

Applications of Non-Isothermal Lumped-Parameter Models; Case Studies of Turkey's İzmir Balçova-Narlıdere and Afyon Ömer-Gecek Fields

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ABSTRACT

Unlike the existing isothermal lumped-parameter models in the literature, non-isothermal models couple both heat and mass balance equations to account for temperature changes in addition to pressure changes. These changes result from production of hot water, re-injection of low-temperature water, and natural recharge of water (possibly with a temperature different than that of the reservoir). In this study, applications of an in-house non-isothermal lumped-parameter model to pressure and temperature measurements from Turkey's İzmir Balçova-Narlıdere and Afyon Ömer-Gecek are presented. The model developed can be used for performing history-matching and predicting both pressure and temperature behaviors of low temperature geothermal reservoirs containing single-phase liquid water are presented. Such a model helps to estimate reservoir bulk volume, porosity, temperature of the recharge source, recharge index, initial reservoir pressure and temperature by history matching measured reservoir pressure and temperature data by minimization of a weighted least-squares objective function. By using history matched models based on the non-isothermal model, as demonstrated for the case of İzmir Balçova-Narlıdere geothermal field, future reservoir temperature behavior which cannot be predicted by a lumped-parameter model assuming isothermal flow can be predicted under various production/injection scenarios. However, as shown in the Afyon Ömer-Gecek field example case, if the temperature and pressure data recorded at an observation well are not representative of the average pressure and temperature of the reservoir for which the non-isothermal model is built on, then matching such pressure and/or temperature may lead to inconsistent parameter estimates, and hence for such data cases, a non-isothermal model should be used and interpreted with caution.

1. INTRODUCTION

Lumped-parameter models provide a good alternative for numerical (or distributed) models due to having fewer parameters involved and the relatively shorter run-times. The behavior of low temperature geothermal reservoirs has been modeled before by Grant *et al.* (1982), Axelsson (1989), Sarak *et al.* (2005), Tureyen *et al.* (2007), and Onur *et al.* (2008). The use of lumped-parameter modeling is similar to the use of distributed models in geothermal reservoir engineering applications. That is; the lumped-parameter models are first history matched to production (pressure or rate) data using non-linear regression techniques. Then, future predictions of pressure or water levels or flow rates 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.

Most of the lumped-parameter models available in the literature are based on the assumption that the reservoir is treated as an isothermal system; for example see; Grant *et al.*, (1982), Axelsson (1989), Sarak *et al.* (2005), and Tureyen *et al.* (2007). With this assumption, while the pressure behavior of the system can be modeled, the changes in the temperature cannot 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 mass is removed from the system, the pressure decreases and hence, the internal energy of the system changes causing a slight changes 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.

To the best of the author's knowledge, Whiting and Ramey (1969) were the first to present a non-isothermal tank model. Their model was based on both the mass balance and the energy balance equations including conduction and convection terms, which are valid for both single-phase liquid and two-phase liquid-vapor geothermal reservoirs. They also presented an application of their model to a real field. However, it should be pointed out that their formulation did not consider variable-rate production/injection scenarios and ignored the non-isothermal effects if the reservoir contains only compressed liquid water. Later, Onur *et al.* (2008) have developed a non-isothermal tank model which is idealized as a single-closed or recharged tank for single-phase liquid geothermal reservoirs. Onur *et al.*'s model accounted for non-isothermal flow based on the numerical solution of the ordinary differential equations describing both mass and energy balances considering only convection. The model also handle variable-rate production/injection scenarios. Using this model, Onur *et al.* investigated the information content of temperature and showed that using temperature data in addition to pressure data enhances reservoir characterization by way of determining individual values of reservoir bulk volume and porosity, which may not have been determined from pressure data alone. Recently, Tureyen *et al.* (2009) extended Onur *et al.*'s approach to an arbitrary number of tanks for modeling the effects of other components such as aquifers or for modeling the behaviors of multiple reservoirs that are in hydraulic communication.

In this paper, the applications of the non-isothermal lumped-parameter model of Onur *et al.* (2008) to pressure and temperature measurements from Turkey's İzmir Balçova-Narlıdere and Afyon Ömer-Gecek are presented. The use of this model is particularly useful for these fields because there are not sufficient data available (to the author) for these fields to consider more general non-isothermal models, e.g., that described by Tureyen *et al.* (2009), and numerical 2D or 3D distributed models (e.g., Tough2 of Pruess

et al. 1999). The paper is organized as follows: Next, a brief description of the non-isothermal lumped-parameter model is provided, and then the details of the history-matching method used for performing match of the observed pressure and temperature data are discussed. Before conclusions, applications of the non-isothermal model to two single-phase liquid water geothermal fields; İzmir Balçova-Narlidere and Afyon Ömer-Gecek, are given.

2. DESCRIPTION OF NON-ISOTHERMAL LUMPED-PARAMETER MODEL

Here a brief description of the non-isothermal model is given. The model considered in this study is based on the model proposed by Onur *et al.* (2008). It uses both conservation of mass and conservation of heat for a single-phase liquid water. The single tank non-isothermal model of Onur *et al.* (2008) is schematically illustrated in Fig. 1.

