

TIn-SFT – the Computer System to Apply the Log-Transformation Regression Method for the Estimation of Static Formation Temperatures of Geothermal Boreholes

Orlando Miguel Espinoza-Ojeda^{1,4}, Eduardo Gessel Pacheco-Venegas² and Edgar Santoyo^{3,4}

¹CONACyT, INICIT - Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México.

²Posgrado en Ciencias de la Tierra - Instituto de Geofísica - Universidad Nacional Autónoma de México, Ciudad de México, México.

³Instituto de Energías Renovables - Universidad Nacional Autónoma de México, Temixco, Morelos, México.

⁴Centro Mexicano de Innovación en Energía Geotérmica (CeMIE-Geo), Ensenada, B.C., México.

omespinozaoj@conacyt.mx

Keywords: Static Formation Temperature, Bottomhole Temperatures, shut-in time, log-transformation, linear and polynomial regression models, geothermal energy

ABSTRACT

A computer system (TIn-SFT) has been developed for the application of the method based on logarithmic transformation regressions for the determination of static formation temperatures (SFTs) in geothermal boreholes. The system was designed to reproduce the full thermal recovery processes occurred during the cessation of the borehole drilling stage. The system is also capable to apply multiple linear and polynomial (from quadratic to eight-order) regression models to BHT and log-transformation (TIn) shut-in times. TIn-SFT has been programmed using advances of the information technology to perform more efficiently computations of the selection of the best regression models by using four statistical criteria: (i) the coefficient of determination as a fitting quality parameter; (ii) the sum of the normalized squared residuals; (iii) the absolute extrapolation, as a dimensionless statistical parameter that enables the accuracy of each regression model to be evaluated through the extrapolation of the last temperature measured of the data set; and (iv) the deviation percentage between the measured and predicted BHT data. TIn-SFT may be friendly and rapidly executed by using any personal computer for the determination of the SFT. The TIn-SFT was validated using synthetic data sets where the true formation temperature (TFT) was known with accuracy. Finally, the practical use and prediction efficiency of the TIn-SFT was highlighted and demonstrated because it only requires the use of the original thermal recovery data (BHT and shut-in time) as the main input data, which represents an enormous advantage over most of the analytical and numerical methods reported in the literature that require a large number of measurements (e.g. circulation time, the thermophysical and transport properties of the formation or drilling fluid, among others).

1. INTRODUCTION

Several scientific works reported in the worldwide literature have demonstrated that the reliable estimation of stabilized formation temperatures (SFT) in geothermal systems has relevance in the evaluation of geoenergy reserves (Santoyo et al., 2000; Kutasov and Eppelbaum, 2011). The estimation of SFT from transient bottomhole temperature (BHT) measurements provides the opportunity to determine the virgin temperatures of the surrounding formation-rock during thermal recovery processes of borehole. For this reason, it is conceived of as a valuable tool in terms of planning, exploration, evaluation and developing geothermal projects (e.g., Verma et al., 2006).

Numerical simulators and simplified analytical methods (based on heat transfer models) were initially developed for the thermal study of petroleum boreholes under drilling and completion conditions, and later extended to the geothermal industry. In the context of practical analytical tools, several works have criticized the validity of some analytical methods for calculating SFT in these geosystems (Luheshi, 1983; Drury, 1984; Shen and Beck, 1986; Deming, 1989; Andaverde et al., 2005; Espinoza-Ojeda et al., 2011). These studies have demonstrated that some of the simplified analytical methods were derived under unrealistic heat transfer assumptions, and with a wrong use of linear regression models in the simplified solutions to estimate the SFT. Significant errors have been actually reported when these analytical methods have been used to estimate the SFT using synthetic BHT datasets, where the true formation temperature (TFT) is known with accuracy (e.g., Drury, 1984; Andaverde et al., 2005; Verma et al., 2006). In addition, large discrepancies have been also reported among the SFT estimates predicted by several analytical methods using the same BHT datasets (e.g., Santoyo et al., 2000; Espinoza-Ojeda et al., 2011; Wong-Loya et al., 2012).

To overcome the conceptual problems detected with the use of previous analytical methods, and the necessity of additional information (e.g., thermophysical and transport properties of drilling materials: mud, cement, rock-formation, etc.), which is rarely available in drilling logging, a new numerical tool has been developed on the basis of the empirical method to estimate SFT by using only transient BHT datasets logged from geothermal boreholes recently published by Espinoza-Ojeda et al (2016). This new numerical tool performs the analysis of transient BHT measurements (logged during borehole shut-in conditions) by applying an innovative mathematical methodology based on logarithmic transformation regressions. The SFT is estimated after reproducing the typical transient asymptotic behavior of BHT measurements (also called thermal recovery or shut-in process) by assuming that the formation has reached a thermal equilibrium state at infinite time.

