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Improved method for estimating static formation temperatures in geothermal and petroleum wells

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ABSTRACT

This paper describes a mathematical method for estimating static formation temperatures using a function based on extrapolation of the measured data in the thermal recovery process of geothermal and petroleum wells. This method uses the least squares fit of a rational polynomial model to describe the transient temperature data and also provides an analytical expression of thermal recovery processes. This expression gives the asymptotic value for final temperature. We then apply this method for estimating static formation temperatures of a geothermal and petroleum drilled well.

In this work we have developed the equations of least squares fit of rational polynomial function and used the equation to estimate the uncertainties of its coefficients. This fitting procedure allows us to obtain a mathematical model that represents the thermal recovery process and to extrapolate the value of final temperature. This is a practical method to estimate static formation temperature, having the advantages that the thermal properties of the drilling mud and its formation are not required; it can also be used in the geothermal and petroleum industries.

1. Introduction

Drilling deep wells are required for the exploitation of petroleum or geothermal resources. During this drilling process a drilling fluid (also known as mud) is used to transport the drilling cuts to the surface. This mud is also used to lubricate and cool the drill bit (Agwu et al., 2015). Thus the complete drilling process affects the static formation temperature (SFT) (Garcia-estrada et al., 2001; Kutasov and Eppelbaum, 2015), which is an important parameter for diverse geothermal and petroleum applications. The SFT (also known as virgin rock temperature) is an important parameter used in: (1) the optimum design of drilling and completion programs of geothermal and petroleum boreholes (Eppelbaum and Kutasov, 2011) and (2) the identification of permeable or porous zones characterized by lost circulation problems (Kutasov and Eppelbaum, 2009). In the geothermal industry the SFT is needed in: (i) the estimation of energy reserves, and (ii) reliable heat flow (Santoyo et al., 2000). In the petroleum industry the SFT is used in the: (i) modeling of hydrocarbon maturation (Lampe and Pearson, 2002), and (ii) determination of transport properties of hydrocarbons (Zhangxin, 2007). The SFT is also important to the development of new and accurate tools: it assists in the (i) development and calibration of geothemometers (Díaz-González et al., 2008; Pérez-Zárate et al., 2015) and in the (ii) calibration of wellbore thermal simulators (Santoyo, 1997; García et al., 1998; Teng and Koike, 2007).

Although measurements of bottom hole temperature (BHT) are registered when the drilling process stops or ends, the drilling mud temperature tends to equilibrate with the temperature formation over a long period of time (from days to months). It is therefore too expensive or impossible to measure temperatures until the equilibrium temperature is reached (Gonzalez-Partida et al., 1997). Therefore, a technique to estimate the SFT from measurements of the thermal recovery process over short periods of time (hours to days) is needed. These measurements are composed of BHTs and time after the mud circulation has stopped (shut-in time). In order to estimate the SFT using BHTs and shut-in times, we find numerous analytical methods (i.e. Horner, 1951; Ascencio et al., 1994; Hassan and Kabir, 1994; Kutasov and Eppelbaum, 2005; Zhou et al.,

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2015) and simulators (i.e. Beirute, 1991; García et al., 1998; Porkhial et al., 2015). These methods, in addition to using the BHT and shut-in time, also involve other parameters like circulation time, and thermophysical properties of mud and formation (Cao et al., 1988; Andaverde et al., 2005). This property dependence makes the uses of these methods difficult in most cases, due to lack of information related to the thermophysical properties of the rock. Accordingly, the applicability of the above methods is rather limited. Thus, a method for accurate SFT estimation that only uses a BHT and a shut-in time is needed.

In the thermal recovery process the temperature tends to an asymptotic value, but follows an unknown mathematical function. This is due to the complicated heat and mass transport conditions, the unknown physical properties of the geological formations; thus it obligates a different fitting approach. Padé approximants have a close relation with variational principles (Baker and Gammel, 1970): Padé approximants can represent data in an efficient analytic expression. Without specific information, but with the certainty that we need to describe a nonlinear behavior, representation using a Padé approximant of first order of both polynomials seems reasonable, as elaborated below.