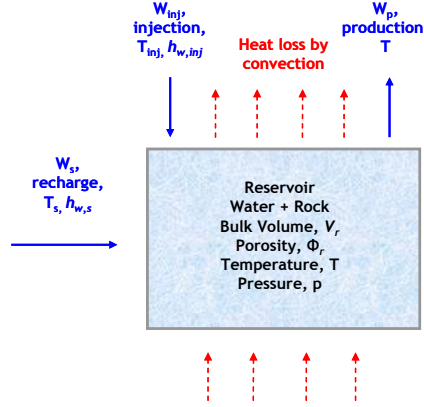


Figure 1: Idealized one tank non-isothermal lumped-parameter model (Onur *et al.* 2008).

The geothermal system is considered as a single tank (Fig. 1). 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:

$$W = W_p - W_{inj} \quad (1)$$

Due to production from the tank, fluid flow will take place from the recharge source into the tank. The mass flow rate of such a recharge is represented by W_s (kg/s) and is approximated by:

$$W_s = \alpha_s [p_i - p(t)] \quad (2)$$

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 (Onur *et al.* 2008):

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

where V_r , ρ_w and ϕ_r are bulk reservoir volume, water density and reservoir porosity. The first term on the left-hand side represents the accumulation of mass in the reservoir, the second term represents the mass flow rate from the recharge source into 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. The reason is that the change in temperature is due mostly because of bulk 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, the conservation of heat to the tank shown in Fig.1 can be given by (Onur *et al.* 2008):

$$V_r \frac{d}{dt} [(1 - \phi_r) V_r \rho_m C_m T + V_r \phi_r \rho_w U_w] - W_{inj}(t) h_{winj}(t) - \alpha_s [p_i(t) - p(t)] h_{ws}(t) + W_p(t) h_{wp}(t) = 0 \quad (4)$$

Here, C_m is the specific heat of the rock matrix in J/(kg°C), ρ_m is density of the rock matrix in kg/m³, U_w is the specific internal energy of the water in J/kg, h_{winj} is the specific enthalpy of injected water in J/(kg°C), h_{ws} is the specific enthalpy of the water from the recharge source in J/kg, and h_{wp} is the specific enthalpy of the produced water in J/kg. The first term on the LHS represents the accumulation of heat, 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. Eqs. 3 and 4 are first order non-linear ordinary differential equations. A fully implicit Newton-Raphson procedure with the initial conditions (i.e., initial pressure p_i and initial temperature T_i) can be used to solve these nonlinear equations simultaneously. 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. It should be noted that both liquid water density and porosity are treated as a function of reservoir pressure (p) and reservoir temperature (T). For instance, the change of porosity with pressure and temperature is modeled using the following equation:

$$\phi_r(p, T) = \phi_{ri} \exp[c_r(p - p_i) - \beta_r(T - T_i)] \quad (5)$$

where ϕ_{ri} is the reservoir porosity at initial reservoir pressure and temperature, c_r is the effective isothermal rock compressibility in 1/bar and β_r is the effective isobaric rock thermal expansion coefficient in 1/°C. Further details on the model including its verification can be found in Onur *et al.* (2008).

3. HISTORY MATCHING ALGORITHM

Here a brief description of the history matching algorithm considered in applications is given here. The algorithm is based on a weighted least-squares objective function which is designed in a general way as to be able to match pressure or temperature or both data sets simultaneously:

$$O(\mathbf{m}) = \frac{1}{2} I_p \sum_{i=1}^{N_p} \left[w_{p,i} \left[\frac{P_{obs,i} - P_{cal}(\mathbf{m}, t_i^p)}{\sigma_p^2} \right]^2 \right] + \frac{1}{2} I_T \sum_{j=1}^{N_T} \left[w_{T,j} \left[\frac{T_{obs,j} - T_{cal}(\mathbf{m}, t_j^T)}{\sigma_T^2} \right]^2 \right] \quad (6)$$

The model parameter vector, \mathbf{m} , in Eq. 6 can, in general, contain ten model parameters as unknown as given by

$$\mathbf{m} = [V_r, \phi_{ri}, \alpha_s, p_i, T_i, \beta_r, c_r, C_m, \rho_w] \quad (7)$$

The I_p and I_T terms in Eq. 6 are indicators which can only be either a “1” or a “0”. These indicators are used for matching either pressure, temperature or both. P_{obs} and T_{obs} represent the observed (measured) pressure and temperature at times t^p and t^T respectively. P_{cal} and T_{cal} are the computed pressures and temperatures at the same times using the non-isothermal lumped parameter model (Fig. 1). 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 deviations 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. The gradient based Levenberg-Marquardt method based on a restricted procedure described by Fletcher (1987) is quite efficient to minimize Eq. 6.

4. APPLICATIONS OF THE NON-ISOTHERMAL MODEL IN TWO GEOTHERMAL FIELDS IN TURKEY

Here, applications of the non-isothermal lumped-parameter model to two geothermal fields in Turkey; İzmir Balçova-Narlıdere and Afyon Ömer-Gecek; are given.

