recharge source. In the first year up to year 6 pressure decreased significantly due to the equilibrium between the outgoing and incoming mass has not happened. In conditions where there is a constant pressure value, equilibrium has been reached between the incoming and outgoing mass. Based on the results of the modeling, a geothermal system with the second case durable and sustainable. The decrease in temperature for both cases is insignificant, amounting to 2°C for a lifetime (30 years). In the second case the temperature on day 2000 (276.5$^o$C) lower than the first case (279.59$^o$C) at the same time. This occurs due to the incoming fluid recharge has a lower temperature than the temperature of the reservoir. So the second case the temperature is lower at the same time. While the temperature of the reservoir first case there is no influence of recharge.

## 6. CONCLUSIONS

Lumped parameter method has been developed for a high-temperature two phase geothermal systems to predict the change of pressure and temperature.

In the first case there is a significant decrease in reservoir pressure until it reaches a value of 0 bar on year 6 because there is no incoming fluid flow from the recharge source. This situation causes the geothermal system could not last long time and unsustainable. The decrease of temperature until year 6 of only 0.43$^o$C.

In the second case, the presence of fluid flow from the recharge source causes a pressure drop of 42 bar untill year 6 and then the pressure became constant at 158 bar. This case indicates that the geothermal system is durable and sustainable. Fluid flow from the recharge source is entered into the system also affects the temperature of the reservoir. The decrease of temperature is 2°C in 30 years occurred in the second case. The second case temperature (276.5$^o$C) lower than the first case temperature (279.59$^o$C) at the same time to which is on day 2000.

Lumped parameter models in this study can be applied to verify it through the use of data derived from secondary data in two phase high-temperature geothermal field in Indonesia. This research is in its early stage and will be continued in the next study.

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