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An Investigation of the Information Content of Temperature Using Non-Isothermal Lumped Parameter Models

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ABSTRACT

In this study we have developed a new generalized non-isothermal lumped-parameter model for predicting both the temperature and pressure behaviors of liquid dominated geothermal reservoirs. The model is capable of modeling the pressure and temperature behavior of multiple tanks. These tanks can represent multiple geothermal reservoirs or geothermal reservoirs with aquifers. Energy and mass balance equations are coupled to predict both the temperature and pressure behavior of a liquid-dominated geothermal system resulting from re-injection of low temperature water into the system, production and natural recharge. The model is coupled with an optimization routine (based on the Levenberg-Marquardt method) for performing history matching to field pressure and/or temperature measurements, from which model parameters could be adjusted.

The primary purpose of this study is to investigate whether using temperature and pressure data together provides benefits in estimating various model parameters that are not accessible from pressure data alone. Our results show that using temperature data in addition to pressure data for history matching improves the estimation of certain reservoir parameters such as the bulk volume of the reservoir and porosity, which are not accessible from history matching of pressure data alone. It is shown that temperature data contains information about certain reservoir parameters such as bulk volume, porosity, and temperatures and hence such parameters could be estimated by using temperature data in addition to pressure data in history matching.

1. INTRODUCTION

Geothermal reservoirs are modeled mainly by using two common approaches given in the literature; using numerical models and using lumped parameter models. Numerical models split the reservoir domain into many cells and apply the mass and/or energy conservation laws on each cell. The resulting equations are then solved using numerical techniques such as the integrated finite difference method. Numerical models have the advantage of being general such that they allow for incorporation of heterogeneities, different reservoir geometries, multiple complex well geometries multiphase/multicomponent flow, etc. However to use these numerical models, one must provide an extensive amount of data. The run-times associated with these models could be long especially when the model becomes more complex. Hence, calibration of the numerical model could be time consuming.

Many parameters of the numerical model are lumped into a few with the use of lumped parameter models. Hence relatively much shorter run-times are associated. These models provide a good alternative especially during the early life of the reservoir where sufficient data are not available to construct a numerical model.

Lumped parameter models, assuming isothermal flow behavior, have been previously proposed in the literature by Grant *et al*., 1982; Axelsson, 1989; Sarak *et al*., 2005 and Tureyen *et al*., 2007. Very recently, Onur et al. (2008) have proposed a non-isothermal lumped-parameter model which enables one to predict both pressure and temperature behavior of a liquid-dominated geothermal reservoir which is idealized as a single-closed or recharged tank. Onur et al. (2008) shows that if information content of temperature data combined with pressure data in history-matching, one could determine reservoir parameters such as bulk volume and porosity, which are not accessible from history matching of pressure data alone by using an isothermal isothermal lumped-parameter model.

Like the numerical models, the lumped parameter models cited in the previous paragraph also need to be history-matched to available production (i.e., pressure and temperature for the problem interest in the paper) data. Then they are used to perform future predictions of pressures for various production/injection schemes.

In this paper, we develop a new generalized lumped-parameter model which enables simulation of pressure and temperature behavior of multiple “tanks.” These tanks can represent multiple geothermal reservoirs or geothermal reservoirs with aquifers and can be used in various different combinations. Figures 1-5 illustrate the various combinations of tanks for the purpose of modeling the geothermal system.

As shown in Figure 1, a single-closed tank may be used to represent the system if the reservoir is isolated. If the reservoir is recharged by an aquifer, then the configurations given in Figures 2 and 3 may be used. Two communicating systems may also be modeled by using the configurations given in Figures 4 and 5. As it is clear, different combinations of tanks allow for a wide range of systems to be modeled and simulated for pressure and temperature behavior.

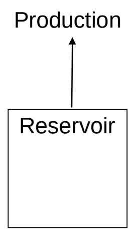

Figure 1: Illustration of a single tank used for representing the reservoir.

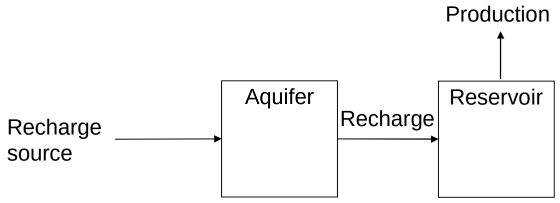

Figure 2: Illustration of a two tanks used for representing the reservoir and the aquifer that recharges the reservoir.

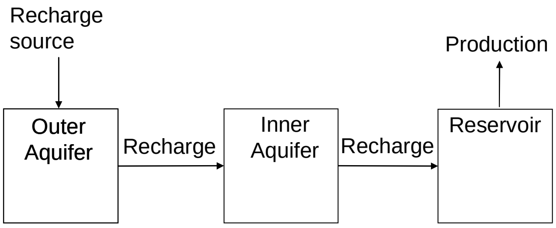

Figure 3: Illustration of three tanks used for representing the reservoir an inner aquifer and the outer aquifer.

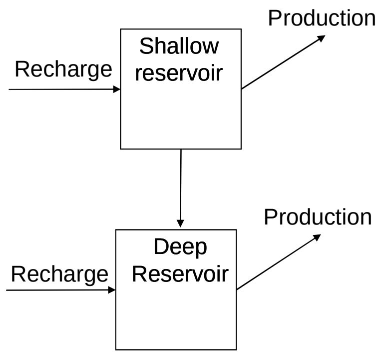

Figure 4: Illustration of two tanks used for representing two communicating reservoirs.

