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A NEW NON-ISOTHERMAL LUMPED-PARAMETER MODEL FOR LOW TEMPERATURE, LIQUID DOMINATED GEOTHERMAL RESERVOIRS AND ITS APPLICATIONS

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ABSTRACT

We have developed a non-isothermal lumped-parameter model for predicting both pressure and temperature behaviors of low temperature geothermal reservoirs containing a single-phase liquid water. Unlike the existing isothermal lumped-parameter models in the literature, the new model couples both energy (or heat) and mass balance equations and hence can be used to predict both temperature and pressure changes in the reservoir resulting from production of hot water, re-injection of a low temperature water into the system, and/or natural recharge. Variable production and re-injection rate histories are also handled. We have also developed an optimization code based on the Levenberg-Marquardt algorithm and coupled it with our new model to obtain a procedure for pressure and temperature data analysis. By considering semi synthetic pressure/temperature data sets, we demonstrate that we can generate estimates of reservoir bulk volume, porosity, temperature of the recharge source, recharge index, initial reservoir pressure and temperature by matching measured reservoir pressure and temperature data to our corresponding model responses by minimization of a weighted least-squares objective function. By using history matched models based on the new non-isothermal model, we also demonstrate that the future performance of a low-temperature geothermal reservoir can be predicted (yet more realistically, particularly for predicting the future reservoir temperature behavior, than those based on existing isothermal lumped-parameter models).

INTRODUCTION

The behavior of geothermal systems can be modeled through two approaches; using numerical models or by using lumped-parameter models. Numerical models have the advantage of being more general such that heterogeneities, various different reservoir geometries, multiple production and re-injection wells and etc. can easily be incorporated in the model. However, these numerical models usually require extensive amounts of data which are usually not available (especially for newly discovered fields) in practice. Furthermore the long run-times associated with these models provide yet another disadvantage for history matching where the model needs to be run many times.

Lumped parameter models provide a good alternative to numerical models due to the much fewer parameters involved and the relatively shorter run-times. The pressure behavior of a low-temperature geothermal reservoir has been modeled before by Grant *et al*., 1982; Axelsson, 1989, Sarak *et al*., (2005) and Tureyen *et al*., 2007. Just as in modeling with numerical models, lumped-parameter models are first history matched to production data using non-linear regression techniques. Then, future predictions of pressure or water levels can be made (by using the parameters obtained during the history matching phase) for various production/injection schemes. By making multiple predictions for multiple schemes, field management can be improved.

The lumped-parameter models given in the above references are all based on the assumption that the reservoir can be treated as an isothermal system. With this assumption, while the pressure behavior of the system can be modeled, the changes in the temperature can not be accounted for. The changes in the temperature can be substantial when there are re-injection operations in a field or when the recharge is at a significantly different temperature. Even in completely closed systems, where there is only production, because an amount of mass is removed from the system, the pressure decreases and hence the internal energy is decreased as well causing a slight decrease in the temperature. In other words, even if there is only production from a closed reservoir, the system acts as a non-isothermal system. 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 recharge rate and the natural recharge temperature.

The mathematical background of the non-isothermal lumped parameter model is given first, followed by the verification of the new model. Then we present some of the benefits and the key factors regarding the non-isothermal model through semi synthetic field applications.

THE NON-ISOTHERMAL LUMPED-PARAMETER MODEL

The model developed in this study is based on the conservation of mass and conservation of energy for a single phase fluid (water). The single tank model is schematically illustrated in Fig.1.

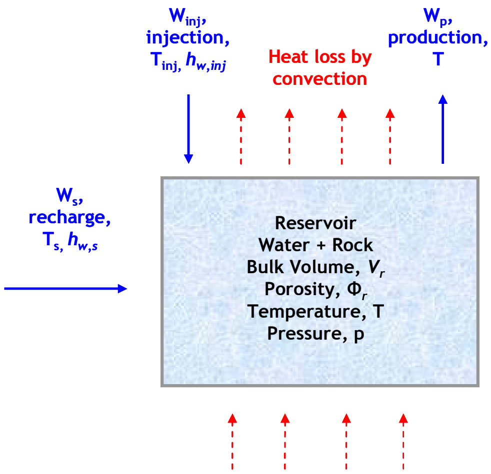

Figure 1. Idealized one tank non-isothermal lumped parameter model.

As illustrated in Fig.1, the geothermal system is considered as a single tank. W_p (kg/s) represents the total production and W_{inj} (kg/s) represents the total injection rate of water from any number of wells in the reservoir. Hence the net production rate W (kg/s) can be determined by:

$$W = W_p - W_{inj} \tag{1}$$

Due to production from the tank, fluid flow will take place from the recharge source in to the tank. The mass flow rate of such a recharge is represented by W_s (kg/s) and is approximated by (Axellson, 1989; and Sarak et al., 2005):

$$W_s = \alpha_s \left[p_i - p(t) \right] \tag{2}$$

Here α_s (kg/(bar-s)) represents the recharge index which gives the amount of mass flow rate per unit pressure drop, p_i (bar) is the initial pressure and $p(t)$ (bar) represents the average pressure of the reservoir as a function of time. Under these assumptions, the conservation of mass may be expressed as follows:

$$V_r \frac{d(\rho_w \phi_r)}{dt} - \alpha_s \left[p_i - p(t) \right] + \left[W_p(t) - W_{inj}(t) \right] = 0 \tag{3}$$

The first term on the LHS represents the accumulation of mass in the reservoir, the second term represents the mass flow rate from the recharge source in to the reservoir and the third term represents the net production rate from the reservoir.

