Computers & Geosciences 85 (2015) 45–59

Contents lists available at ScienceDirect

Computers & Geosciences

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

Case study

RPM-WEBBSYS: A web-based computer system to apply the rational polynomial method for estimating static formation temperatures of petroleum and geothermal wells

J.A. Wong-Loya [a,b], E. Santoyo [b,*], J.A. Andaverde [c], A. Quiroz-Ruiz [b]

[a] Colegio de Ciencias y Humanidades, Plantel Vallejo, Universidad Nacional Autónoma de México, Avenida Cien metros s/n, Colonia Magdalena de las Salinas, Distrito Federal, 07760, México
[b] Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Priv. Xochicalco s/n, Colonia Centro, Temixco, Morelos 62580, México
[c] Centro de Investigación en Recursos Energéticos y Sustentables, Universidad Veracruzana, Av. Universidad Veracruzana Km. 7.5, Coatzacoalcos, Veracruz 96538, México

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form
18 August 2015
Accepted 3 September 2015
Available online 8 September 2015

Keywords:
Geothermal energy
Petroleum technology
Well drilling
Shut-in
Formation temperature
Bottomhole temperature

ABSTRACT

A Web-Based Computer System (RPM-WEBBSYS) has been developed for the application of the Rational Polynomial Method (RPM) to estimate static formation temperatures (SFT) of geothermal and petroleum wells. The system is also capable to reproduce the full thermal recovery processes occurred during the well completion. RPM-WEBBSYS has been programmed using advances of the information technology to perform more efficiently computations of SFT. RPM-WEBBSYS may be friendly and rapidly executed by using any computing device (e.g., personal computers and portable computing devices such as tablets or smartphones) with Internet access and a web browser. The computer system was validated using bottomhole temperature (BHT) measurements logged in a synthetic heat transfer experiment, where a good matching between predicted and true SFT was achieved. RPM-WEBBSYS was finally applied to BHT logs collected from well drilling and shut-in operations, where the typical problems of the under- and overestimation of the SFT (exhibited by most of the existing analytical methods) were effectively corrected.

1. Introduction

Petroleum (non-renewable) and geothermal (renewable) systems are currently used as primary energy to make secondary sources of energy, like electricity and heat production (Lukawski et al., 2014; Templeton et al., 2014). To evaluate energy potential of these systems, accurate knowledge of the static formation temperatures (SFT) are needed (Ricard and Chanu, 2013). SFT are also referred as the stabilized, virgin or undisturbed formation temperatures, which represent the original equilibrium temperature of these geoenergy systems before they had been affected by wellbore drilling operations (Kutasov and Eppelbaum, 2015). Petroleum and geothermal wellbore completion involve a complex heat transfer due to the drilling fluid injection, heat generation (produced by the drilling bit rotation and rock-friction), and heat exchange between drilling fluids and surrounding rock-formation (Marshall and Bentsen, 1982).

Due to drilling fluid circulation (required for cooling the drill bit and transporting the drilling cuttings to the surface), the temperature of the formation at the sandface/bore-wall is lower than the SFT (Espinosa-Paredes et al., 2009). Such a circulation affects not only the borehole temperature but also the adjacent rock-formation (Yang et al., 2013). Temperature changes at the borehole and the surrounding formation have effects on the transport and thermophysical properties of drilling fluids. After the drilling fluid circulation, a slow return to the equilibrium formation temperatures is expected at very long shut-in times, which is know in the technical literature as the thermal recovery process (e.g., Hasan and Kabir, 1994; Santoyo et al., 2000).

The accurate prediction of SFT is required for an improved design of the wellbore drilling, completion and production programs. In this context, the knowledge of the SFT is specifically required as an essential task for:

- Drilling operations: borehole stability (Yan et al., 2014), selection of suitable drilling fluids (Chen and Novotny, 2003),

Abbreviations: ASCII, American Standard Code for Information Interchange; BHT, Bottom Hole Temperature; CPU, Central Processing Unit; HM, Horner Method; NRSS, Sum of Normalized Squared Residuals; OLR, Ordinary Linear Regression; PDF, Portable Document Format; QR, Quadratic Regression; RAM, Random Access Memory; RP, Rational Polynomial; RPF, Rational Polynomial Function; RPM, Rational Polynomial Method; RSD, Relative Standard Deviation; SD, Standard Deviation; SFT, Static Formation Temperature; SRM, Spherical Radial Model; TFT, True Formation Temperature (Experimental); 1D, One-dimension; 2D, Two-dimension; 3D, Three-dimension

* Corresponding author.
E-mail address: esg@ier.unam.mx (E. Santoyo).

http://dx.doi.org/10.1016/j.cageo.2015.09.001

- Data evaluation and interpretation: petrophysics and the determination of temperature gradients (Kabir et al., 2014),
- Wellbore and reservoir production enhancement (Mengbo et al., 2015),
- A better calibration of wellbore thermal simulators (Wu et al., 2014), among other important applications

SFT are usually calculated by analytical methods based on either simplified or complex heat transfer models, which concentrate at deeper conditions, where the bottom-hole temperature (BHT) is measured. The BHT measurements reflect thermal anomalies caused by the drilling fluid circulation to the rock-formation. The ability to develop a reliable method for predicting SFT requires a comprehensive understanding of the heat exchange between the surrounding formation and borehole interfaces under drilling and shut-in.