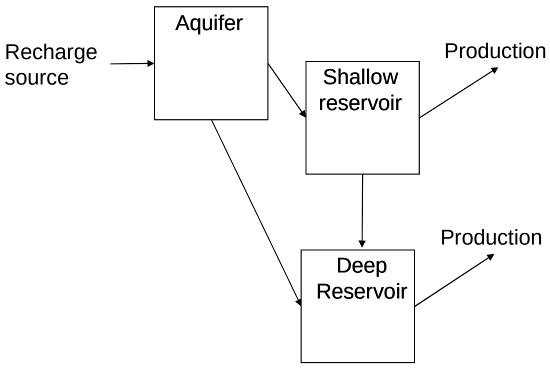

Figure 5: Illustration of three tanks used for representing two communicating reservoirs and a common aquifer.

The lumped parameter models given by Grant *et al*., 1982; Axelsson, 1989 and Sarak *et al*., 2005 are isothermal models. With this assumption while the pressure of the field can be modeled to a certain degree, the changes in temperature behavior of the system can not be accounted for. The changes in the temperature could be substantial when there are reinjection operations in a field or when the recharge is at a considerably different temperature. Even in completely closed systems, where there is only production from a closed reservoir, the system acts non-isothermally (Onur et al., 2008). This is because when mass is removed from the system, the internal energy is also decreased causing a slight decrease in the temperature. The behavior of the *average* temperature of the reservoir is naturally a function of the reservoir volume, production rate, re-injection rate, re-injection temperature, natural re-charge rate and the natural recharge temperature.

In this paper, we extend the work of Onur *et al*. (2008) to multiple tanks. We first describe the necessary mass balance and energy balance equations and further describe the generalization procedure. This is followed by various synthetic examples that illustrate the utilization of such models and the contribution of temperature information to parameter description.

2. THE GENERALIZED NON-ISOTHERMAL MODEL

The model developed in this study is based on the conservation of mass and energy for a single phase fluid (water). The system is assumed to be composed of N_t number of tanks. The mass balance and energy balance equations are then solved semi-numerically on all tanks jointly. Figure 6 illustrates the properties of a single tank for the model.

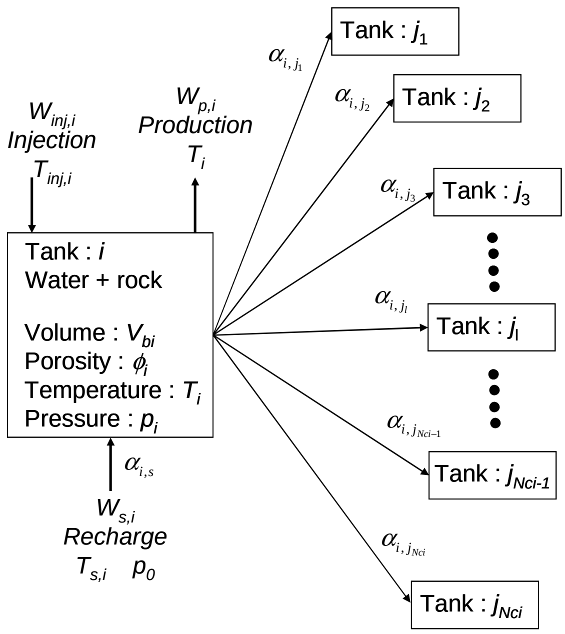

Figure 6: Illustration of tank *i* and its connections to other tanks denoted by the index j_l.

As it is clear from Figure 6, the tanks are composed of water and rock and that any tank *i* will have a bulk volume of V_{bi} (m^3), a porosity ϕ_i, a temperature T_i (°C), and a pressure p_i, (bar). Furthermore, any tank *i*, for *i*=1, 2,…, N_t, can make connections with any other tank j_l in the model. The total number of connections the tank *i* makes will be represented by the number N_{ci} and any connecting tank will be represented by j_l, *l*=1, 2,…, N_{ci} The tank *i* will have an injection term with a specified mass rate of $W_{inj,i}$ (kg/s) injecting fluid of a specified temperature, $T_{inj,i}$ (°C). The production term will be represented by the mass rate of $W_{p,i}$ (kg/s), which will be producing the fluid with the reservoir temperature T_i (°C). Furthermore, the tank could be associated with a recharge source whose pressure and temperature are assumed to remain constant at the initial pressure p_0 (bar) and a recharge temperature T_s (°C) respectively. The mass rate, W_s (kg/s), from the recharge source to the tank *i* in this case will be determined from the Schilthuis (1936) relationship given in Eq. 1.

$$W_s = \alpha_{i,s}\left(p_i - p_0\right) \quad (1)$$

Here the $\alpha_{i,s}$ (kg/(bar-s)) represents the recharge index which represents the amount of mass flow rate per unit pressure drop from the recharge source to the tank *i*. Similarly the mass flow rate, W_{i,j_l} (kg/s), from any tank j_l to tank *i* or vice versa can be determined by using Eq-2.

$$W_{i,j_l} = \alpha_{i,j_l}\left(p_{j_l} - p_i\right) \quad (2)$$

Under these assumptions the conservation of mass may be expressed as follows:

$$\begin{aligned} &V_{bi}\frac{d\left(\rho_w\phi_r\right)_i}{dt} + \alpha_{i,s}\left(p_0 - p_i(t)\right) + \\ &\sum_{l=1}^{N_{ci}}\alpha_{i,j_l}\left(p_{j_l}(t) - p_i(t)\right) + \\ &\left[W_{p,i}(t) - W_{inj,i}(t)\right] = 0 \end{aligned} \quad (3)$$

for i =1, 2,…, N_t. Here, $\rho_{w,i}$ (kg/m^3) is the density of the water in the tank and *t* (s) represents time. The first term on the LHS of Eq. 3 represents the accumulation of mass in the reservoir, the second term represents the mass flow rate from the recharge source in to the reservoir, the third term represents the net flow rate from the tanks that are connected and the fourth term represents the net production rate from the tank.