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 as 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 Fig.1 we have:

$$\frac{d}{dt}\left[(1-\phi_r) V_r \rho_m C_m T + V_r \phi_r \rho_w u_w \right] - W_{inj}(t) h_{w,inj}(t) - \alpha_s \left[p_i - p(t) \right] h_{ws}(t) + W_p(t) h_{w,p}(t) = 0 \tag{4}$$

The first term on the LHS represents the accumulation of energy, the second term represents the heat flow to the system from the injected fluid, the third term represents the heat flow to the system from the recharge source and the fourth term represents the heat flow due to the produced fluid. In this model the change of porosity with pressure and temperature is modeled using the following equation:

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

The variables given in Eqs. 3-5 are given in the nomenclature.

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 discretization scheme is used for the terms involving the derivative of the time. The primary variables are set as pressure and temperature. So far we have developed the model for a single tank. The extension to multiple tanks should be straightforward. For example, for a two tank system, two mass balance and two energy balance equations need to be solved for the pressures and temperatures of the tanks.

VERIFICATION OF THE MODEL

The results of the non-isothermal lumped-parameter model have been verified by comparing the results with the PetraSim (Petrasim) geothermal software which is based on the well known simulator Tough-II (Pruess *et al.*, 1999) and with our in house 1D simulator developed during the course of this study. The comparisons have been performed on a number of different cases, where the pressures and temperatures of the non-isothermal lumped parameter model have matched perfectly with the output of PetraSim and our in house simulator. In this section we only present two synthetic examples; one with recharge and one without recharge. The model is compared for both cases based on the parameters given in Table.1.

Table 1: Parameters used in the model verification.

β_r, 1/°C	0
ϕ_r, [fraction]	0.2
c_r, 1/bar	1.33×10^{-4}
ρ_w, kg/m^3	928.5*
ρ_r, kg/m^3	2650
C_m, J/(kg °C)	1000
V_r, m^3	1.0×10^{7}
p_i, bar	50
Ti, °C	140
T_{inj}, °C	60
$h_{w,inj}$, J/kg	255.3
* Density of water at p_i=50 bar and T_i=140°C	

The production and injection flow rate histories for the examples are given in Fig.2. During the period between 0-10 days, there is a production rate of 20 kg/s and an injection rate of 15 kg/s. Then the wells are all shut in for 10 days followed by another 10 days of a production/injection period with rates the same as before.

Case with no recharge

In this case, because the system is closed, there will be no flow from the recharge source. In other words, α_s=0 in Eqs 2, 3 and 4. . The PetraSim model for this case is composed of a single grid block with a volume of $V_r = 10^7$ m^3, which is closed to any fluid flow or heat flow from the surroundings. The results are given in Figs. 3 and 4.

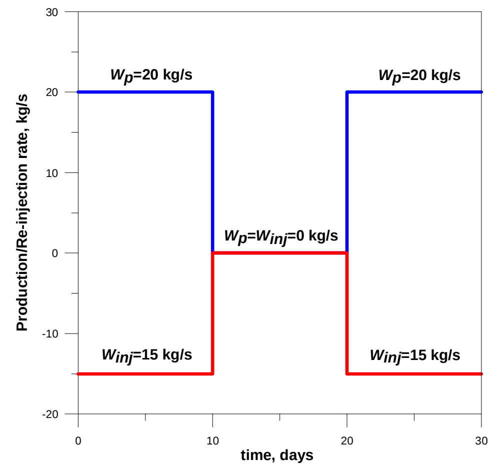

Figure 2: The production / injection rate scenario.

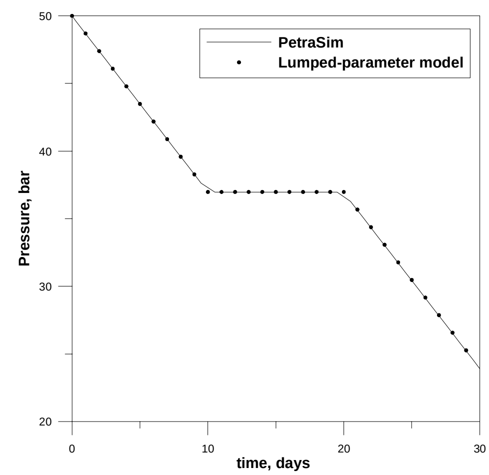

Figure 3: Comparison of PetraSim and the lumped-parameter model for pressure.

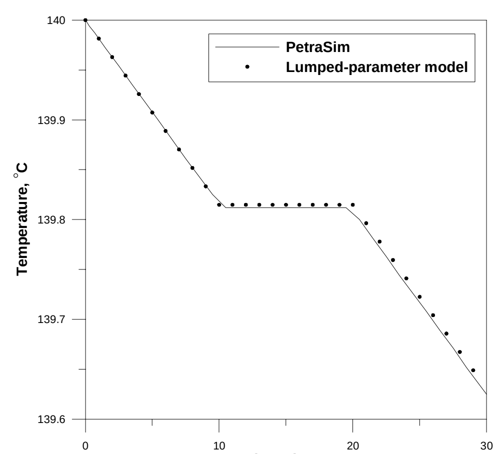

Figure 4: Comparison of PetraSim and the lumped-parameter model for temperature.