4.1 İzmir Balçova-Narlıdere Geothermal Field

The Balçova-Narlıdere geothermal field is situated about 10 km away from the west of İzmir (Fig. 2). The geothermal water with the temperature ranging from 80 to 140°C is produced from the wells with the depths between 48.5 m and 1100 m. The first well was drilled by General Directorate of Mineral Research and Exploration (MTA) in 1963. There are about 50 wells drilled to date and they are classified as gradient, shallow and deep wells. The field started to feed a district heating system with a capacity of approximately 5,000 residences in 1996-2001 (Gok *et al.* 2005). In a very recent study, Ertunç and Parlaktuna (2013) states that the system is the biggest district heating application in Turkey with heating capacity of 159 MWt heating an area of 2,470,000 m². Based on Ertunç and Parlaktuna (2013), the field has production characteristics of 1800 m³/h at peak times of the heating period and about 300 m³/h during summer months. On average, 85% of the produced fluid is reinjected after its energy is taken into heating centers. The field currently has 11 production, 6 reinjection and 4 observation wells.

As we have no access to the latest production/injection rate history as well as pressure and temperature measurements from the wells in the field, for the purpose of demonstration of the use of non-isothermal model for history matching, the flow rate history available in the years from 2000 to 2005 as given in Onur *et al.* (2008) and shown here in Fig. 3 is considered in history matching.

Using the net rate history shown in Fig. 3, Tureyen *et al.* (2007) performed history matching of water level data using 5 different isothermal lumped-parameter models, from which they determined that the model that best described the system was a single-tank open model. The recharge index was estimated to be $\alpha_s=45$ kg/(bar-s) and the storage capacity as $\kappa=8.4 \times 10^7$ (kg/bar). Note that κ is a group parameter defined by:

$$\kappa = V_r \phi_{ri} c_t \rho_w \quad (8)$$

The c_t term in Eq. 8 represents the total compressibility of the system, $c_t = c_r + c_w$, where c_w is the isothermal compressibility of water. It is important to note that c_w changes with pressure and temperature in the non-isothermal lumped parameter model, 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_{ri} 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, one may think of κ as being evaluated at the initial conditions. The parameter κ is expected 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 İzmir Balçova-Narlıdere geothermal field is assumed to be approximately around $p_i=50$ bar and $T_i=140^\circ\text{C}$. Hence at these initial conditions, the density and compressibility of water are computed as $\rho_w=928.5$ kg/m³ and $c_w=5.92 \times 10^{-5}$ 1/bar. The rock compressibility and reservoir porosity of the İzmir Balçova-Narlıdere geothermal field are unknown. However, if the rock compressibility is assumed to be $c_r=1.33 \times 10^{-4}$ 1/bar and porosity to be $\phi=0.05$ in fraction, then the bulk volume of the reservoir is computed to be $V_r=9.42 \times 10^9$ m³. 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.

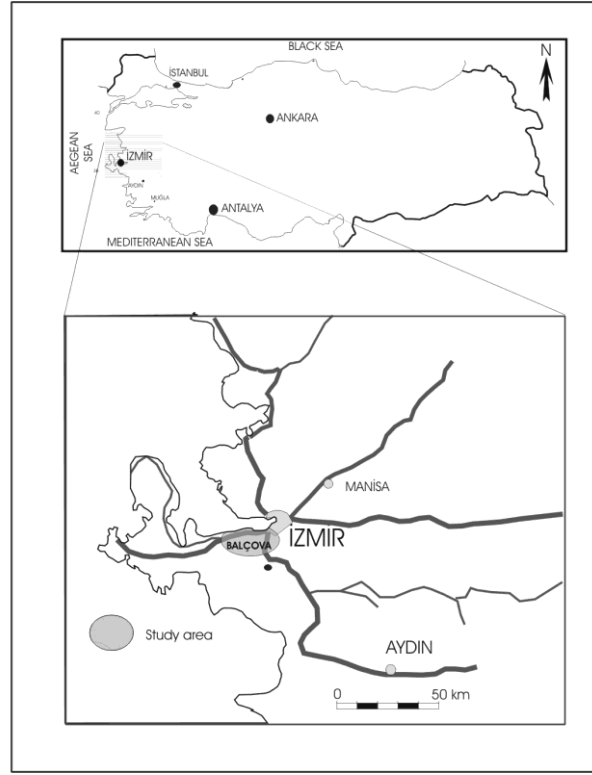


Figure 2: Location map of İzmir Balçova-Narlıdere geothermal field (modified from Aksoy and Filiz 2001).

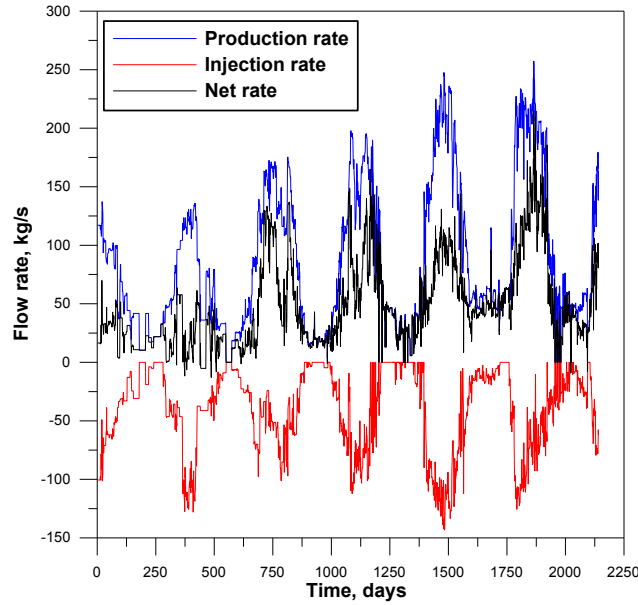


Figure 3: Production/Injection scheme between 01 January 2000 and 15 November 2005 (Onur et al. 2008).