The new computer system (Tln-SFT) was developed to improve the applicability of the empirical method which proposes the application of a logarithmic transformation (*Tln*) in a regression model (GRM) either linear or polynomial, which can be represented by the following generalized equation:

$$y(x) = \sum_{i=0}^m a_i x^i \tag{1}$$

where *y* represents the dependent variable (BHT), *x* the independent variable (Δt or shut-in time), and a_i the coefficients of the regression model. As an initial step, three different logarithmic transformations (*Tln*) should be applied to the independent variables of the GRM to obtain three new improved independent variables [(i.e., single (Tln1), double (Tln2), and triple (Tln3) functions which determine the new values of the independent variable: $\ln \Delta t$; $\ln(\ln \Delta t)$; and $\ln(\ln(\ln \Delta t))$, respectively]. The Tln-SFT assumes that by applying linear or polynomial regression models to the BHT and the improved shut-in time data, the SFT will be estimated at infinite time conditions. Based upon the fit results and the calculated residuals, the best regression model was selected to determine the SFT.

2. COMPUTING ARCHITECTURE OF TLN-SFT

The computer system named Tln-SFT, was developed for facilitating the application of the Tln to estimate SFT from transient BHT measurements logged in geothermal wells. Tln-SFT is also capable to reproduce the full thermal recovery or shut-in processes occurred during the well completion. Tln-SFT has been developed using advances of the information technology for helping to geoscientists to perform more efficient and rapid computations of SFT for the geothermal industry.

Figure 1 shows schematically the main computer interactions used by Tln-SFT. The description of the three computing tasks (Input Data, Tln Application, and Output Data) is given as follows:

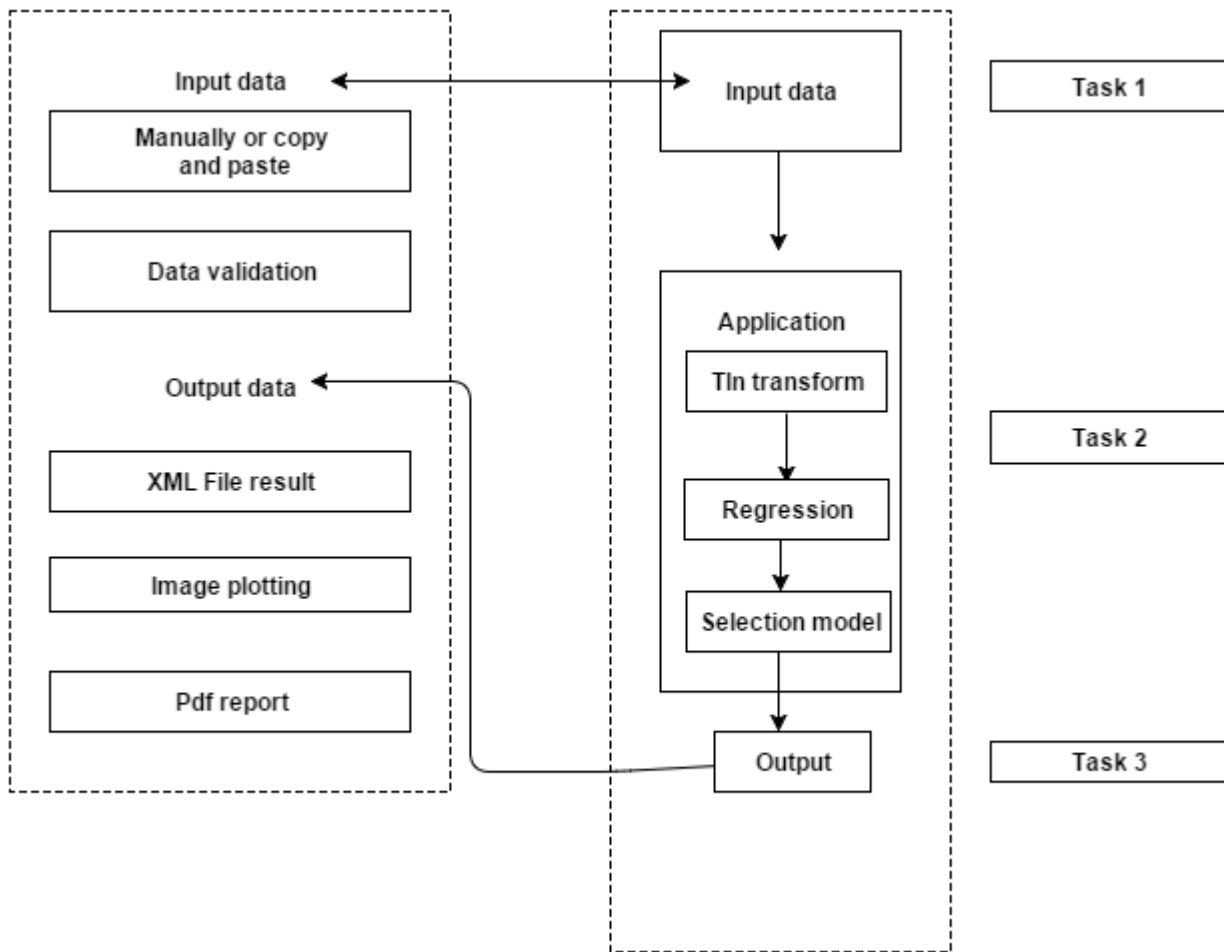


Figure 1: General diagram of the main components and computing tasks of the Tln-SFT, including its interaction with users.