As it is clear from Figs 3 and 4, production from a closed system causes a decrease in both the pressure and temperature. The non-isothermal lumped parameter model agrees well with the results of the PetraSim model.

Case with recharge

The lumped-parameter model is also verified for a case where there exists a recharge source. The results are again compared with the PetraSim program. The production/injection is the same as that given in Fig.2. The recharge source is assumed to have a recharge index of α_s=1 kg/(s-bar). Furthermore, the recharge source is assumed to have a temperature equal to the initial temperature of the reservoir, $T_s=T_i$=140°C and the enthalpy of the recharge water is assumed to be the same as the enthalpy at the initial conditions.

The PetraSim model used for this case is given in Fig. 5.

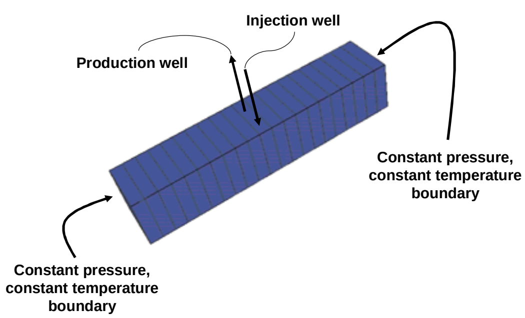

Figure 5: Illustration of the PetraSim model used for the verification.

We have used a 1D model that has the same volume as that of the lumped parameter model with a production well and an injection well at the center of the reservoir. To model the recharge to the reservoir, we have considered constant pressure and constant temperature boundaries on both sides of the system (Fig. 5). Because of the boundaries of this type, we would now need to consider flow from the boundaries to the wells. Hence, to minimize the discretization errors, we have considered a grid system consisting of 21 grid blocks. Comparisons with the lumped parameter model are therefore made with the average reservoir temperature and pressure of the PetraSim model for any given time (the averages are computed based on pore volume weighted averaging).

The permeability of the PetraSim model and our 1D in house simulator needs to be assigned such that the amount of flow from the outer boundaries should be equal to that provided by Eq. 2 with α_s=1 kg/(s-bar) for the lumped-parameter model. In other words, the permeability should be such that the two models have the same amount of recharge. To adjust the permeability we have used the relationship derived by Ay (2005), which gives the relation between α_s and the permeability.

$$\alpha_s = 8\frac{wz}{L_x}\frac{k}{\mu_w}\rho_w \qquad (6)$$

From Eq.6, for α_s=1 kg/(s-bar), we have computed the ratio $k/\mu_w = 1.343\times10^{-5}$ m^2/(bar-s). The viscosity of water at p_i=50 bar and T_i=140°C is $\mu_w=2.024\times10^{-9}$, hence the permeability is determined to be $k=2.719\times10^{-14}$ m^2. This permeability and a porosity of ϕ=0.2 is used for all 21 grid blocks and the output pressures and temperatures of the blocks are averaged and compared with the lumped-parameter model. A further comparison and verification was also made with our in house 1D simulator developed during the course of this study (see Figs. 6 and 7).

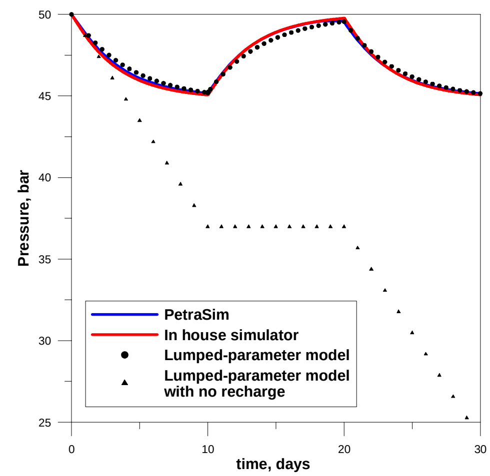

Figure 6: Comparison of PetraSim, our in house simulator, lumped parameter model and the lumped parameter model without recharge for pressure.

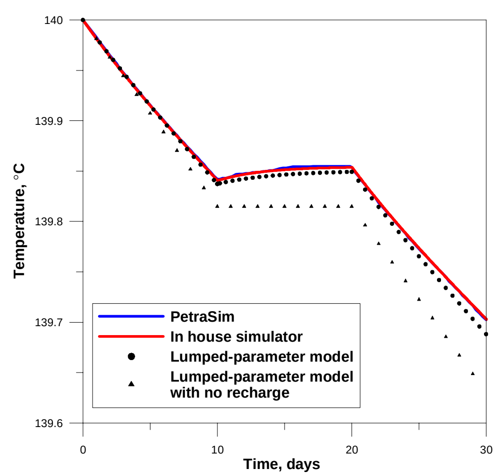

Figure 7: Comparison of PetraSim, our in house simulator, lumped parameter model and the lumped parameter model without recharge for temperature.

