The influence of solar heating upon ground temperature

A M Sousa¹, L Azevedo¹, M J Pereira¹ and H A Matos¹
CERENA, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa

E-mail: ana.margarida.sousa@tecnico.ulisboa.pt

Abstract. To predict the superficial ground temperature due to solar radiation as a function of the depth and rock physical properties, the Finite Volume Method was employed upon an energy conservation model. ANSYS Transient Thermal was selected to simulate a 3D geological volume, 1625 m wide, 2000 m long and with variable height as a function of topographical data. As a result, the variability of ground temperature during a 24h day was assessed. A set of climatological data was used to evaluate the ground temperature for the colder periods. The numerical results were compared against the Kusuda and Achenbach’s analytical solution to evaluate the possibility of extending the validity of a widely used method, from daily to intraday data.

1. Introduction
Ground temperature varies with time and in-depth, showing higher amplitudes at the surface. This effect decreases with depth. The temperature variation rate depends on the subsurface rock properties and it behaves as a periodic function around the mean value.

While there is not a plethora of published research on this matter, an influence depth of a maximum of 20 m is usually assumed [1-2].

Among the aspects that play a major role in superficial temperature, solar radiation and environmental temperature must be highlighted [3].

Kusuda and Achenbach [3] proposed a thermal transient equation that allowed computing the ground surface temperature, for each day. Although very useful for industrial applications, this equation has not been evaluated for intraday temperature fluctuations. Such fact is paramount since extreme temperatures occur during a day, and it is, therefore, in the daily context that extreme temperatures will affect oil or geothermal wells. Consequently, these ground temperatures will be the ones interested in this study, given its role in predicting the paraffinic deposition inside oil wells. Thus, this study aimed to evaluate the possibility of extending the validity of a widely used method.

2. Methodology
A transient thermal analysis was performed using finite element methods in a 3D volume to determine the temporal evolution of ground temperature due to solar radiation. The problem was designed in ANSYS Transient Thermal software, according to the methodology summarized in figure 1.
2.1. Engineering data

Rock physical properties required to perform the energy calculations were added in the ‘Engineering data’ section and these material characteristics are synthesized in table 1.

Table 1. Material properties

| Rock type     | Density (kg/m³) | Isotropic Thermal Conductivity (W/mK) | Specific Heat (J/kg-K) |
|---------------|-----------------|---------------------------------------|------------------------|
| Carbonate     | 2300            | 2.259                                  | 837                    |
| Siliciclastic | 2860            | 4.085                                  | 962                    |

2.2. Geometry

The 3D geological volume, which is a synthetical model comprising the reservoir and upper geological layers, is 1625 m wide, 2000 m long and has a variable height as a function of topographical data. It is depicted in figures 2 and 3.

2.3. Model setup

The model setup was established, the mesh grid was defined, and the analysis settings were specified.

2.3.1. Meshing

Attaining a balanced mesh density was the main challenge. If the mesh is too coarse, the results will have undefinitions. On the other hand, if the mesh is too fine, a waste of computational resources will occur. In this case study, the mesh grid was optimized to what is depicted in figure 4.

2.3.2. Analysis settings

The first step for applying transient loads was defining solar radiation and then set the initial conditions. In this study, a uniform starting temperature of 28.73°C was set, as it represents the monthly average temperature for the colder month. This scenario was chosen to be modelled, as it provides the extreme
conditions that influence the operations of the well. Climatological data was gathered from the nearest meteorological station. The synthetic month of August, with 31 similar days, represented in figure 5, was considered as input for this transient model. The minimum temperature is 22.9ºC, and the maximum is 35.4ºC.

The solar radiation was applied to the topographical data surface.

3. Findings

3.1. Results

The results obtained for the time step in which the lowest temperature is reached are illustrated below, along the profiles AA’ and BB’ located in figure 6. Figure 7 shows the ground temperature variability for those profiles, considering the effect of solar radiation.

The model showed that the topographic level and the well location influence their ground temperature. To the best of our knowledge, this topic was not addressed by other researchers. Usually, the ground temperature is studied as a function of depth, and does not consider topographic effects.

3.2. Comparison between the computational model and the analytical method

According to Kusuda and Achenbach [3] the average temperature at the surface is given by Eq. (1):

\[
\text{temperature} = A - B \times \cos \left( \frac{2\pi (\theta - P)}{T} \right)
\]

Here, A is the annual average temperature (ºC), B is the annual amplitude of the monthly average temperature cycle (ºC), \( \theta \) is the time coordinate which starts at zero on January 1st (h), T is the period of the temperature cycle (8766 h), and P is the phase angle of the earth temperature cycle (rad).

For the oil field location, it was possible to determine which A, B, and P parameters minimize the squared error to the case study, considering the average monthly temperature (figure 8). For the present case study, \( A = 28.8^\circ C \), \( B = 1.3^\circ C \), and \( P = 2.6 \) rad.

The Kusuda and Achenbach [3] analytical solution for the soil temperature, as a function of depth and time, is given by Eq. (2):
\[ t = A - Be^{-\sqrt{\frac{\pi}{D}} z} \cos \left( \frac{2\pi \theta}{T} - \sqrt{\frac{\pi}{D}} z - P \right) \]  

(2)

Where \( z \) is the downward distance coordinate from the earth's surface (m), \( D \) is the ground thermal diffusivity (m\(^2\)/s).

Figure 9 presents the comparison between the analytical method (Eq. (2)) and the numeric model (Profiles AA' and BB').

This study shows that the analytical method proposed by Kusuda and Achenbach may overestimate the ground temperature, when evaluating an intraday extreme scenario. Furthermore, according to the Finite Volume Method, solar radiation is felt deeper than the analytical model predicts.

4. Conclusion

A transient thermal 3D numerical study was conducted to determine the ground temperature distribution in an oil field. The results obtained were compared against the Kusuda and Achenbach [3] analytical method. The main finding is that, although this method can be applied for average scenarios, it shall not be extrapolated for extremely cold or hot days. Furthermore, the effect of the topographic level is not considered. In order to study flow assurance problems inside wells, we suggest that a numerical method is employed. The advantage of such numerical model is the ability to predict the ground temperature while considering the colder scenarios and the topographical effect.

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References

[1] Lenhard R and Malcho M 2013 Numerical simulation device for the transport of geothermal heat with forced circulation of media Mathematical and Computer Modelling 57 111–125
[2] Márquez J, Bohórquez M, Melgar S 2013 Ground thermal diffusivity calculation by direct soil temperature measurement. Application to very low enthalpy geothermal energy systems Sensors 16(3) 306
[3] Kusuda T and Achenbach P 1965 Earth temperature and thermal diffusivity at selected stations in the United States, 8979, (USA: National Bureau of Standards Report)
[4] Mihalakakou G., Santamouris M., Lewis J O, Asimakopoulos D N 1997 On the application of the energy balance equation to predict ground temperature profiles Solar Energy 60(3-4) 181–190.