When heat transfer is considered for geothermal systems, usually convection dominates the process. In other words, the change in temperature is due mostly because of fluid movement such which arises from production, re-injection or flow from a recharge source. Heat transfer due to conduction and heat losses to the surroundings (such as flow out from springs or heat loss to the surrounding rocks) are neglected. Under these assumptions if we apply the conservation of energy to the tank shown in Figure 6 we have:

$$\begin{aligned} &\frac{d}{dt}\left[(1-\phi)V_b\rho_m C_m T + V_b\phi\rho_w u_w\right]_i - \\ &W_{inj,i}(t)h_{w,inj,i}\left(T_{inj,i},t\right) + W_{p,i}(t)h_{w,i}\left(T_i,t\right) - \\ &\alpha_{i,s}\left[p_i(t) - p_0\right]h_x + \\ &\sum_{l=1}^{N_{ci}}\alpha_{i,j_l}\left(p_{j_l}(t) - p_i(t)\right)h_y = 0 \end{aligned} \quad (4)$$

for, i=1, 2,…, N_t. Here, ρ_m (kg/m^3)is the density of the rock matrix, C_m (J/(kg°C)) is the rock specific heat capacity of the rock matrix, ρ_w (kg/m^3) is the density of the water , $h_{w,ini}$ (J/kg) is the specific enthalpy of the injected water and u_w (J/kg) is the specific internal energy of water. For the h_x and the h_y terms, we perform an upwinding scheme as follows:

$$h_x = \begin{cases} h_{w,i}\left(T_i,t\right) & \text{if } p_i > p_0 \\ h_{ws,i} & \text{if } p_i < p_0 \end{cases} \quad (5)$$

And

$$h_y = \begin{cases} h_{w,i}\left(T_i,t\right) & \text{if } p_i > p_{j_l} \\ h_{w,j_l}\left(T_{j_l},t\right) & \text{if } p_i < p_{j_l} \end{cases} \quad (6)$$

where, $h_{w,s}$ (J/kg) is the specific enthalpy of the recharge water and h_w (J/kg) is the specific enthalpy of the water in the tank.

The first term on the LHS of Eq. 4 represents the accumulation of energy in the rock and the fluid. The second term represents the heat flow to the tank from the injected fluid, the third term represents the heat removed from the tank via production, the fourth term represents the heat flow to the system from the recharge source and the fourth term represents the heat flow to the system from the connecting blocks. In this model the change of porosity with pressure and temperature is modeled using the following relationship:

$$\phi(p,T) = \phi_0\left[1 + c_r\left(p - p_0\right) - \beta_r\left(T - T_0\right)\right] \quad (7)$$

Here, ϕ_0 is the porosity of the tank at initial conditions, c_r (1/bar) is the compressibility of the rock and β_r (1/°C) is the thermal expansivity of the rock.

The model has been developed for the general case of varying injection/production rates and enthalpies. The internal energy, enthalpy and density of the water are calculated from the equations based on the steam tables (Steam Tables, 1967) for the range of 0.0061-1000 bar for pressure and 0.01-350°C for temperature. Eqs. 3 and 4 are non-linear differential equations. Hence a fully implicit Newton-Raphson procedure is used to handle the non-linearity. A forward finite difference discretization scheme is used for the terms involving the derivative of the time. The primary variables are set as the pressures and temperatures of the tanks i for i=1, 2,…, N_t.

3. EXAMPLE SYNTHETIC APPLICATIONS

In this section, we provide a few synthetic applications of the generalized non-isothermal model. We aim to provide insight and understanding to the utilization of the non-isothermal models and to the problem of jointly modeling pressure and temperature behaviors of tank models along with their benefits.

3.1 The Re-injection Problem

One of the areas that the multi-tank non-isothermal model could be beneficial is the re-injection problem. In this section we study the temperature and pressure behaviors of two tanks, one representing the reservoir and the other representing the aquifer for a re-injection scheme. Our aim is to study the effects of temperature on the location of re-injection (whether the re-injection should be performed into the reservoir or into the aquifer). We compare the pressure and temperature performances of two different cases where the fluid is either (case i) re-injected into the aquifer or (case ii) injected into the reservoir. The two tank system representing the reservoir and the aquifer is given in Figure 7. Note that for the two-tank system shown in Figure 7, we solve two mass balance equations (Eq. 3) and two energy balance equations (Eq. 4) for each tank, i.e., for i = 1 and 2, and take N_{ci} = 1 for each i.

The common properties of the reservoir and the aquifer used for this example are given in Table 1.