As it is clear from Figs. 6 and 7, the non-isothermal lumped-parameter model reproduces well the results of PetraSim and our in house simulator both for pressure and for temperature. The results of the case without any recharge are also shown in Figs. 6 and 7 for comparison. As expected, due to the recharge, both pressure and temperature tends to decrease less when compared with the case without recharge. Another interesting feature can be observed during the shut-in period where both pressure and temperature increase. However, while the increase in pressure during this period is substantial (the pressure has increased almost to the initial pressure), the increase in temperature is very small compared to the increase in pressure.

APPLICATIONS WITH THE NON-ISOTHERMAL LUMPED-PARAMETER MODEL

In this section we present applications with the non-isothermal lumped-parameter model using a semi synthetic example with field properties taken from the İzmir Balcova-Narlidere field. The objective here is to conduct a sensitivity of the model parameters on the pressure and temperature responses of the system. Some of the parameters under investigation are; the natural recharge temperature (T_s), the recharge index (α_s), porosity (ϕ), bulk volume (V_r) and the rock compressibility (c_r).

Sensitivity on the Model Parameters; The Izmir Balcova Synthetic Example

The production/reinjection scheme used through out this section is given in Fig. 8. The data reflect the period between 01 January 2000 and 10 November 2005. The "0" point on the time axis corresponds to 01 January 2000. The last data (at 2141 days) has been obtained on 10 November 2005. The scenario in Fig. 8 represents the total production and injection rates.

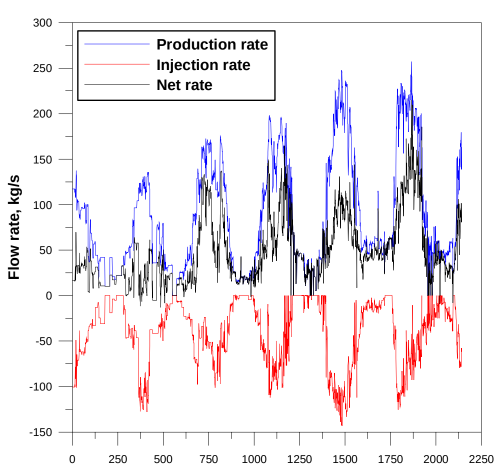

Figure 8: The production/Injection scheme between 01 January 200 and 15 November 2005.

Using the net rate given in Fig. 8, Tureyen *et al.* (2007) have performed history matching using 5 different isothermal lumped-parameter models, from which they have determined that the model that best described the system was a single tank open model. After the history matching step, the recharge index was determined to be α_s=45 kg/(bar-s) and the storage capacity as κ=8.4×10^7 (kg/bar). Note that κ is a group parameter defined by:

$$\kappa = V_r \phi_r c_t \rho_w \tag{7}$$

The c_t term in Eq. 7 represents the total compressibility of the system, c_t=c_r+c_w. At this point it is important to note that in the non-isothermal lumped parameter model, the change of c_w is accounted for while c_r is treated as a fixed parameter. On the other hand, c_w, and the density of water ρ_w is treated as a constant in the isothermal lumped-parameter model. In the applications regarding the isothermal lumped-parameter model, c_w, ρ_w, and ϕ_r are computed at the initial pressure and temperature p_i and T_i and hence κ is held constant for all times. Since the bulk volume is always treated constant, we may think of κ as being evaluated at the initial conditions. On the other hand, we would expect κ to change with pressure and temperature, though not significantly, in the non-isothermal model due to changes in reservoir porosity, water density and compressibility. The initial pressure and temperature of the Izmir Balcova-Narlidere geothermal field is assumed to be approximately around p_i=50 bar and T_i=140°C. Hence at these initial conditions, the density and compressibility of water is computed as ρ_w=928.5 kg/m^3 c_w=5.92×10^{-5} 1/bar. The rock compressibility and reservoir porosity of the Izmir Balcova-Narlidere geothermal field are unknown. However, if we assume the rock compressibility to be c_r=1.33×10^{-4} 1/bar and assign a porosity of ϕ=0.05, then we compute the bulk volume of the reservoir to be V_r=9.42×10^9 m^3. It is important to note that due to the uncertainties in the rock compressibility and reservoir porosity the computed bulk volume is also uncertain, and hence the value of V_r considered for the field in our applications given here may not represent the actual, unknown reservoir bulk volume.

The effect of the recharge temperature T_s on the reservoir pressure and temperature

The sensitivity regarding the recharge temperature T_s is carried out by considering three different temperatures; T_s =80, 100 and 140°C for the flow scenario given in Fig. 8. Other parameters regarding the field are given in Table 2.

The effect of the recharge temperature (T_s) on the pressure is given in Fig. 9 along with the behavior of the isothermal lumped-parameter model.

Table. 2 Parameters used with the non-isothermal lumped-parameter model.