1. Input Data: the Tln-SFT system reads the input data (BHT and shut-in time measurements), which may be introduced either manually by the user (one by one), by a copy-paste function from a created text file or direct open file (XML or TXT file format).
2. Tln Application: where the numerical algorithm of Tln is executed in accordance with the following numerical steps:
 - To apply the logarithmic transformation (Tln) functions (Tln1, Tln2, and Tln3) to the shut-in time data associated with each BHT data set, which will define the new improved value of the independent variable (Equation 1).
 - To apply the applicability criterion to the maximum order of the GRM, which is defined as $m \leq (n - 1)/2$, where m and n are the maximum order of the regression model to be used, and the total number of BHT data, respectively. This first applicability criterion also allows to the maximum order of the polynomial model (in the GRM) based on the total number of data set to be evaluated. The nomenclature to determine the polynomial models to be used in the GRM (Equation 1) was as follows: Linear [L]; Quadratic [Q]; Cubic [C]; Fourth [FO]; Fifth [FI]; Sixth [SI]; Seventh [SE]; and Eight [EI].
 - To calculate the GRM coefficients of Equation 1 by using the regression numerical routines programmed in the Tln-SFT system.
 - To select the best GRM model that allows to reproduce the BHT data with reliability, and hence, to estimate the SFT at infinite recovery time ($\Delta t \rightarrow \infty$) by using the following statistical criterions of evaluation:
 - a) Coefficient of determination (R^2). From a statistical point of view, the parameter R^2 was used to evaluate the quality of the regression in terms of the variation between two variables (x and y) to be correlated in any regression model. This parameter is calculated for each regression model using the complete BHT data set, and a numerical value that approaches to the unit will be expected when the regression is statistically acceptable ($R^2 \approx 1$: Bevington and Robinson, 2003).
 - b) Sum of the normalized squared residuals ($RSSn$). The different regression models applied to the relationship BHT – Tln1, Tln2 or Tln3 were also evaluated through the estimation of the well-known statistical parameter $RSSn$. The best fit model will be given by the smaller $RSSn$ numerical values. The $RSSn$ was estimated by means of the equation:

$$RSSn = \frac{\sum_{i=1}^n (BHT_i - T_i)^2}{n} \quad (2)$$
 where BHT_i and T_i are the measured and calculated (Tln-SFT) transient temperatures, respectively.
 - c) Absolute extrapolation ($Ext-Abs$). A dimensionless statistical parameter that enables the accuracy of each regression models to be evaluated through the extrapolation of the last temperature measured (BHT_n) of the data set. In this case, the evaluation criterion establishes the small numerical value of the parameter Ext-Abs belongs to the best predictor of BHT_n. The parameter Ext-Abs was calculated as:

$$Ext-Abs = \left| \frac{BHT_n - T_n}{BHT_n} \right| \quad (3)$$
 - d) Deviation percentage ($\%Dev$). The dimensionless parameter %Desv is a combination of conditions used to calculate the SFT estimates and their associated uncertainty, and it was determined by means of the following equation:

$$\%Dev = \left| \frac{T_{i+1} - T_i}{T_{i+1}} \right| \times 100 \quad (4)$$

For the analysis of geothermal cases, and according to the temperature magnitude, a $\%Dev \leq 0.01$ was used as strict convergence criterion for estimating the SFT through the numerical simulation of each GRM (Tln) at infinity time. This means that in the case of using the value 0.01, if the numerical simulation does not accomplish the complementary conditions, the next value (0.001) will be used, and so on. The complementary condition to be accomplished is that the SFT calculated at infinity time by the Tln-SFT must be greater than the last BHT measured data [Tln-SFT(SFT) > BHT_n]. The general complementary condition to the systems under analysis was the simulation time (Δt_{n+i}) and in order to obtain the SFT by these means, the simulation time [Tln-SFT(Δt_{n+i})] must be greater than the BHT_n shut-in time (Δt_n) measurements [Tln-SFT(Δt_{n+i}) > Δt_n].

For the determination of the SFT which corresponds to the BHT data sets under evaluation, the four statistical evaluation criteria were together applied both to decide the best GRM to fit the analyzed BHT and to reproduce the thermal recovery behavior of each data set. The results of the statistical evaluation parameters (R^2 , $RSSn$, $Ext-Abs$ and $\%Dev$) were reported with the most possible number of digits to facilitate the final analysis of selection.

3. Output Data: the Tln-SFT system provides the final results (i.e., the best estimation of the SFT using the best GRM equation model), the graphical results where the thermal recovery data are plotted (BHT and shut-in time measurements), and the best fitted curve; a XML file with the summarize of the statistical criterions of evaluation results for all the GRM with Tln values estimated during the numerical analysis; an image plot of the thermal recovery data; and a PDF file in which a complete report may be downloaded.

3. Tln-SFT PROCESS

The Tln-SFT executable system can be requested to the first author, a personal cloud storage link will be provided.

Figure 2 describes the containing text box for capturing the transient BHT measurements of a drilled well at certain depth. The “File” tool (Figure 2) gives the options to open the different sources file, a direct location (Open) or even several files located in the directory (through the option “Directory”). Inside the text box, the user requires to type the shut-in time and the corresponding BHT data in their corresponding cell (t and BHT, respectively). As was already mentioned, such a data set can be also entered by a copy and paste function when the data set was already written using a word processor, spreadsheet, or text files.