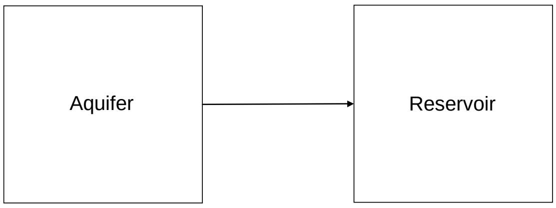

Figure 7: Illustration of the two tank system representing the reservoir and the aquifer.

Table 1: Properties of the reservoir and the aquifer.

α_r, (kg/(bar-s)	10
$V_{reservoir}$, m^3	1×10^8
$V_{aquifer}$, m^3	1×10^9
p_i, bar	50
$T_{0,reservoir}$, °C	140
$T_{0,aquifer}$, °C	100
$\phi_{reservoir}$	0.1
$\phi_{aquifer}$	0.1
$c_{r,reservoir}$, 1/bar	1×10^{-4}
$C_{,raquifer}$, 1/bar	1×10^{-4}
$\beta_{r,reservoir}$, 1/°C	0
$\beta_{r,aquifer}$, 1/°C	0
$\rho_{m,reservoir}$, kg/ m^3	2600
$\rho_{m,aquifer}$, kg/ m^3	2600
$C_{m,reservoir}$, J/(kg°C)	1000
$C_{m,aquifer}$, J/(kg°C)	1000

The production/injection scenario is given in Figure 8. During the first 100 days, there is only production from the reservoir tank with a rate of 10 kg/s. Then for the following 100 days, the production is increased to 20 kg/s and re-injection is performed at 10 kg/s. During the final 2300 days, there is an equal amount of production and re-injection at a rate of 50 kg/s. The total time of production/re-injection period is 2500 days. We assume that the re-injection is performed at a temperature of 60°C. In Figure 8, negative rate history represents re-injection rate history. For re-injection, as mentioned previously, two different cases are considered. In the first case (case i), there is re-injection into the reservoir and in the second case (case ii) there is re-injection into the aquifer.

Figures 9 and 10 illustrate the pressure and temperature behaviors of the reservoir for both cases respectively. As it is clear from Figure 9, there is better pressure maintenance in the reservoir when the cold fluid is injected in to the reservoir. This is expected since when we re-inject into the aquifer, the fluid is not immediately transferred to the reservoir. It is interesting to see that in both cases the pressure of the reservoir decreases even though the production and re-injection rates are the same during the last 2300 days. In other words, although the net rate of mass is zero, the pressure still decreases. This is due to the fact that we are injecting fluid that is cooling the reservoir. Since the system is closed as shown in Figure 7, the fluid volume is decreased because of the cooling which causes a decrease in the pressure as well.

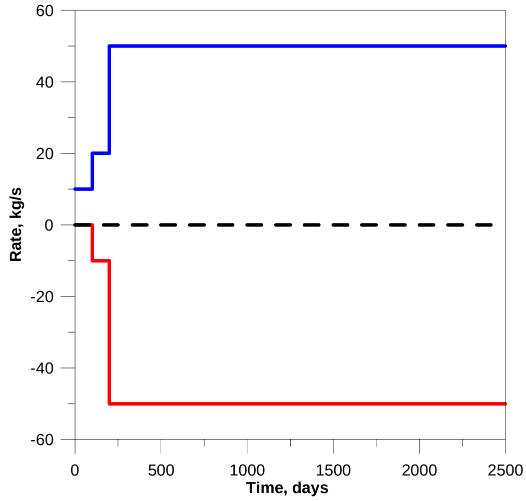

Figure 8: The production/injection scenario.

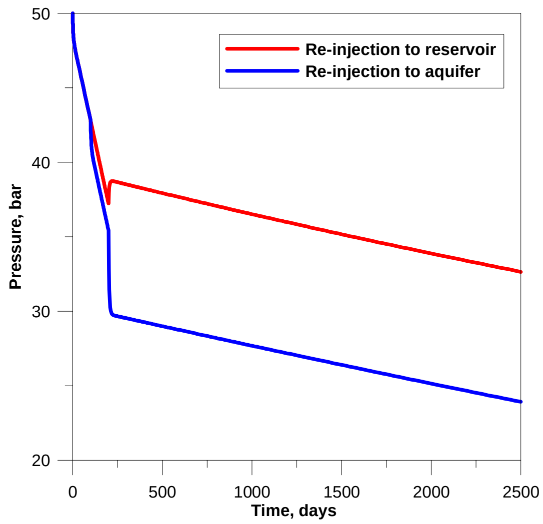

Figure 9: The pressure behavior of the reservoir comparing re-injection into the aquifer and the reservoir.

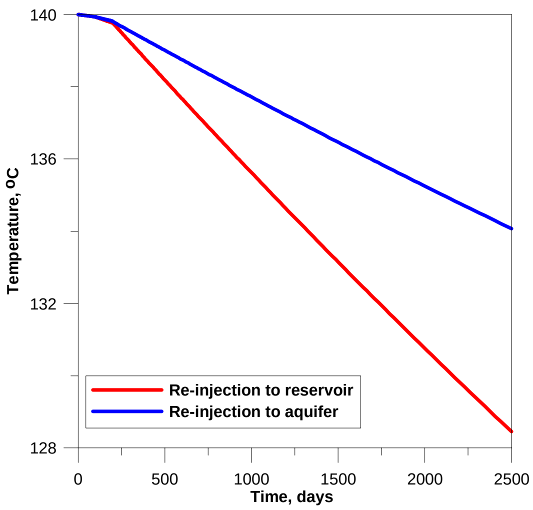

Figure 10: The temperature behavior of the reservoir comparing re-injection into the aquifer and the reservoir.