α_s	45	c_r	1.33×10^{-4}
p_i	50	c_w	5.92×10^{-5} @p_i and T_i
T_i	140	c_t	1.92×10^{9}
ϕ_i	0.05	ρ_w	928.5 @p_i and T_i
V_r	9.42×10^{9}	ρ_m	2650
C_m	1000	β_r	0
T_{inj}	60	$h_{w,inj}$	255263
h_{ws}		592125 @50 bar and 140°C	
		422742 @50 bar and 100°C	
		338850 @50 bar and 80°C	

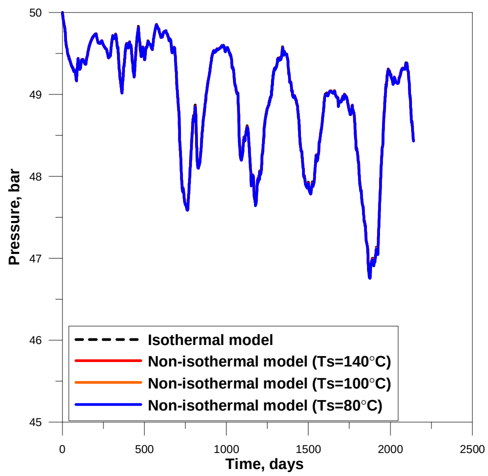

Figure 9: The effect of the recharge temperature on pressure for T_s=80, 100 and 140°C.

As it is clear from Fig.9, the recharge temperature has almost no effect on the pressure. In fact, even the isothermal model response is almost identical with the results of the non-isothermal model.

The effect of the recharge temperature (T_s) on the temperature of the reservoir is given in Fig. 10. The temperature of the reservoir in this case decreases. The main reasons are that there is recharge and injection into the reservoir at temperatures lower than the reservoir temperature. Furthermore, because there is a positive net flow rate (indicating that mass is removed from the reservoir), the temperature decreases.

The effect of the recharge index α_s on the reservoir pressure and temperature

In this section, we study the sensitivity of the recharge index α_s on the pressure and temperature behavior. Three different values of the recharge index are considered, α_s=10, 25 and 45 kg/(bar-s). For all cases, the recharge temperature is kept at T_s=140°C. The effect on the pressure is given in Fig. 11.

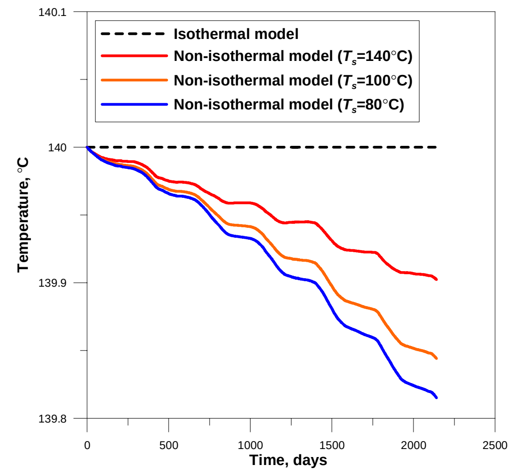

Figure 10: The effect of the recharge temperature on reservoir temperature for T_s=80, 100 and 140°C.

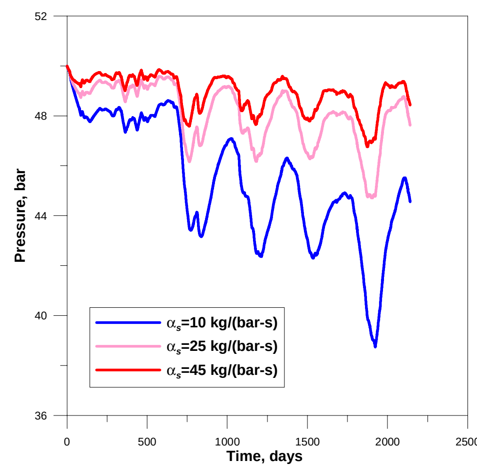

Figure 11: The effect of the recharge index α_s on the pressure.

As the recharge index α_s decreases, the pressure decreases more. Because the recharge index controls the amount of flow into the reservoir, for smaller values of α_s there is less pressure maintenance. Although not shown in Fig. 11, the model results for the isothermal model are exactly the same. In other words the effects of non-isothermal flow on reservoir pressure behavior are negligible.

Fig. 12 illustrates the effects of the recharge index on temperature.

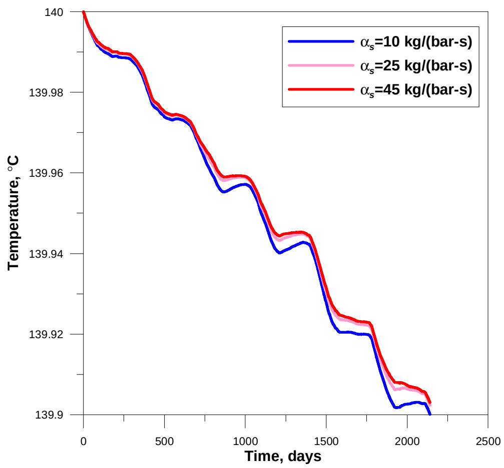

Figure 12: The effect of the recharge index α_s on the temperature.

Because the recharge temperature (T_s) is identical for all three cases considered in Fig. 12, there is practically no effect of the recharge index α_s on the temperature behavior of the reservoir.

The effects of bulk volume, porosity and rock compressibility on the reservoir pressure and temperature

As we have seen previously, practically there is no distinction between the results of the isothermal model and the newly developed non-isothermal lumped-parameter model when the pressure behavior is considered, as long as the recharge index α_s and the storage capacity κ are kept constant. Hence as long as we are interested only in making pressure predictions, the isothermal lumped-parameter models should be sufficient.