4.1.1 History Matching Application

For demonstration of parameter estimation based on the non-isothermal model, pseudo-synthetic pressure and temperature data were generated by using the rate history given in Fig. 3 and input model parameters given in Table 1. The recharge temperature for the system was taken to be $T_s=140^\circ\text{C}$. To imitate a real field data set, 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 $\sigma_p = 0.08$ bar and the noise added to the temperature data has a standard deviation of $\sigma_T = 0.002$ °C. The generated “measured” data is shown in Fig. 4. History matching is performed simultaneously on both the pressure and temperature (this is accomplished by taking $I_p=I_T=1$ in Eq. 6) for seven different parameters; p_i , T_i , T_s , α_s , ϕ_{ri} , 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 ($\sigma_p=0.08$ bar and $\sigma_T=0.002$ °C). Table 4 summarizes the results along with the 95% confidence intervals. The history matched model responses are also shown in Fig. 4. Based on the inspection of the confidence intervals of the parameters V_r , ϕ_{ri} and c_r , it can be concluded 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 within the 95% confidence interval.

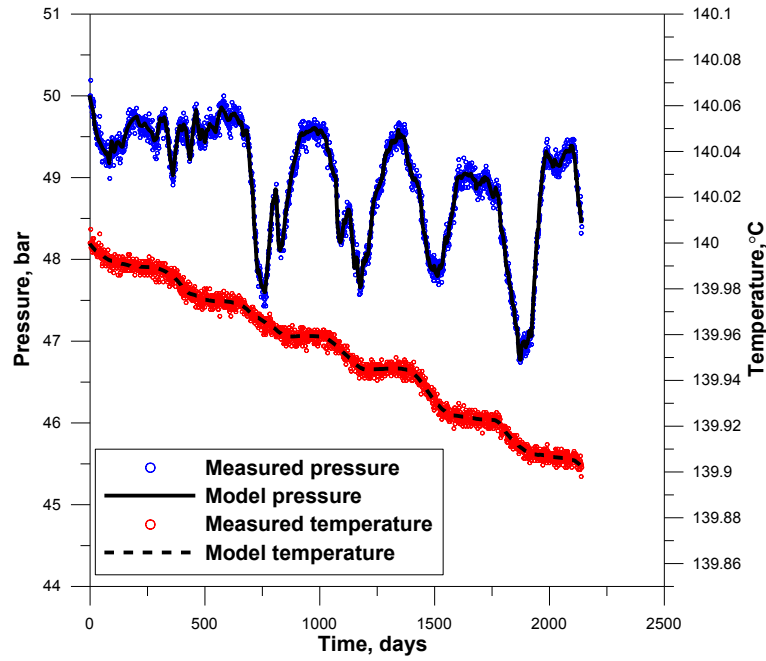


Figure 4: Pseudo-synthetic pressure and temperature data along with history matched model response (Onur *et al.* 2008).

Table 1: Input parameter used for pseudo-synthetic Balçova pressure and temperature data.

α_s , kg/(bar s)	45	c_r , bar ⁻¹	1.33×10^{-4}
p_i , bar	50	c_w , bar ⁻¹	5.92×10^{-5} @ p_i and T_i
T_i , °C	140	c_t , bar ⁻¹	1.92×10^9
ϕ_{ri} , fraction	0.05	ρ_w , kg/m ³	928.5 @ p_i and T_i
$V_{r,}$, m ³	9.42×10^9	ρ_m , kg/m ³	2650
C_m , J/(kg °C)	1000	β_r (°C ⁻¹)	0
T_{inj} , °C	60	h_{winj} , J/kg	255263
h_{ws} , J/kg		592125 @ 50 bar and 140°C	
		422742 @ 50 bar and 100°C	
		338850 @ 50 bar and 80°C	

Table 2: Results of history matching of pseudo-synthetic Balçova pressure and temperature data.

Model Parameter	Unknown true value	Initial guess	Estimated parameters ±95% confidence intervals
p_i	50	55	$50 \pm 6 \times 10^{-3}$
T_i	140	145	$140 \pm 3 \times 10^{-4}$
T_s	140	70	139 ± 1.32
α_s	45	10	45 ± 0.3
ϕ_{ri}	0.05	0.01	0.051 ± 0.01
c_r	1.33×10^{-4}	5.33×10^{-5}	$1.27 \times 10^{-4} \pm 4 \times 10^{-5}$
V_r	9.42×10^9	9.42×10^8	$9.57 \times 10^9 \pm 2 \times 10^8$
For pressure root-mean-square (RMS) error = 0.08 bar and for temperature RMS = 0.002°C			

4.1.2 Performance Prediction

In this section, future performance predictions were performed by 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. 5 and 6. The model parameters used for the future performance predictions are given in Table 2. The recharge temperature is taken to be $T_s=140^\circ\text{C}$. Figs. 18 and 19 illustrate the results for pressure and temperature, respectively. The results of the isothermal model are also given for comparison purposes.