The cooling effect of the injected fluid on the reservoir is clearly illustrated in Figure 10 for both cases. It is clear that re-injection of the cold fluid into the aquifer is more favored in terms of temperature maintenance since it causes the temperature to be maintained at a higher level.

In the previous example, the aquifer initial temperature was at 100°C and the temperature of the re-injected fluid was at 60°C. Now we look at how the pressure and the temperature of the reservoir behave if the initial temperature of the aquifer is at 60°C and the temperature of the re-injected fluid is at 100°C. The other input data are the same as given in Table 1.The pressure and temperature behaviors of the reservoir for this case are given in Figure 11 and 12.

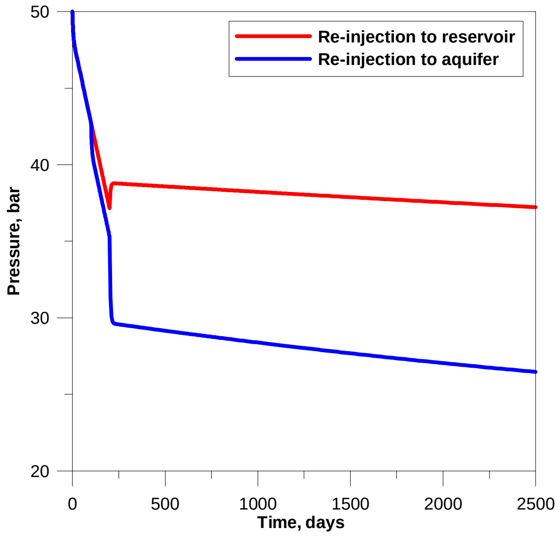

Figure 11: The pressure behavior of the reservoir comparing re-injection into the aquifer and the reservoir.

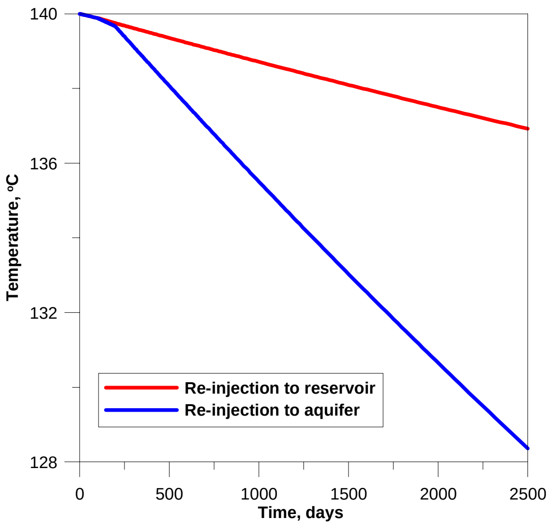

Figure 12: The temperature behavior of the reservoir comparing re-injection into the aquifer and the reservoir.

Inspecting Figure 11, we see that in terms of pressure maintenance, re-injecting into the reservoir is still favorable. However, Figure 12 clearly shows that this time re-injection into the reservoir becomes favorable in terms of temperature since it provides higher temperature maintenance.

As a result of the two examples given above, we may conclude that in terms of pressure maintenance, it does not matter what the temperatures of the aquifer and the re-injected fluid are, re-injection into the reservoir is always preferred. For maintaining the temperature, the location of the re-injection operation depends on the temperature of the re-injected fluid and the temperature of the recharge source. It is shown that if the re-injected fluid temperature is higher than the temperature of the recharge fluid then the re-injection should be performed into the reservoir. If the opposite is true, then re-injection should be performed into the aquifer.

3.2 The Information Content of Temperature

In this section we look at the additional information content of using temperature data in terms of reservoir and aquifer properties. We illustrate this point through the following example on a single tank which represents a closed reservoir. The properties of the reservoir are given in Table 2.

Table 2: Properties of the reservoir

α_r, (kg/(bar-s))	0
$p_{0,reservoir}$, bar	40
$T_{0,reservoir}$, °C	100
$c_{r,reservoir}$, 1/bar	1×10^{-4}
$\beta_{r,reservoir}$, 1/°C	0
$\rho_{m,reservoir}$, kg/ m^3	2600
$C_{m,reservoir}$, J/(kg°C)	1000

Two cases are considered and are given in Table 3. We look at two different scenarios of reservoir volume and reservoir porosity. However in both cases we keep the product of the volume and porosity to be the same.

Table 3: Variation of the reservoir volume and the reservoir porosity.

	V_b, m^3	ϕ	$V_b\phi$
Case-1	4×10^8	0.1	4×10^7
Caes-2	2×10^8	0.2	4×10^7

The production history for the two cases is illustrated in Figure 13. First there is a flow period, then a shut in and finally a second flow period. All flow and shut in periods are 200 days and production is achieved at 5 kg/s. Figure 14 illustrates the pressure behavior for the two cases. As it is clear, both pressure responses are almost identical. This is expected since the pore volume ($V_b\phi$) is a dominating factor for pressure and in both cases the pore volume is the same.