If the data set contains some typing mistakes, the Tln-SFT will send a text message inside an error framework (shown as a rectangle) where the mistake value will be located (Figure 3). In this case, the user must correct the mistake before to perform again the data set validation.

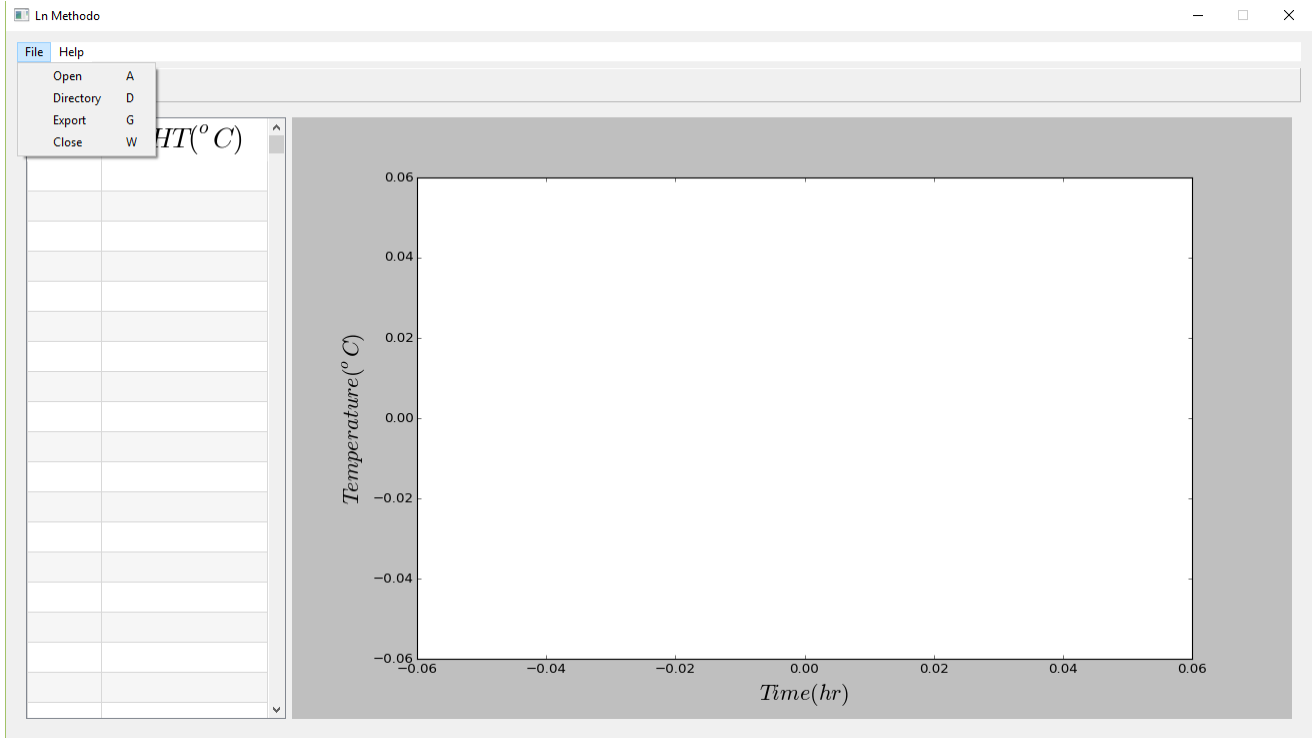


Figure 2: Input data screen-module used by the Tln-SFT for interacting with the users. For typing the transient BHT measurements (i.e., shut-in time and BHT data) or direct open a text or spreadsheet file.