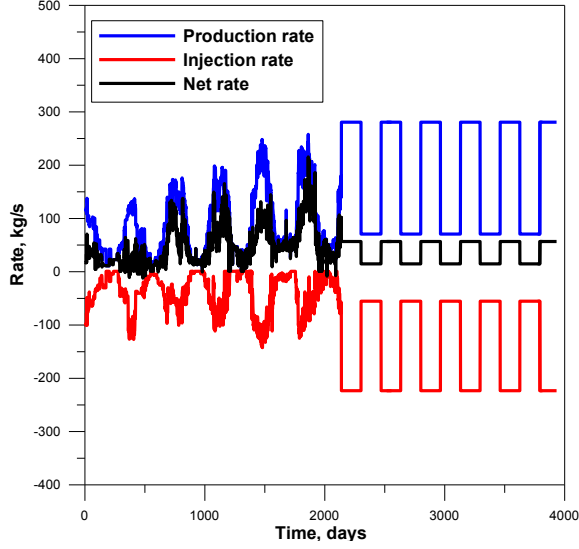


Figure 5: Rate history for Scenario 1.

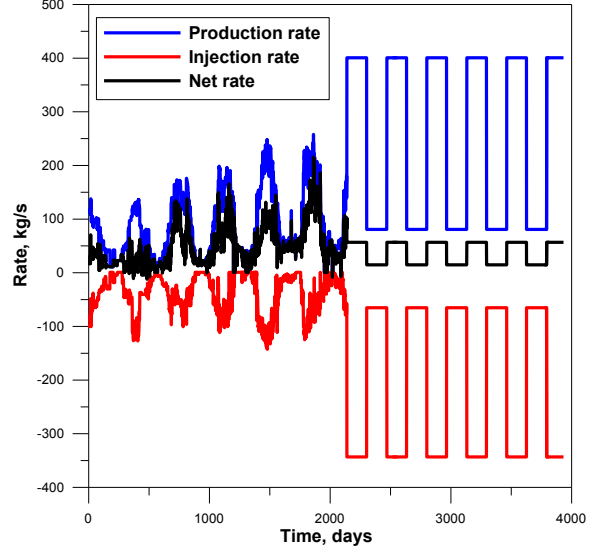


Figure 6: Rate history for Scenario 2.

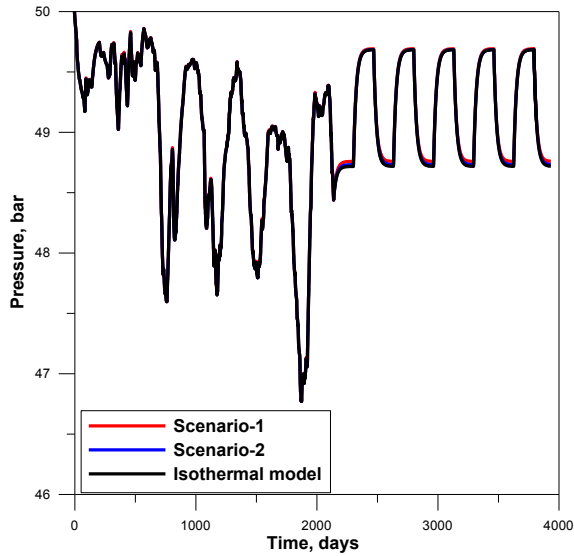


Figure 7: Performance predictions for pressure for Scenarios 1 and 2.

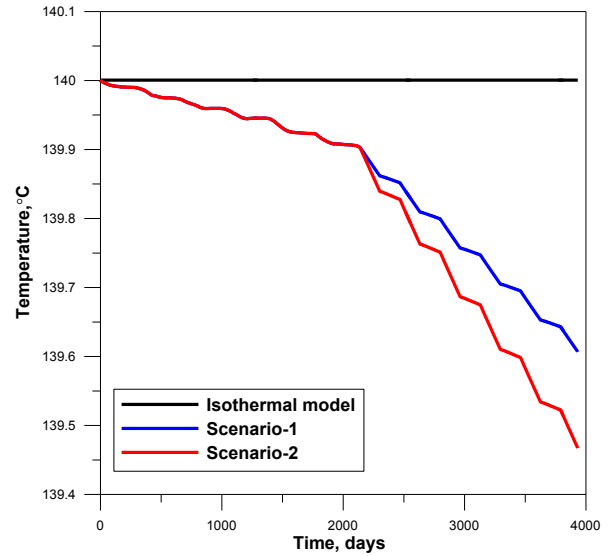


Figure 8: Performance predictions for temperature for Scenarios 1 and 2.

Based on the results of Fig. 7, for both scenarios, the non-isothermal and isothermal models predict almost the same pressure behavior. This shows that the pressure behavior is mainly controlled by the net rate of the system. However, the same is not quite true for the temperature behavior (Fig. 8) 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. 7), the temperature is always decreasing (Fig. 8).

