Geothermics 51 (2014) 300–311

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Assessment of uncertainty in future performance predictions by lumped-parameter models for single-phase liquid geothermal systems

Ömer İnanç Türeyen*, Ayşe Kırmacı, Mustafa Onur

Department of Petroleum and Natural Gas Engineering, Istanbul Technical University, 34469 Maslak, Istanbul, Turkey

ARTICLE INFO

Article history:
Received 18 August 2011
Received in revised form 13 October 2013
Accepted 30 January 2014
Available online 13 March 2014

Keywords:
Geothermal
Lumped-parameter models
Isothermal
Non-isothermal
History matching
Production data
Randomized maximum likelihood
Uncertainty prediction

ABSTRACT

A stochastic simulation methodology is presented for assessing the uncertainty in future pressure and/or temperature data simulated by using history-matched lumped-parameter models for single-phase liquid water geothermal systems. The methodology consists of a two-step procedure; first selecting the appropriate lumped-parameter model that can best describe the geothermal system based on history matching observed pressure and/or temperature datasets and then using a randomized maximum likelihood (RML) like method for the assessment of uncertainty. Any uncertainties in both the model and the measured data may be incorporated into the future performance predictions for the pressure. Once the uncertainty in predicted performance is characterized and assessed, it becomes possible to make reservoir management decisions that account for an incomplete knowledge of the actual geothermal system. One synthetic application and one field application from the Balçova-Narlıdere geothermal field in İzmir, Turkey are presented to illustrate the methodology.

1. Introduction

The behavior of geothermal reservoirs under exploitation can be simulated using either lumped-parameter (or tank-type) models (Grant et al., 1982; Axelsson, 1989; Alkan and Satman, 1990; Axelsson et al., 2005; Sarak et al., 2005; Onur et al., 2008; Tureyen and Onur, 2009) or distributed (numerical) models (Bodvarsson et al., 1986; O'Sullivan et al., 2001). Numerical models are, of course, more general than the lumped-parameter models in that one can account for spatial variations in thermodynamic, rock, and fluid properties of the reservoir as well as for well spacing, locations and geometries. However, the numerical models require a large amount of input data for history-matching, and future performance predictions. Also, the numerical models usually require long run times. This work specifically focuses on the modeling of single-phase water geothermal reservoirs through the use of simple lumped-parameter models assuming either isothermal or non-isothermal flow conditions in the reservoir. Here and throughout in this paper, we will use lumped-parameter and tank models interchangeably.

Over the last several years, a number of lumped-parameter models, assuming isothermal flow, have been used for history matching and predicting pressure (or water level) changes in low-temperature geothermal systems in Iceland, Turkey, The Philippines, China, Mexico and other countries (Axelsson et al., 2005; Sarak et al., 2005; Tureyen et al., 2007). With the isothermal flow assumption, while the pressure of the system as a function of time can be modeled, the changes in temperature with time cannot be accounted for. The changes in temperature can be substantial in cases where there are significant injection operations in a field or when the recharge to a geothermal reservoir is at a significantly different temperature. Onur et al. (2008), Tureyen and Onur (2009), and Tureyen and Akyapi (2011) have developed non-isothermal lumped-parameter models that can be used to predict both reservoir pressure and temperature for single-phase liquid water geothermal reservoirs. In this work, we consider both the isothermal and non-isothermal lumped-parameter models to show the applicability of our methodology for the assessment of uncertainty in future reservoir pressure and/or temperature predictions.

The model parameters can be estimated using gradient-based non-linear least-squares estimation methods (such as the Levenberg–Marquardt method) to history-match measured field pressure and/or temperature data to the corresponding model response (Axelsson, 1989; Sarak et al., 2005; Onur and Tureyen, 2006; Tureyen and Onur, 2009). History-matched models can be used to predict the future performance of the reservoir (in terms of reservoir pressure and/or temperature) for different

---

* Corresponding author. Tel.: +90 212 2856150; fax: +90 212 2856263.
E-mail address: inanct@itu.edu.tr (Ö.İ. Türeyen).

0375-6505/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.geothermics.2014.01.015

Nomenclature

$\mathbf{C}_D$	covariance matrix for measurement errors
C_p	solid rock specific heat capacity (J/(kg K))
c_r	rock compressibility (1/Pa)
c_t	total (rock + fluid) compressibility (1/Pa)
$\mathbf{f}$	vector of computed response
$\mathbf{m}$	vector of model parameters
M	total number of unknown model parameters
n	the number of conditional realizations
N	the number of measurements or observed data
p_i	initial pressure (Pa)
t	time (s)
T_i	initial temperature (K)
T_{inj}	injection temperature (K)
T_s	recharge temperature (K)
V_b	bulk volume (m^3)
$\mathbf{y}_{obs}$	vector of measured or observed data
$\mathbf{y}_{uc}$	vector of unconditional realization of measured or observed data
$\mathbf{z}_u$	vector of independent standard random normal deviates

Greek letters

α	Recharge constant (kg/(Pa s))
β	rock thermal expansion coefficient (1/K)
κ	storage capacity (kg/Pa)
ϕ	porosity (fraction)
ρ	rock density (kg/m^3)
σ_d	standard deviation of errors on measured or observed data

Subscripts

$o1$	first outer part
$o2$	second outer part
p	pressure
r	reservoir
T	temperature

production/injection scenarios to optimize the management of a given geothermal system.