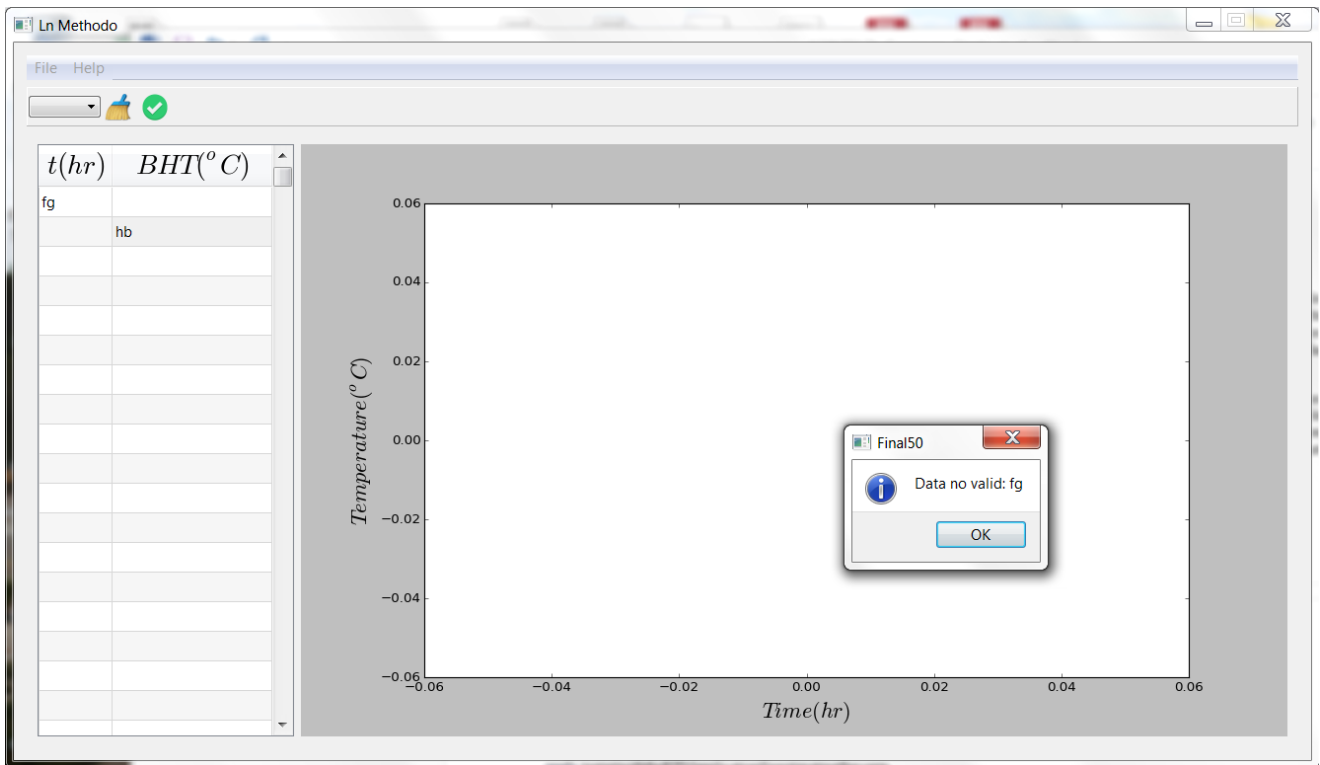


Figure 3: Error alert.

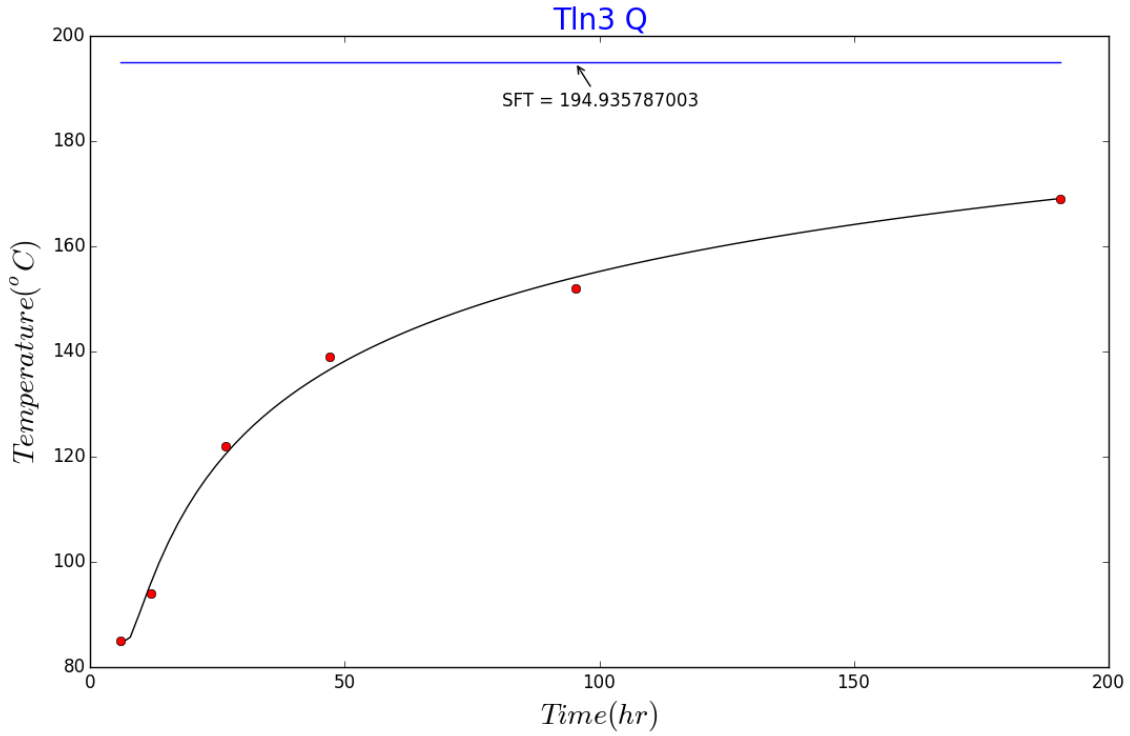


Figure 5: Image plot as result obtained from the analysis of the geothermal CH-A4 data set using the capability of the Tln-SFT.