4.2 Afyon Ömer-Gecek Geothermal Field

Located in the central Aegean region of Turkey and 15 km northeast of the city of Afyon (Fig. 9), the Ömer-Gecek geothermal field is one of the oldest geothermal fields in Turkey. The geothermal system can be classified as a low temperature, single-phase liquid-dominated one containing geothermal water (having salinity of 4000 to 6000 ppm and dissolved CO₂ content about 0.4% by weight) with temperatures ranging from 50 to 111.6 °C (Onur *et al.* 2007). The wells (nearly 30) drilled in the field range in depth from 56.8 to 902 m. The total production rate from the field is about 236 kg/s and the geothermal water produced has been utilized to support a district heating system with a capacity of approximately 4500 residences since 1996. The Ömer-Gecek geothermal system is a convective hydrothermal type which commonly occurs in areas of active geological faulting and folding, and areas where the regional heat flow is above normal, as in much of the western Turkey. As for the geology of the system, mica schist and marbles of Paleozoic age forms the basement of the field. At the same time, these rocks form the reservoir system. Neogene deposits composed of conglomerate, sandstone, clayey limestone-sandstone, and volcanic glass-trachandesitic tuff unconformably overlie the Paleozoic basement (Onur *et al.* 2007).

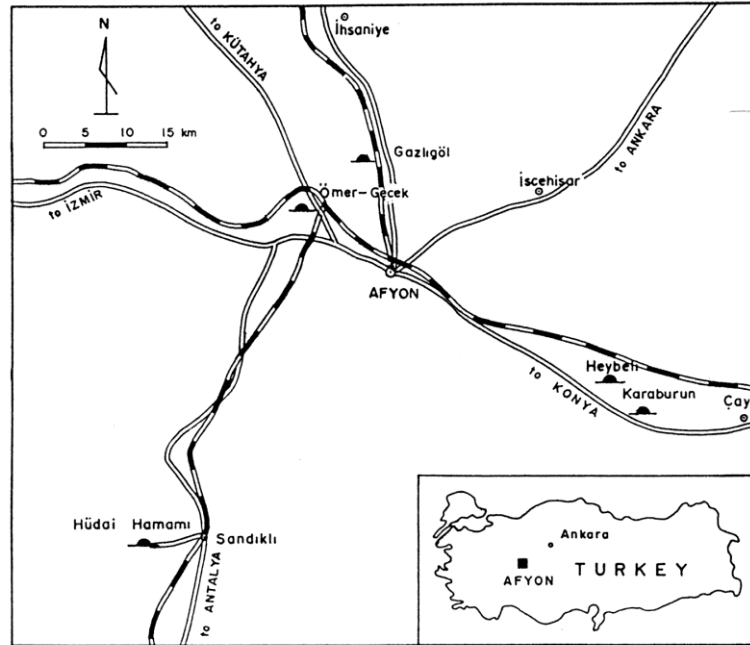


Figure 9: Location map of the Afyon Ömer-Gecek geothermal field (Onur *et al.* 2007).

4.2.1 History Matching Application

Now, real field pressure and temperature data recorded during a two-well interference test conducted between the wells AF-21 and R-260 are considered; where the well AF-21 was an active well, while R-260 was an observation well. During the interference test, the only production well in the field was AF-21. The distance between the two wells is 78.5 m. The depth of the Well AF-21 is 212 m, whereas the depth of the Well R-260 is 166 m. The interval open to flow for the Well AF-21 is between the depths of 121 and 212 m, whereas the interval open to flow for the Well R-260 is between the depths of 100-166 m (Onur *et al.* 2007). Pressure and temperature data at the Well R-260 were measured at a depth of 116 m. Fig. 10 presents flow-rate history at the active well (AF-21) together with pressure recorded at the observation well (R-260), whereas Fig. 11 presents the flow-rate history at the active well and temperature recorded at the well R-260.

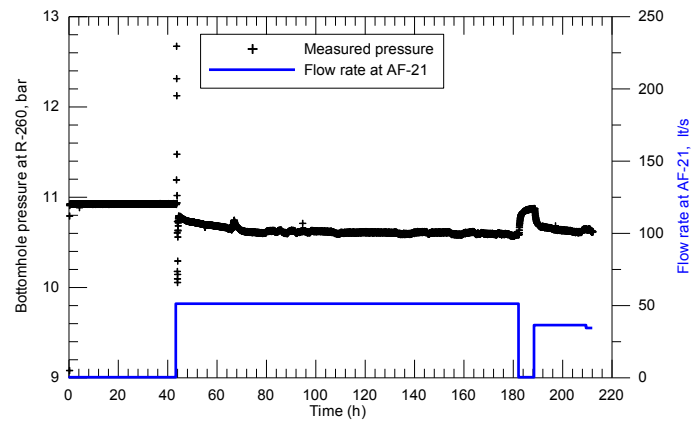


Figure 10: Flow rate and pressure history for the AF-21/R-260 interference test.