Figure 15 illustrates the temperature behavior for the two cases. It is clear that individual values of the volume and porosity (even when they give the same pore volume) cause a different temperature behavior for the reservoir. Hence we may conclude that temperature data may be used to distinguish the bulk volume from the porosity.

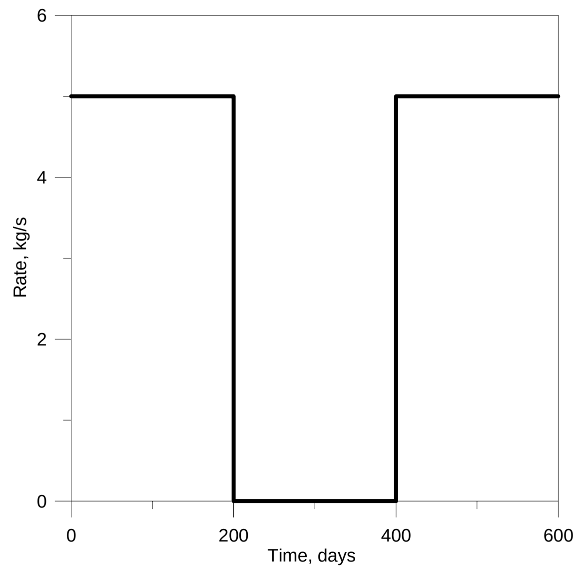

Figure 13: The production scenario for the two cases.

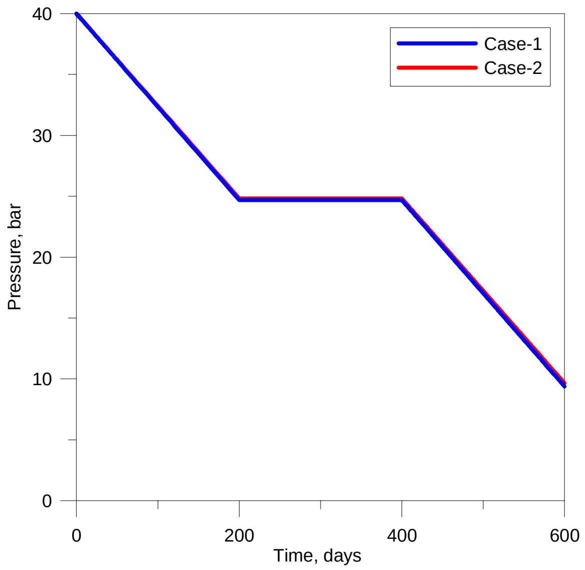

Figure 14: The pressure behavior for the two cases.

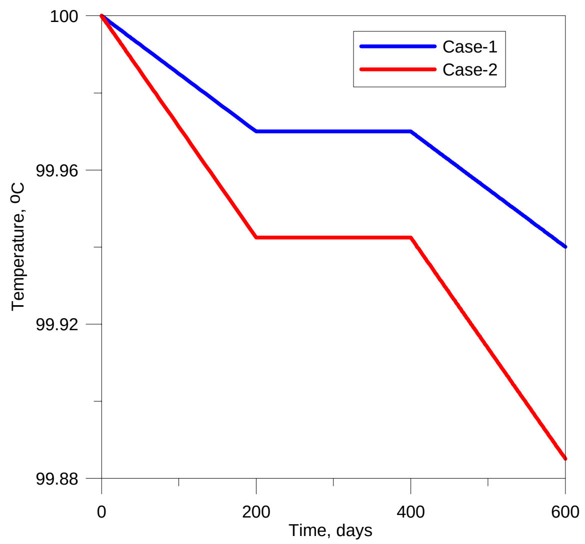

Figure 15: The temperature behavior for the two cases.

3.3 Estimation of Model Parameters by History Matching

In this section, we present an optimization method based on the Levenberg-Marquardt algorithm and couple it with our new model to obtain a procedure for pressure and temperature data analysis and demonstrate which of the model parameters could be estimated reliably through history matching. First the history matching method is described, followed by the application.

<u>The history matching problem</u>

The weighted least-squares objective function (Eq. 8) is used for the parameter estimation. The objective function is designed in a general way as to be able to match pressure or temperature or both data sets simultaneously obtained from any number of tanks.

$$O(\boldsymbol{m}) = \sum_{i=1}^{N_t} \left\{ \frac{1}{2} I_p \sum_{l=1}^{N_{pi}} \left[\frac{p_{m,l,i} - p_{c,l,i}}{\sigma_{p,l,i}} \right]^2 + \frac{1}{2} I_T \sum_{k=1}^{N_{Ti}} \left[\frac{T_{m,k,i} - T_{c,k,i}}{\sigma_{T,k,i}} \right]^2 \right\} \tag{8}$$

The I_p and I_T terms in Eq. 8 are indicators which can only be either a "1" or a "0". These indicators are used for matching either pressure, temperature or both. p_m and T_m represent the measured pressure and temperature. P_c and T_c are the computed pressures and temperatures using the non-isothermal lumped parameter model. N_p and N_T are the total number of data points to be matched for pressure and temperature respectively. σ_p and σ_T represent the standard deviation of the errors associated with the pressure data and the temperature data respectively. The vector of model parameters (denoted by the bold face letter m in LHS of Eq. 8), for any tank *i*, that could be optimized through the minimization of Eq. 8 contains the bulk volume, porosity, recharge indices for the recharge source or any connecting tank, initial temperature, initial pressure, recharge temperature, rock compressibility, rock thermal expansivity, rock specific heat and the rock density.