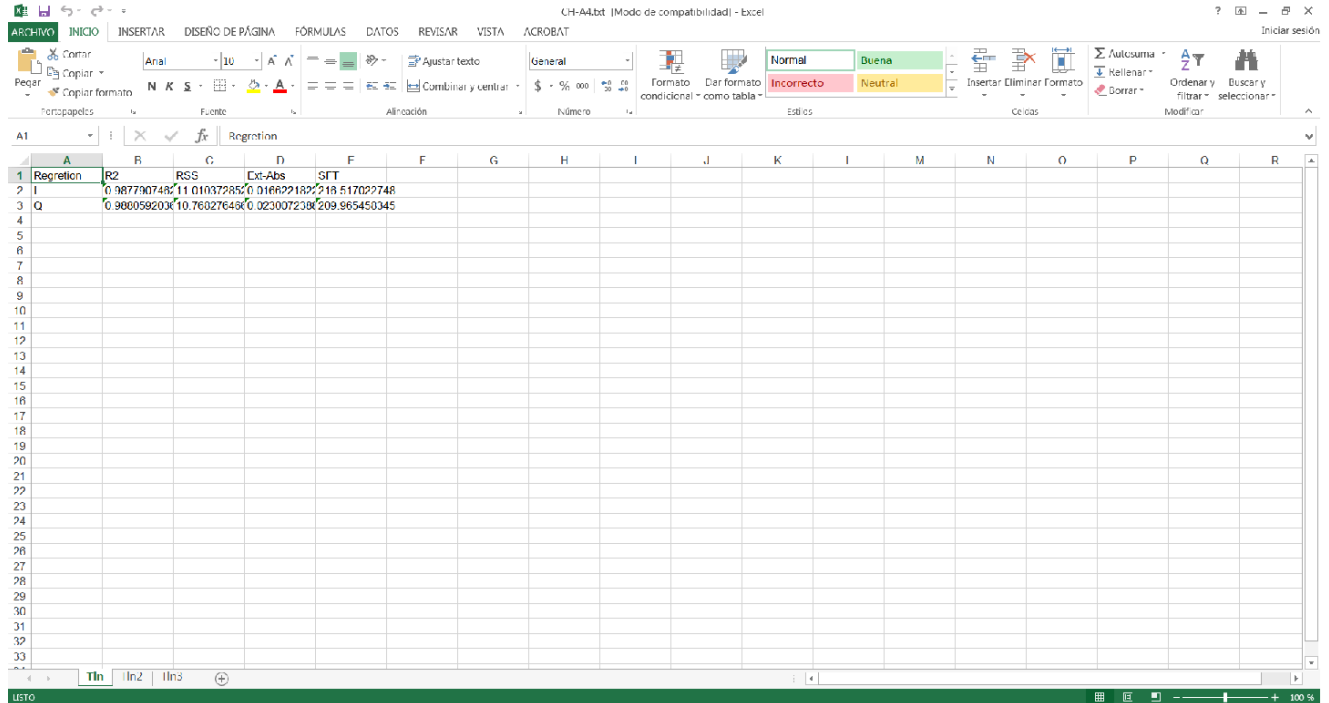


Figure 6: XML file, where all the statistical criteria values obtained by each GRM model is shown. One “worksheet” per Tln model (sheet1:Tln; sheet2:Tln2; sheet3:Tln3).

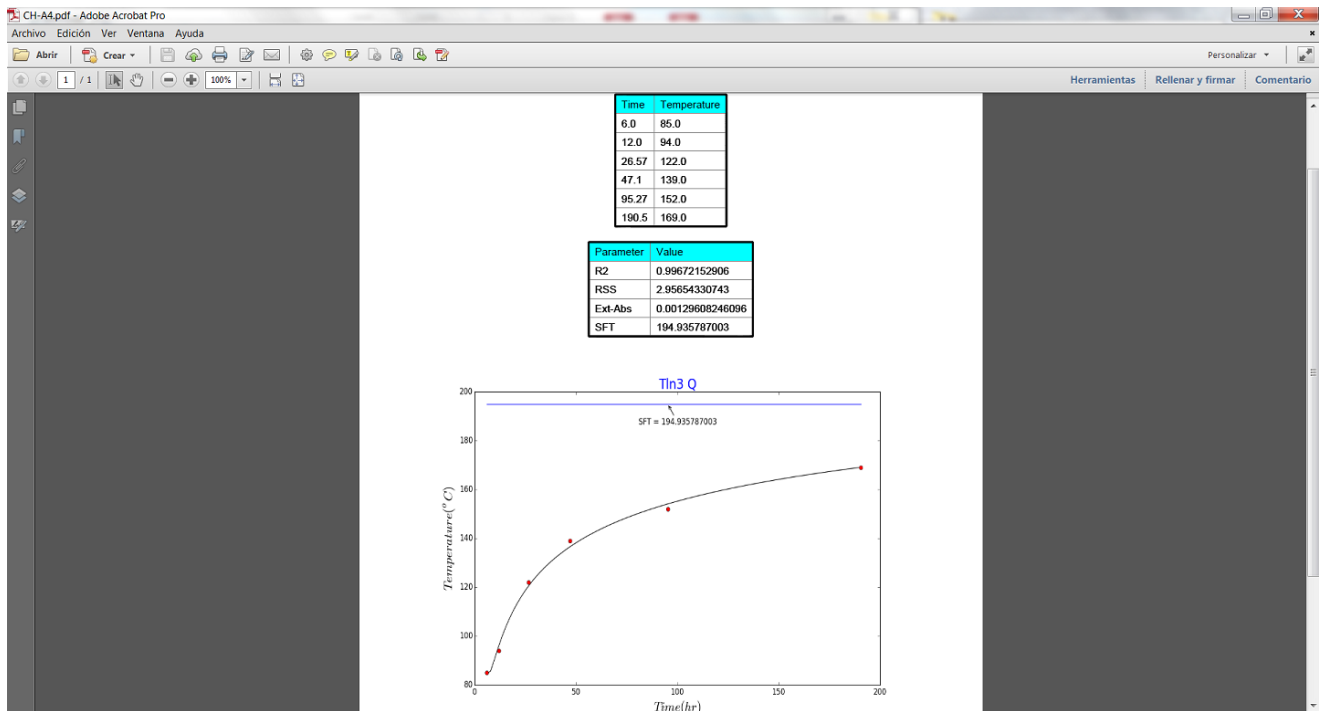


Figure 7: PDF file as output data, containing the original transient BHT data, statistical evaluation results and the thermal recovery plot, where the SFT calculated by Tln-SFT is indicated.