However, the isothermal model lacks the capability of modeling the behavior of temperature. For this reason we investigate the information contents of pressure and temperature responses predicted by the non-isothermal model. In this section we analyze the effects of the parameters that make up the group parameter κ, as given in Eq. 7. We consider four cases. For all cases we keep κ constant but vary the individual parameters V_r, ϕ_i and c_r. Table 3 summarizes these cases. Figs 13 and 14 illustrate the results.

Table 3: Variation of V_r, ϕ_i and c_r for the four cases.

	V_r	ϕ_i	c_r	c_t	ρ_w	κ
1	9.42×10^9	0.05	1.33×10^{-4}	1.92×10^{-4}	928.5	8.4×10^7
2	1.89×10^9	0.25	1.33×10^{-4}	1.92×10^{-4}	928.5	8.4×10^7
3	9.42×10^8	0.5	1.33×10^{-4}	1.92×10^{-4}	928.5	8.4×10^7
4	1.89×10^9	0.07	5.99×10^{-4}	6.58×10^{-4}	928.5	8.4×10^7

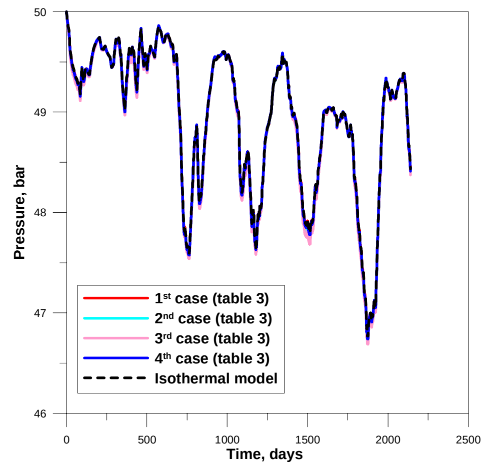

Figure 13: Effects of V_r, ϕ_i and c_r on pressure.

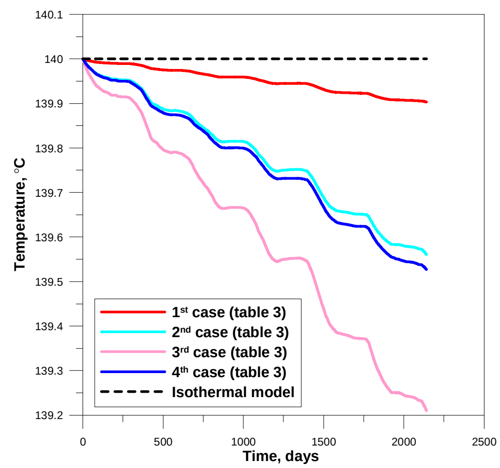

Figure 14: Effects of V_r, ϕ_i and c_r on temperature.

The results given in Figs 13 and 14 can be summarized as follows:

(a) The reservoir pressure (Fig. 13) is controlled by two parameters, α_s and κ. Hence these two parameters may be uniquely estimated from the pressure data through history matching. The individual parameters V_r, ϕ_i and c_r can not be estimated uniquely from the pressure data alone. This result is valid for both isothermal and non-isothermal models.

(b) The reservoir temperature behavior (Fig. 14) on the other hand is affected from all parameters that compose κ. Among these parameters, the bulk volume, V_r, seems to be dominating the temperature behavior for the case under investigation.

(c) From the results of Figs. 13 and 14, it seems possible to estimate uniquely the parameters α_s, V_r, ϕ_i and c_r through history matching both pressure and temperature data under the assumption that ρ_m, β_r and C_m are known.

(d) The above statements clearly indicate the importance of history matching temperature data along with the pressure data.

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. We will present an application using the Izmir Balcova-Narlidere synthetic field. First the history matching method is described, followed by the application.

The history matching problem

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 simulataneously.

$$O(\mathbf{m}) = \frac{1}{2} I_p \sum_{i=1}^{N_p} \left[w_{p,i} \left[\frac{p_{m,i} - p_{\mathrm{model}}\left(\mathbf{m}, t_i^p\right)}{\sigma_p} \right] \right]^2 + \frac{1}{2} I_T \sum_{j=1}^{N_T} \left[w_{T,j} \left[\frac{T_{m,j} - T_{\mathrm{model}}\left(\mathbf{m}, t_j^T\right)}{\sigma_T} \right] \right]^2 \tag{8}$$

The model parameter vector, **m**, in Eq. 8 is composed of ten model parameters which are given in Eq. 9.

$$\mathbf{m} = \left[V_r, \phi_i, \alpha_s, p_i, T_i, T_s, \beta_r, c_r, C_m, \rho_m \right] \tag{9}$$

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 at times t^p and t^T respectively. p_{model} and T_{model} are the computed pressures and temperatures at the same times using the non-isothermal lumped parameter model. N_p and N_T are the total number of data to match 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. $w_{p,i}$ and $w_{T,j}$ are the weights assigned to the pressure and temperature data respectively. These weights are assigned by the user as 0 or a positive number.