<u>Application of history matching to the re-injection problem</u>

In this section we apply history matching to the re-injection problem given previously. The system is given in Figure 7 with aquifer and reservoir properties given in Table 1.

First we generate synthetic pressure and temperature data to be matched using the production/injection scenario given in Figure 8. Then noise is added to mimic real reservoir data. The noise added to pressure has a standard deviation of σ_p=0.1 bar and the noise added to temperature has a standard deviation of σ_T=0.05°C. The pressure and temperatures are given in Figures 16 and 17 respectively. It is important to note that we have considered the case where the aquifer initial temperature is 100°C and the re-injected fluid is at a temperature of 60°C. Since for this case re-injection into the aquifer provided better temperature maintenance we choose to re-inject into the aquifer.

With the application of history matching we attempt to estimate the following parameters; initial pressure, initial temperatures of the reservoir and the aquifer, recharge constant between the reservoir and aquifer, porosities of the reservoir and the aquifer and finally the volumes of the reservoir and the aquifer. This totals to eight parameters to be estimated.

We approach the problem in three steps; first history matching is performed on only the pressure data from the reservoir, then the reservoir temperature is also used for history matching and finally pressure and temperatures from both the aquifer and the reservoir are used together. Tables 4-6 give the estimated parameters and their 95% confidence intervals for the three steps respectively. At this point it is important to note that confidence intervals are very important statistics for non-linear parameter estimation. They provide insight as to how sensitive a parameter is to the variable that is being matched. If the confidence interval of an estimated parameter is small, this means that the variable that is matched (such as pressure and temperature) provides information about the parameter. We will consider a computed confidence interval to be acceptable if the confidence interval is smaller than the estimated parameter.

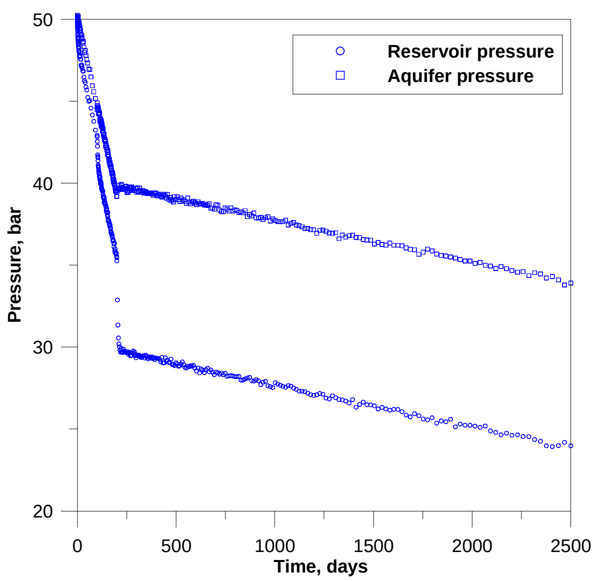

Figure 16: The synthetically generated pressures for the reservoir and the aquifer.

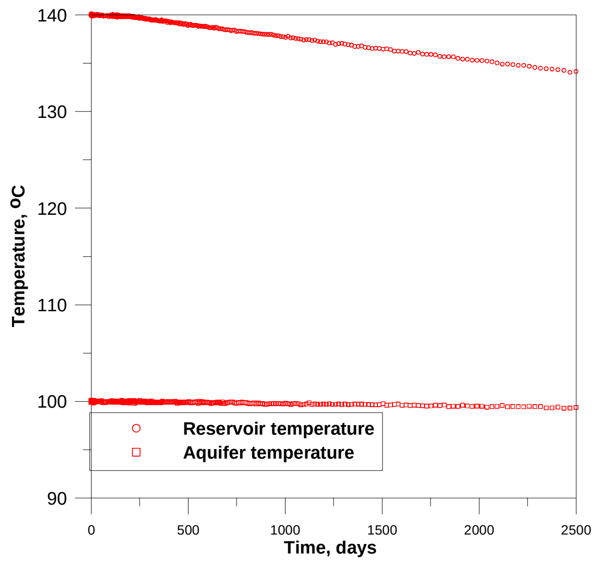

Figure 17: The synthetically generated temperatures for the reservoir and the aquifer.

An inspection of Table 4 indicates that matching to reservoir pressure data alone is enough only for determining the initial pressure and the recharge index with small confidence intervals. Other parameters have very high confidence intervals indicating that these parameters can not be determined accurately. Based on Table 4 we can also state that the initial pressure and the recharge index are the two parameters that influence the pressure the most.

Table 5 gives the results of the estimation when temperature data is also used in addition to pressure data. It is clear that all estimated parameters now have acceptable confidence intervals, indicating that we have accurately estimated all parameters. The benefits of adding temperature information in addition to pressure data allows us to estimate parameters other than the initial pressure and the recharge index which are the only parameters that can be determined if pressure is used alone. On top of this if we further add pressure and temperature data from the aquifer, as expected, we make even better estimations with even smaller confidence intervals as shown in Table 6. Finally, Figures 18 and 19 show the overall quality of the match for the pressure and temperatures of the reservoir and aquifer.

Table 4: Estimation of parameters as a result of matching only the pressure data from the reservoir.