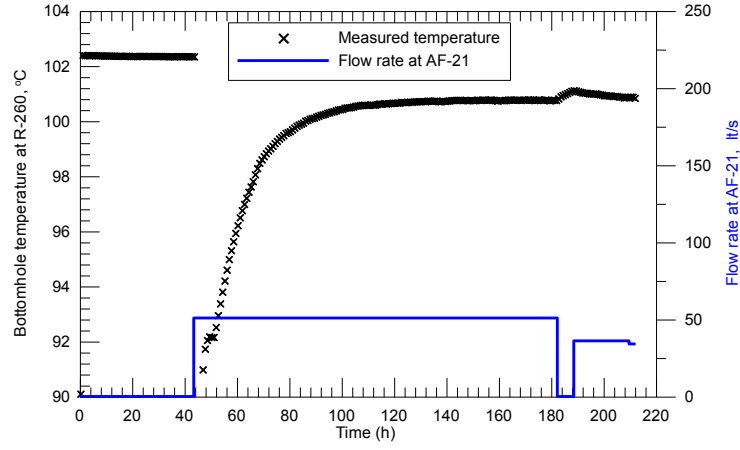


Figure 11: Flow rate and temperature history for the AF-21/R-260 interference test.

Although it is not evident from Figs. 10 and 11, the effect of production at AF-21 is felt at R-260 in about 100 seconds. This may be an indication of a highly permeable fracture/fault network existing between the wells. The total test duration after production started at well AF-21 is about 170 h (or about 7 days). The static pressure measured at the well R-260 at the depth of 116 m is 158.5 psi. After first 140 hours of production at AF-21, the well R-260 was shut-in about 6 hours due to some operational problems occurred at the well AF-21. This shut-in period provided a 6-hour buildup test data in the time interval from 182 to 188 h (in cumulative time) as shown Fig. 10. The buildup pressure data were previously analyzed by Onur *et al.* (2007). It is also important to note that there are sudden changes or oscillations in both the pressure (Fig. 10) and temperature (Fig. 11) data just at the moment when the production started at the active well AF-21 at about 43 h. Although it is not known what exactly caused these sudden changes, perhaps it may be due to slipping and/or movement of the pressure/temperature gauges inside the well, at the observation well R-260. Certainly, it is a sign of instability in pressure and temperature gauges. Although pressures seem to recover from this “instability” quite fast (within a few hours), the recovery of temperature data from this event is not as fast as the pressure data. It is assumed that the temperature data from 44 to 140 h are not representative of the reservoir temperature behavior. Hence, in history matching, all the temperature data from 44 to 140 h were assigned with zero weights (see $w_T = 0$ in Eq. 6), whereas pressure data from 44 to 48 h were assigned with zero weights (see $w_p = 0$ in Eq. 6).

First, only pressure data were matched by using the non-isothermal model; i.e., $I_T = 0$ in Eq. 6. The unknown parameters were chosen as initial pressure p_i , the recharge index α_s , and the bulk volume of the reservoir V_r . The porosity-compressibility-thickness product was estimated to be as $\phi c h = 4.22 \times 10^{-3}$ m/bar by deconvolution analysis (Onur *et al.* 2007). As is typical of geothermal reservoirs, the reservoir thickness is unknown. By assuming that the intervals open to flow at both wells represent the reservoir thicknesses, an arithmetic average of the open intervals is taken as an approximation for the reservoir thickness. This arithmetic average is 78.5 m. By assuming porosity as $\phi = 20\%$, the isothermal compressibility was estimated to be $c_i = 2.69 \times 10^{-4}$ 1/bar. The isothermal water compressibility at 100 °C and 11 bar is 4.82×10^{-5} 1/bar. The isothermal rock compressibility c_r is computed as $c_r = c_i - c_w = 2.21 \times 10^{-4}$ 1/bar. It is assumed that the recharge source and the reservoir have the same temperature; $T_s = T_i = 102.36$ °C. The thermal input parameters were selected accordingly to well-log and geological data; $C_m = 950$ J/(kg °C), $\rho_m = 2750$ kg/m³. The isobaric thermal expansion coefficient for the rock is assumed to be $\beta_r = 0$ °C⁻¹.

The match of the pressure data obtained is shown in Fig. 12, whereas the parameters estimated from this match with the initial guesses used for the parameters are given in Table 3. The numbers given as plus/minus represent the 95% confidence intervals. As the confidence intervals are small, the estimated parameters are reliable. The match is also acceptable as the root-mean-square error (RMS) is small; RMS = 0.037 bar.

Table 3: Results of history matching of the Well R-260 pressure data; Afyon Ömer-Gecek.

Model Parameter	Initial guesses	Estimated Parameters by history matching \pm 95% confidence intervals
Initial Pressure, p_i , bar	10.9	10.84 ± 0.01
α_s , kg/(s-bar)	0.06	226 ± 12
V_r , m ³	10^5	$2.96 \times 10^7 \pm 5.29 \times 10^6$
Root-Mean-Square (RMS) error for the pressure match = 0.037 bar		

Next, only temperature data were matched by using the non-isothermal model; i.e., $I_p = 0$ in Eq. 6. The unknown parameters were chosen as initial temperature T_i , recharge source temperature T_s , the recharge index α_s , porosity ϕ , and the bulk volume of the reservoir V_r . The other input parameters were fixed at their given values for the pressure match. The match of the temperature data obtained is shown in Fig. 13, whereas the parameters estimated from this match with the initial guesses used for the parameters are given in Table 4. As the RMS value (0.033 °C) for the match and the 95% confidence intervals for the estimated parameters are small, indicating confidence in the nonlinear regression analysis.