Application to the Izmir Balcova-Narlidere field

In this section we investigate which of the model parameters can be estimated reliably using the history matching of pressure and/or temperature data. We first generate synthetic data with a single forward run of the non-isothermal lumped parameter model. The parameters used in this forward run are given in Table 2. The flow rate scenario is taken to be the same as that given in Fig. 8. The recharge temperature for the system is taken to be T_s=140°C. In order to reflect the nature of real field data noise is added to the data from a normal distribution with zero mean and a specified standard deviation. The noise added to the pressure data has a standard deviation of σ_p=0.08 bar and the noise added to the temperature data has a standard deviation of σ_T=0.002 °C. The generated "measured" data is given in Fig. 15.

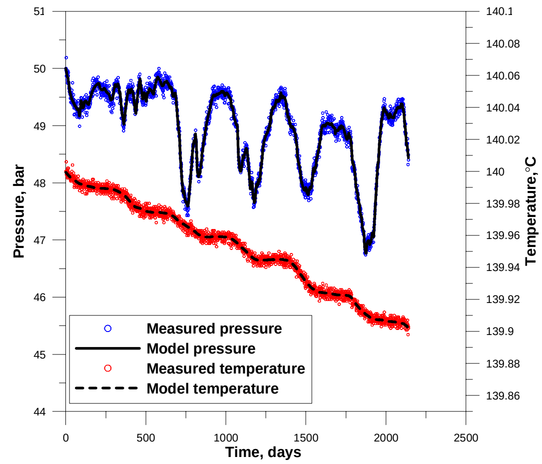

Figure 15: Synthetically generated pressure and temperatures along with the history matched model responses.

At this point it is worth noting that current pressure and temperature gauges used in the industry have about resolutions of 0.01 psi and 0.001°C, respectively. Hence, the range in which temperature varies in Fig. 15 can in real life be recorded. Next, history matching is conducted on both the pressure and temperature (this is accomplished by taking I_p=I_T=1 in Eq. 7) for seven different parameters; p_i, T_i, T_s, α_s, ϕ_i, c_r, V_r. The weights for all data points are taken as w_p=w_T=1. The standard deviation of the errors are assumed to be known (σ_p=0.08 bar and σ_T=0.002 °C). Table 4 summarizes the results along with the %95 confidence intervals. The history matched model responses are also shown in Fig. 15.

Table 4: Results of the history matching.

Model Parameter	Unknown true value	Initial guess	Estimated parameters
p_i	50	55	$50\pm6\times10^{-3}$
T_i	140	145	$140\pm3\times10^{-4}$
T_s	140	70	139±1.32
α_s	45	10	45±0.3
ϕ_i	0.05	0.01	0.051±0.01
c_r	1.33×10^{-4}	5.33×10^{-5}	$1.27\times10^{-4}\pm4\times10^{-5}$
V_r	9.42×10^{9}	9.42×10^{8}	$9.57\times10^{9}\pm2\times10^{8}$
For pressure RMS=0.08 bar and for temperature RMS=0.002°C			

Based on the inspection of the confidence intervals of the parameters V_r, ϕ_i and c_r, we may conclude that V_r is the parameter that has been estimated most reliably. This shows that the temperature measurements are quite sensitive to the bulk volume of the system. After the history matching, it is clear from Table 4 that all of the estimated parameters are very close to the true but unknown values and all are with in the %95 confidence interval.

Performance predictions with the nonisothermal lumped-parameter model : Izmir Balcova-Narlidere synthetic application

In this section we present future predictions made with the non-isothermal lumped-parameter model based on two scenarios of production. In both cases the net production rate is taken to be the same. The reinjection to production ratio is %80 for scenario 1 and %86 for scenario 2. These two scenarios are given in Figs. 16 and 17.

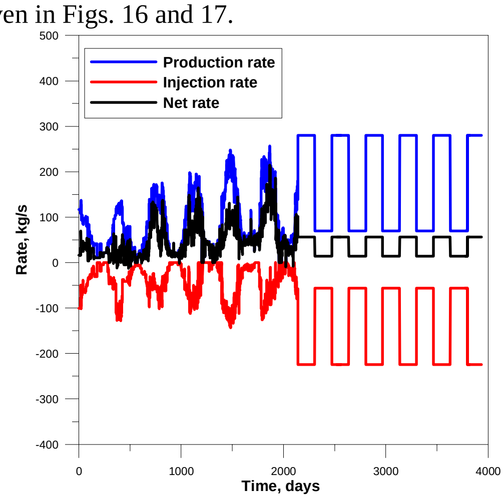

Figure 16: Rate scenario 1 – The reinjection to production ratio is %80.

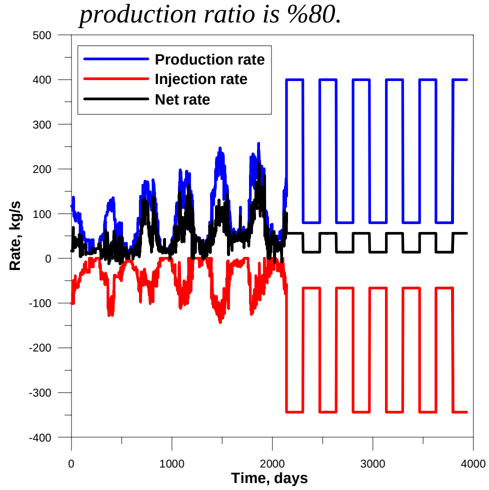

Figure 17: Rate scenario 2 – The reinjection to production ratio is %86.