Model parameter	Unknown true value	Estimated parameters
p_0, bar	50	50.006 ± 0.027
$T_{0,\ reservoir}$, °C	140	162.71 ± 2724.77
$T_{0,\ aquifer}$, °C	100	103.27 ± 3566.98
α, kg/s	5	5.024 ± 1.397
$\phi_{reservoir}$	0.1	0.081 ± 5.754
$\phi_{aquifer}$	0.1	0.005 ± 3.159
$V_{reservoir}$, m^3	1×10^8	$1.17\times10^8 \pm 7.77\times10^9$
$V_{aquifer}$, m^3	1×10^9	$2\times10^8 \pm 1.25\times10^{11}$

For pressure RMS=0.1 bar

Table 5: Estimation of parameters as a result of matching both the pressure and temperature data from the reservoir.

Model parameter	Unknown true value	Estimated parameters
p_0, bar	50	50.006 ± 0.025
$T_{0,\ reservoir}$, °C	140	140 ± 0.008
$T_{0,\ aquifer}$, °C	100	101.7 ± 4.45
α, kg/s	5	5.006 ± 0.039
$\phi_{reservoir}$	0.1	0.102 ± 0.014
$\phi_{aquifer}$	0.1	0.098 ± 0.016
$V_{reservoir}$, m^3	1×10^8	$9.56\times10^7 \pm 1.28\times10^7$
$V_{aquifer}$, m^3	1×10^9	$1.02\times10^9 \pm 1.62\times10^8$

For pressure RMS=0.1 bar and for temperature RMS=0.05°C

Table 6: Estimation of parameters as a result of matching both the pressure and temperature data from the reservoir and the aquifer.

Model parameter	Unknown true value	Estimated parameters
p_0, bar	50	50.008 ± 0.015
$T_{0,\ reservoir}$, °C	140	140 ± 0.006
$T_{0,\ aquifer}$, °C	100	100 ± 0.005
α, kg/s	5	4.99 ± 0.01
$\phi_{reservoir}$	0.1	0.099 ± 0.002
$\phi_{aquifer}$	0.1	0.1 ± 0.003
$V_{reservoir}$, m^3	$1{\times}10^8$	$1{\times}10^8 \pm 3.79{\times}10^5$
$V_{aquifer}$, m^3	$1{\times}10^9$	$9.99{\times}10^8 \pm 2.75{\times}10^7$

For pressure RMS=0.1 bar and for temperature RMS=0.05°C

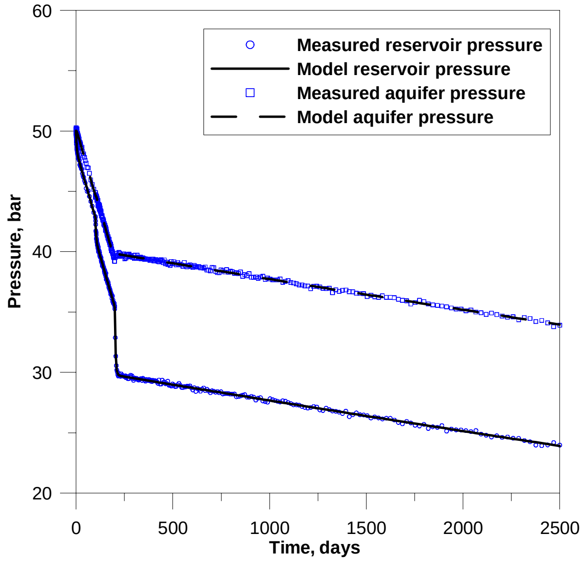

Figure 18: History match of reservoir and aquifer pressure data.

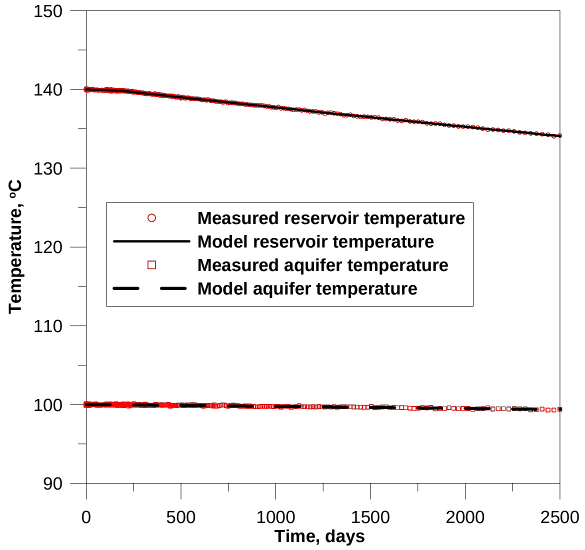

Figure 19: History match of reservoir and aquifer temperature data.

4. CONCLUSIONS

The following conclusions are obtained from this study:

A generalized non-isothermal lumped parameter model has been developed. The model is based on solving the mass balance and energy balance equations simultaneously for each tank in the system. This allows for modeling temperature behavior as well as pressure behavior.

It is shown that in terms of maintaining pressure, re-injection operations should be carried out in the reservoir. From a temperature maintenance point of view, the re-injection location depends on the temperature of the aquifer. If the temperature of the re-injected fluid is higher, than the re-injection should be performed into the reservoir. Otherwise the re-injection should be performed into the aquifer.

It is shown that using temperature data as well as pressure data allows for better estimation of various parameters. In the given example, while pressure allows estimation for only the initial pressure and the recharge index, the additional temperature information allows estimation for other parameters, particularly for the bulk volumes and porosities of the reservoir and aquifers.

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