Many researchers have modeled such heat transfer processes, using either numerical or analytical methods to analyze BHT measurements to estimate both the circulating drilling fluid temperatures, and SFT (e.g., García et al., 1998; Santoyo et al., 2000; Danis, 2014). Numerical simulators are preferred to describe the transient thermal behavior of wellbore drilling systems (e.g., Marshall and Bentsen, 1982; Beirute, 1991; Reid et al., 2012; Ricard and Chanu, 2013; Wu et al., 2014), whereas the analytical methods are better recommended for estimating SFT from BHT logs (e.g., Dowdle and Cobb, 1975; Ascencio et al., 1994; Kutasov and Eppelbaum 2005; Bassam et al., 2010; Espinoza-Ojeda et al., 2011). Numerical simulators and analytical methods have been sometimes evaluated by using synthetic heat transfer experiments, where the true formation temperature (TFT) is known with accuracy (e.g., Luheshi, 1983; Andaverde et al., 2005).

1D, 2D or 3D thermal simulators have been developed for modeling the wellbore and the surrounding rock-formation using a wide variety of assumptions (e.g., Marshall and Bentsen, 1982; Beirute, 1991; Li and Zhu, 2010; Danis, 2014; Wu et al., 2014).

On the other hand, a large number of analytical methods have been derived from simplified heat transfer models. For example, the classical 'Horner-plot' method (HM) was derived from the study of the line source/sink conductive model (Dowdle and Cobb, 1975). Other methods developed for predicting SFT include: (i) the conductive radial source (Brennand 1984); (ii) the generalized Horner method (Kutasov and Eppelbaum 2005); (iii) the conductive cylindrical heat source method (Leblanc et al., 1981); (iv) the conductive cylindrical heat source method (Manetti, 1973); (v) the conductive spherical–radial method, SRM (Ascencio et al., 1994); (vi) the conductive–convective cylindrical heat source method (Hasan and Kabir, 1994); and (vii) the artificial neural network method (Bassam et al., 2010).

Although the availability of a large number of analytical methods, significant discrepancies are still reported when these tools are applied to the analysis of BHT data for estimating SFT (e.g., Espinosa-Ojeda et al., 2011, Zhou et al., 2015). Most of these problems rely on error sources, such as: (a) unrealistic physical models to describe the borehole drilling process; (b) the use of simplified heat transfer models to predict the SFT, especially those based on approximate solutions which use linear regressions to analyze the BHT data; (c) the measurement errors of BHT and shut-in times; (d) the knowledge of the thermo-physical and transport properties for drilling fluids, formation, drilling pipe and cement materials; (e) the limited number of BHT measurements logged during borehole drilling operations; and (f) the total uncertainties propagated in the SFT estimation.

For minimizing the uncertainties, the number of independent variables that affect the drilling and shut-in (and therefore, the SFT estimation) should be either reduced or optimized, together with suitable regression models for a better description of the thermal behavior observed between BHT and shut-in times.

Within this context, Wong-Loya et al. (2012) proposed the Rational Polynomial Method (RPM) to estimate SFT from BHT (y) and shut-in time (x). This method applies Padé approximations to derive a simplified equation that enables an extrapolation of the BHT measurements at infinite time to predict the SFT, which is given by the ratio of two polynomials of k and j degree (1st, 2nd or 3 rd-degree):

$$y(x) \cong \frac{p_0 + p_1 x + p_2 x^2 + \cdots + p_r x^k}{1 + q_1 x + q_2 x^2 + \cdots + q_s x^j} \tag{1}$$

The polynomial coefficients p_i and q_l, {from $i=0, 1, 2, \ldots, r$, and $l=1, 2, \ldots, s$ respectively} in Eq. (1) may have different real values. The total number of coefficients in the Eq. (1) is given by the sum $n=k+j+1$, and n-pairs of data (x, y) are therefore required to obtain n-equations, which must be solved for determining their coefficients.

A fundamental condition to extrapolate the y variable at infinite time is given when the k and j exponents are equal ($k=j$). According to this, Eq. (1) may be reduced to:

$$\lim_{x\to\infty} y(x) = \text{SFT} = \frac{p_r}{q_s} \tag{2}$$

Eq. (2) enables the SFT to be estimated. The full thermal recovery history (i.e., BHT versus shut-in times) may be reproduced by means of Eq. (1). The main practical feature of the RPM is the use of only transient BHT measurements (shut-in times and BHT) to predict the SFT, which constitutes an advantage over most of the available analytical methods. RPM does not require additional input data typically essential by other existing methods (e.g., the drilling fluid circulation times, the thermophysical properties of drilling fluids, rock-formation and pipe materials, and transport properties of drilling fluids), which are rarely known with accuracy, and which increase the SFT estimation uncertainties.

Although a first version of the RPM algorithm was proposed by Wong-Loya et al. (2012), its applicability was limited due to some problems detected with the use of a simple Fortran code developed, such as: (i) the absence of a friendly-interactive interface for capturing input data; (ii) the non-existence of a suitable plotting routine to analyze the thermal recovery process, and the quality of the fitting procedure applied to the transient BHT measurements; (iii) the strict dependence of the windows platform and hardware (a personal computer with high performance: RAM memory and CPU processor) to run the computer code for performing tedious numerical calculations and a large number of combinatory equation arrays which require to be solved and stored; and (iv) the final interpretation of results for defining the best mathematical function to describe the thermal recovery process, and to estimate the SFT.

To solve all these problems, the development of an improved computer system for a better application of the RPM to estimate SFT in geothermal and petroleum wells is still justified. With the purpose to achieve a wider application of the RPM, a new visual computer system (RPM-WEBBSYS) based on Web server facilities has been developed. A detailed description of the computer system is here reported.

2. Computing architecture of rpm-webbsys

A simple Web-Based Computer System, named RPM-WEBBSYS, was developed for facilitating the application of the RPM to estimate SFT from transient BHT measurements logged in geothermal and petroleum wells. RPM-WEBBSYS is also capable to reproduce the full thermal recovery or shut-in processes occurred during the well completion. RPM-WEBBSYS has been developed using