The specific form of Padé approximants is the simplest structure to describe the behavior that we want to obtain. Padé approximants have been used in many fitting applications, from transport coefficients in effective medium theories to equations of state (i.e. del Río et al., 1998; Robles and López de Haro, 2003). All these cases exhibited the ability to reproduce the desired behavior. Wong-Loya et al. (2012) proposed a rational polynomial method (RPM) based on Padé approximants to describe the thermal recovery process in geothermal and petroleum wells, and also to estimate the SFT. The method proposed in that paper consists of the use of Padé approximants to determine the rational function that fits a BHT–shut-in time data series. The rational function proposed was composed of polynomials of the same order for both numerator and denominator. The order proposed was first, second and third degree, respectively. The methodology used consists of creating all the possible combinations with smaller data subsets of BHT and shut-in times (from the total number of data pairs stored in the original BHT data set), then determining the coefficients of the rational polynomial functions per data subset and calculating the statistical parameters of central tendency (mean) and dispersion (standard deviation and relative standard deviation values) for all SFT estimates inferred per rational polynomial function. The degree function of the rational polynomial model to be used as the best-fitting approach for estimating the SFT is the degree function with the lowest relative standard deviation. To select the best rational polynomial function to obtain the best SFT estimate, an evaluation of residuals is used. The limitations of this method are: (1) a long computing time due to the number of all optimal combinations and calculations to be done, (2) the dependency on the number of data analyzed, (3) the failure to obtain the uncertainty of the SFT value and either of the coefficients and (4) the increased difficulty of the physical interpretation when using different degree polynomials.

The aims of this work are to improve on the RPM proposed by Wong-Loya et al. (2012) using statistical tools based on least squares fitting and to provide a method to calculate the uncertainties of the static formation temperature estimation. Such uncertainty estimates for SFT are of immense value because they restrict the uncertainties to inferring both the reservoir thermal conditions and the available geothermal energy for exploitation. These measurements have important bearing on the investment risk for field development (Verma et al., 2006). To achieve this improvement, the least squares rational polynomial method (LSRPM) is required. With this method, the mathematical model that represents the thermal recovery process is obtained. Due to the structure of LSRPM from the coefficients of the equation, the SFT values may be obtained. Also, the equations to obtain the uncertainties associated with the fitting process are presented.

In Section 2 we describe the LSRPM and the development of equations for calculation of the uncertainties in the rational polynomial coefficients; these are used to estimate the SFT and describe the thermal recovery process.

In Section 3 this method is applied and validated using seven different data sets: two synthetic data series reported by Shen and Beck (1986) and Cao et al. (1988), one experimental series reported by Cooper and Jones (1959), one field series with SFT known, reported by Steingrimsson and Gudmundsson (2006) and then applied at two geothermal data series, one measured in Kyushu, Japan geothermal field (Hyodo and Takasugi, 1995) the other measured in Chipilapa, El Salvador geothermal field (Iglesias et al., 1995), and one petroleum data series obtained from an Oklahoma (MISS) Petroleum field, USA (Kutasov, 1999). The LSRPM is applied to the data series, and the results obtained for this method are compared with the most commonly used methods. Finally, the thermal recovery process obtained by the model is compared with the data series reported in order to demonstrate the applicability of the LSRPM. The paper ends with some concluding remarks.

2. Least squares rational polynomial method

In this section we explain in detail the least squares rational polynomial method (LSRPM). This explanation is comprised of three main tasks. First, we describe the development of the equations to obtain the best fit model using a rational polynomial function. The fit method was determined using a least squares fit. Next, we explain the development of equations to calculate the uncertainties in the rational polynomial coefficients, which are then used to estimate the SFT and describe thermal recovery process. Finally, we use the LSRPM together with synthetic, experimental and field data in order to illustrate and validate the method.

2.1. Development of the equations of LSRPM

2.1.1. Rational function

A rational function model is a generalization of the polynomial model, because it contains this model as a subset when the denominator is a constant. Taking in to account that the thermal recovery processes is continuous and the temperature increases until the stabilization is reached, we propose that both polynomials are of first degree. Considering the model for fitting the thermal recovery process using rational function, we can express the temperature $y(x)$ as:

$$y(x) = \frac{P(x)}{Q(x)} = \frac{a + bx}{1 + cx}, \tag{1}$$

where x is time and a, b, and c are the constants to be determined.

An important characteristic of this mathematical structure is that for estimating the SFT we can obtain an exact expression though the limit $\lim_{t\to\infty} y(x) = b/c$. The SFT equation then sets as follows:

$$SFT = \frac{b}{c}. \tag{2}$$

Thus, this method only requires the BHT-time data in order to calculate the coefficients b and c to estimate the SFT, without requiring the use of any formation or mud thermo-physical parameter. An additional benefit of this method is that it allows simulation of the thermal recovery process.