The ultimate goal in any geothermal reservoir study is to predict future performance. It is equally important to predict the uncertainty in future predictions for different reservoir management options. This is necessary to determine the production/injection practices that will provide sustainable exploitation of the geothermal system under consideration. Uncertainty in all future predictions of pressure and temperature data arises due to (i) measurement errors or noise in observed pressure and/or temperature data, (ii) modeling errors, and (iii) limited historical data.

The principal objective of this paper is to present a methodology for the assessment of uncertainty in future predictions made by lumped-parameter models. This is accomplished with a stochastic methodology that incorporates the effect of uncertainties both in the model and in the observed data on the future performance predictions. Our methodology relies on the determination of the lumped-parameter model that best describes the geothermal system based on observed pressure and/or temperature datasets and then the application of a randomized maximum likelihood (RML) like method for the assessment of uncertainty. The RML method has been shown to be quite efficient for the assessment of uncertainty in performance predictions for non-linear history matching problems (Kitanidis, 1995; Oliver et al., 1996; Liu and Oliver, 2003; Gao et al., 2005; Oliver et al., 2008). Onur and Tureyen (2006) and Tureyen et al. (2007) have applied a RML type method to isothermal lumped-parameter models. In this work, we extend the application of the RML like method to non-isothermal lumped-parameter models for single-phase water geothermal systems.

The paper begins with a brief review of isothermal and non-isothermal lumped-parameter models. Then, history matching, model identification, and future performance prediction problems are discussed. This is followed by a synthetic application which demonstrates the validity of the methodology proposed in this study. Finally we present an application of our methodology to history match the long-time pressure data available from the Balçova-Narlıdere Geothermal field in İzmir, Turkey.

2. Lumped-parameter modeling

Lumped-parameter modeling is a highly simplified form of numerical modeling. In numerical models, a geothermal system is discretized by many (>100 to 10^6) grid blocks. On the other hand, in lumped-parameter modeling, a geothermal system is represented by only a few homogeneous tanks and is visualized as consisting of three parts: (1) the central part of the reservoir; (2) outer parts of the reservoir, and (3) the recharge source. The first two parts are treated as series of homogeneous tanks with average properties. The recharge source can be connected to the other parts of the reservoir or directly to the central part of the reservoir and is treated as a "point source" that recharges the system. If there is no recharge source, the model is said to be closed. Three different open models (i.e., models with recharge) are depicted in Fig. 1.

The model shown in Fig. 1a represents a one-tank open model, which represents the innermost (or central) part of the geothermal system. Fig. 1b represents a two tank open model. The first tank represents the central part of the system whereas the second tank represents the outer part of the reservoir that is connected to the recharge source. Fluid production causes the pressure in the reservoir to decline, which results in influx of water from the outer to the central part of the reservoir. The recharge source represents the outermost part of the geothermal system. Similarly Fig. 1c represents a three-tank open model. The models shown in Fig. 1 can be used for both isothermal and non-isothermal flow conditions.

2.1. Isothermal lumped-parameter models

The isothermal lumped-parameter modeling considered here is very similar to those presented by Axelsson (1989) and by Sarak et al. (2003a,b, 2005). The isothermal models are based on the conservation of mass only and are valid for low-temperature water reservoirs when the variations in temperature within the system can be neglected.

The simulated lumped-parameter model (output) response represents pressure or water level changes for an observation well for a given net production history (input). The number of model parameters increases as the number of tanks increases. The recharge constant α gives the amount of water mass flow rate per unit pressure drop that may occur either between a tank and the recharge source or between two tanks. The parameter κ denotes the reservoir storage capacity and is defined as $\kappa_r = V_r\phi_r\rho_w c_t$. It is related to the change in fluid mass due to the expansion or contraction of the pore volume subject to a unit pressure change. Finally p_i represents the initial pressure of the recharge source. The geothermal system is assumed to be in hydrodynamic equilibrium initially; i.e., the initial pressure, p_i, is uniform in the system.

2.2. Non-isothermal lumped-parameter models

The non-isothermal lumped-parameter modeling considered here is similar to those presented by Onur et al. (2008), Tureyen