The model parameters used for the future performance predictions are given in Table 2. The recharge temperature is taken to be T_s=140°C. Figs 18 and 19 illustrate the results for pressure and temperature respectively. The results of the isothermal model are also given for comparison purposes.

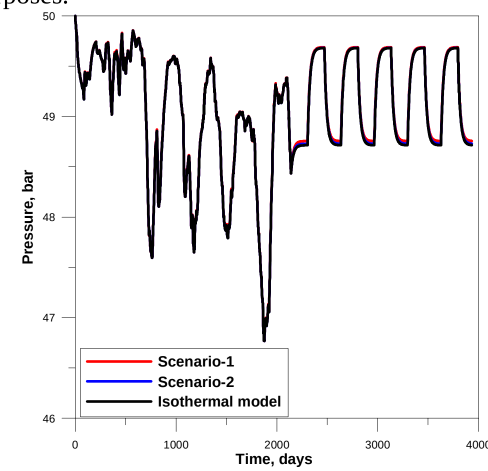

Figure 18: Future predictions of pressure for both scenarios.

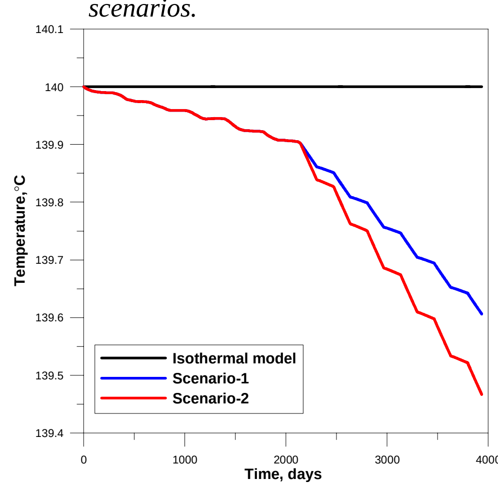

Figure 19: Future predictions of temperature for both scenarios.

Based on the results of Fig. 18, we see that for both scenarios, the non-isothermal and isothermal models predict the same pressure behavior almost exactly. This shows that the pressure behavior is mainly controlled by the net rate of the system. However the same is not true for the temperature behavior (Fig. 19) because the temperature is controlled by the ratio of injected water to the produced water. Because this ratio is higher for the scenario 2, there is more decrease in the temperature behavior of the system. Note also that even though the pressure of the system is able to rebuild itself during the summer seasons (in fact there is a cycle of around 1 bar, Fig. 18), the temperature is always decreasing (Fig. 19).

CONCLUSIONS

(i) A new single-tank non-isothermal lumped-parameter model has been developed to predict the changes in both reservoir temperature and pressure resulting from production of hot water, re-injection of a low-temperature water into the system, and/or natural recharge.

(ii) It has been found that the reservoir pressure is mainly controlled by two parameters; α_s and κ. The isothermal models hence may be sufficient to model the reservoir pressure behavior for a low-temperature geothermal reservoir. History matching of reservoir pressure data allows us to estimate uniquely the parameters α_s and κ, but not the individual values of the parameters V_r, ϕ_i and c_r (the parameters that make up κ).

(iii) The individual values of the parameters V_r, ϕ_i and c_r may be estimated reliably by matching both pressure and temperature data. This shows the importance of temperature data.

(iv) Based on two different scenarios, we have made future predictions regarding the Izmir Balcova-Narlidere geothermal field. We found that the temperature may decrease about 0.4°C for the future 5 years and a cycle of 1 bar is obtained between the summer and winter seasons. As an important remark, we note that these results were based on the assumption that the reservoir bulk volume, V_r is 9.42×10^9 m^3. This value of V_r may not represent the true, unknown bulk volume of the reservoir due to uncertainties in the values of rock compressibility and reservoir porosity. In addition, because there are no field temperature data available to us, we could not check the validity of this volume by history matching of temperature data.

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NOMENCLATURE

c_r : Compressibility of porosity (or effective rock) at constant temperature, 1/bar.
C_m : Specific heat capacity of the rock matrix, J/(kg°C).
$h_{w,inj}$: Specific enthalpy of the injected water, J/kg.
$h_{w,s}$: Specific enthalpy of the water from the recharge source, J/kg.
$h_{w,p}$: Specific enthalpy of the produced water, J/kg.
k : Permeability, m^2.
t : time, s.
L_x : Length of the reservoir, m.
$T(t)$: The average temperature of the reservoir at any time t, °C.
T_i : Initial temperature of the reservoir, °C.
T_{inj} : Temperature of the injected water, °C.
T_s : Temperature of the recharge water, °C.
u_w : The specific internal energy of water at any time t, J/kg.
V_r : The bulk volume of the reservoir, m^3.
w : Width of the reservoir, m.
z : Height of the reservoir, m.
α_s : The recharge index, kg/(bar-s).
β_r : Thermal expansion coefficient of porosity at constant pressure, 1/°C.
ρ_m : Density of the rock matrix, kg/m^3.
ρ_w : Density of the geothermal water, kg/m^3.
ϕ_i : The porosity at initial temperature and pressure.
ϕ_r : The porosity at any time t.
μ_w : The viscosity of water, bar-s.

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