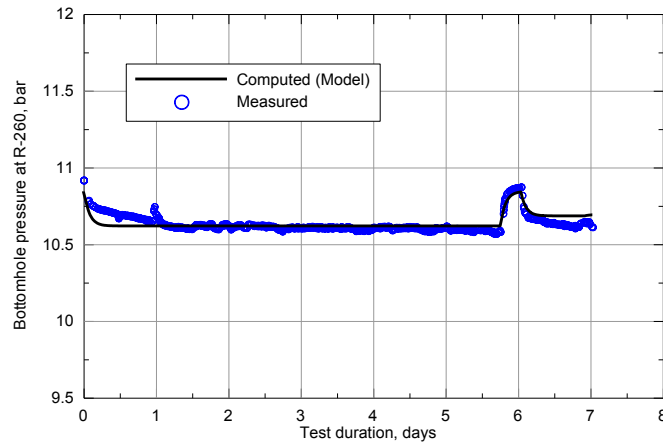


Figure 12: Model match of pressure data at the observation well R-260.

Several attempts were made to simultaneously match both pressure and temperature data. However, matches that are acceptable as those shown in Figs. 12 and 13 for both the pressure and temperature could not be obtained. Actually, this is expected if one inspects the parameters estimated by matching only pressure (see Table 3) and temperature (see Table 4) data. It is important to note that the estimates of the bulk volume V_b and the recharge index α_s from pressure match alone and temperature match alone are quite different. Specifically, the estimates of V_b and α_s from pressure are much larger than the corresponding ones from temperature. As the propagation of the temperature into the reservoir is slower than that of the pressure, it is not surprising that the reservoir volume investigated by pressure data is far larger than that the reservoir volume investigated by the temperature data. There could be several reasons for this discrepancy; (i) temperature data recorded inside the wellbore may not represent the (behavior of) reservoir temperature as they may be affected by some other phenomena in the wellbore; e.g., the effect of wellbore storage on temperature. (ii) pressure and temperature data recorded at the Well R-260 more likely do not represent the (behavior of) average reservoir pressure and temperature data for which the non-isothermal (as well as isothermal) models are built on. So, pressure and temperature data are not consistent.

Table 4: Results of history matching of the Well R-260 temperature data; Afyon Ömer-Gecek.

Model Parameter	Initial guesses	Estimated Parameters by history matching \pm 95% confidence intervals
Initial temperature, T_i , °C	102.36	102.04 ± 0.029
Recharge temperature, T_s , °C	102.36	85.72 ± 1.96
α_s , kg/(s-bar)	0.06	0.054 ± 0.008
ϕ_{ri} , fraction	0.12	0.171 ± 0.015
V_r , m ³	10^5	$7.62 \times 10^4 \pm 1470$
Root-Mean-Square (RMS) error for the temperature match = 0.033 °C.		

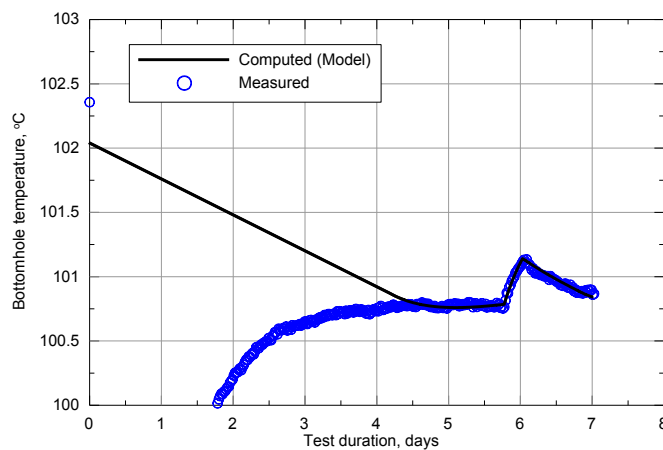


Figure 13: Model match of temperature data at the observation well R-260.

5. CONCLUSIONS

The main conclusions of this work can be stated as follows:

- (i) The use of non-isothermal lumped-parameter models allows one to use of temperature data together with pressure data. This allows for a better estimation of reservoir parameters from the average pressure and temperature data of the reservoir.
- (ii) While average pressure data of the reservoir allows estimation of the initial pressure and the recharge index, using average temperature data of the reservoir at the same time allows estimation of other parameters, particularly the bulk volume and the porosity. It should be noted that determination of the latter parameters is very important since they are needed to estimate the thermal energy in place and to predict the future reservoir temperature behavior subject to different production/injection scenarios, as demonstrated for İzmir Balçova-Narlıdere geothermal field.
- (iii) The non-isothermal lumped-parameter models could only predict the average pressure and temperature of the reservoir as they treat the reservoir and its associated components (aquifers) as tanks ignoring spatial variability.
- (iv) As shown in the Afyon Ömer-Gecek field example case, if the temperature and pressure data recorded at an observation well are not representative of the average pressure and temperature of the reservoir for which the non-isothermal model is built on, then matching such pressure and/or temperature may lead to inconsistent parameter estimates, and a non-isothermal model should be used with caution for such data cases.

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