4. RESULTS

4.1 Validation

The numerical algorithm of Tln was verified (Espinoza-Ojeda et al., 2016) with the synthetic series SHEN (Shen and Beck, 1986), CAO (Cao et al., 1988) and CJON (Cooper and Jones, 1959), the new software developed (Tln-SFT) was validated too using these synthetic data sets, where the true SFT is reported with accuracy CJON=20.25°C, SHBE=80.0°C, and CLAH=120.0°C.

4.2 Application cases

The recently published empirical method Tln (Espinoza-Ojeda et al., 2016) was developed to be used with BHT data from geothermal, petroleum and permafrost systems. Therefore, after validating the Tln-SFT capability, the transient BHT measurements logged from a drilled geothermal (CH-A4: Gonzalez Partida et al., 1997), petroleum (USAM: Kutasov, 1999) and permafrost (MOKKA: Taylor et al., 1982) wells were analyzed. As example, the final and plotting results obtained for the analysis of the permafrost well MOKKA is shown in Figure 8. This last analysis was carried out to validate and corroborate that the Tln-SFT has the same conception as the empirical method Tln.

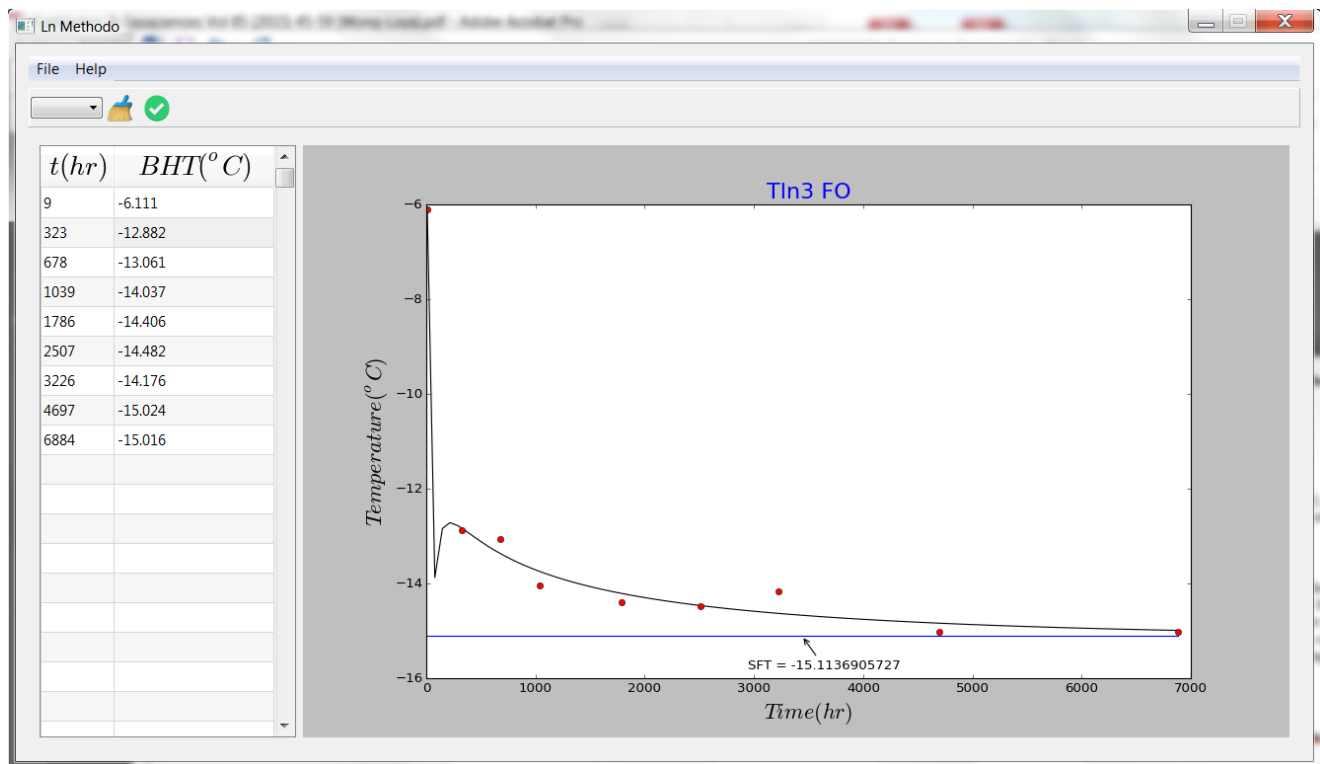


Figure 8: Application results obtained from the analysis of the permafrost MOKKA data set using the capability of the Tln-SFT.

5. CONCLUSIONS

The new visual computer system, named Tln-SFT, based on the Tln method for the estimation of SFT in geothermal wells was successfully developed.

The Tln-SFT computer system was fully validated and applied by using transient BHT measurements collected from synthetic experiments and actual wellbore drilling data.

Inside this context of difficulties and limitations, the Tln-SFT computer system offers several technical and practical advantages over the existing numerical methods, among which the next ones stand out: (i) the knowledge of circulation time is not required, as it is a physical parameter that is very hard to determine with high precision and accuracy under the field conditions; (ii) neither are the thermophysical and transport properties data from the formation, cementation, mud and drilling tubing required; and (iii) the input data the BHT and thermal recovery time (shut-in time) measurements are also required.

REFERENCES

- Andaverde, J., S. P. Verma, and E. Santoyo (2005). Uncertainty estimates of static formation temperatures in boreholes and evaluation of regression models. *Geophysical Journal International*, **160**, 1112-1122. doi: 10.1111/j.1365-246X.2005.02543.x.
- Bevington, P. R., and D. Robinson (2003). *Data reduction and error analysis for the physical sciences*. Third ed. McGraw Hill Higher Education. 320 pp.
- Cao, S., I. Lerche, and C. Hermanrud (1988). Formation temperature estimation by inversion of borehole measurements. *Geophysics*, **53**(7), 979-988. doi: 10.1190/1.1442534.
- Cooper, L. R., and C. Jones (1959). The determination of virgin strata temperatures from observations in deep survey boreholes. *Geophysical Journal of the Royal Astronomical Society*, **2**, 116-131. doi: 10.1111/j.1365-246X.1959.tb05786.x.
- Deming, D. (1989). Application of bottom-hole temperature corrections in geothermal studies. *Geothermics*, **18**(5-6), 775-786. doi:10.1016/0375-6505(89)90106-5.
- Drury, M. J. (1984). On a possible source of error in extracting equilibrium formation temperatures from borehole BHT data. *Geothermics*, **13**(3), 175-180. doi: 10.1016/0375-6505(84)90014-2.

- Espinoza-Ojeda, O. M., E. Santoyo, and J. Andaverde (2011). A new look at the statistical assessment of approximate and rigorous methods for the estimation of stabilized formation temperatures in geothermal and petroleum wells. *Journal of Geophysics and Engineering*, **8**, 233-258. doi:10.1088/1742-2132/8/2/010.
- Espinoza-Ojeda, O. M., and E. Santoyo (2016). A new empirical method based on log-transformation regressions for the estimation of static formation temperatures of geothermal, petroleum and permafrost boreholes. *Journal of Geophysics and Engineering*, **13**(4), 559-596. doi:10.1088/1742-2132/13/4/559.
- Gonzalez Partida, E., A. Garcia Gutierrez, and V. Torres Rodriguez (1997). Thermal and petrologic study of the CH-A well from the Chipilapa-Ahuachapan geothermal area, El Salvador. *Geothermics*, **26**(5/6), 701-713. doi:10.1016/S0375-6505(97)00020-5.
- Kutasov, I. M. (1999). *Applied Geothermics for Petroleum Engineers*. First ed. Elsevier Scientific Publishing Company. 347 pp.
- Kutasov, I. M., and L. V. Eppelbaum (2011). Recovery of the thermal equilibrium in deep and super deep wells: Utilization of measurements while drilling data. In: *proceedings of the 36th Workshop on Geothermal Reservoir Engineering*. Stanford University, Stanford, California, January 31 - February 2, 7.
- Luheshi, M. N. (1983). Estimation of formation temperature from borehole measurements. *Geophysical Journal of the Royal Astronomical Society*, **74**(3), 747-776. doi: 10.1111/j.1365-246X.1983.tb01902.x.
- Santoyo, E., A. Garcia, G. Espinosa, I. Hernandez, and S. Santoyo (2000). STATIC_TEMP: a useful computer code for calculating static formation temperatures in geothermal wells. *Computers & Geosciences*, **26**, 201-217. doi:10.1016/S0098-3004(99)00087-4.
- Shen, P. Y., and A. E. Beck (1986). Stabilization of bottom hole temperature with finite circulation time and fluid flow. *Geophysical Journal of the Royal Astronomical Society*, **86**, 63-90. doi: 10.1111/j.1365-246X.1986.tb01073.x.
- Taylor A E, Burgess M M, Judge A S and Allen V S 1982 Canadian geothermal data collection - Northern Wells 1981 *Earth Physics Branch, Energy, Mines and Resources Canada. Geothermal Series 13* pp.153.
- Wong-Loya, J. A., J. Andaverde, and E. Santoyo (2012). A new practical method for the determination of static formation temperatures in geothermal and petroleum wells using a numerical method based on rational polynomial functions. *Journal of Geophysics and Engineering*, **9**, 711-728. <http://dx.doi.org/10.1088/1742-2132/9/6/711>.
- Verma, S. P., J. Andaverde, and E. Santoyo (2006). Application of the error propagation theory in estimates of static formation temperatures in geothermal and petroleum boreholes. *Energy Conversion and Management*, **47**, 3659-3671. doi:10.1016/j.enconman.2006.02.028.