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A feedback-based inverse heat transfer method to estimate unperturbed temperatures in wellbores

Gilberto Espinosa-Paredes [a,*], Erick G. Espinosa-Martínez [b]

[a] Área de Ingeniería en Recursos Energéticos, Universidad Autónoma Metropolitana-Iztapalapa, Apartado Postal 55-534, México D.F. 09340, Mexico
[b] Retorno Québec 6, Col. Burgos de Cuernavaca 62580, Temixco, Mor., Mexico

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ABSTRACT

This paper presents a feedback-based strategy to solve an inverse heat transfer problem for the estimation of unperturbed formation temperatures (UFT) from measured temperatures in wellbores. The feedback function uses the error between the measured and estimated temperatures during the shut-in process. Thus, an inverse heat transfer problem was solved in this way since the UFT represents the unknown initial conditions and the measured temperatures in the wellbore represents the particular solution of the PDE'S governing the heat transfer process in the formation and in the wellbore system. The performance of the method is illustrated via numerical simulations of two wells: (a) oil well FE-1227 from the Gulf of Mexico maritime zone and (b) well CP-0512 from Cerro Prieto Mexican geothermal field.

1. Introduction

Unperturbed formation temperature (UFT), also known as static formation temperature, is the temperature prevailing before the drilling of a well and before the formation disturbed thermally. The knowledge of the UFT is essential for many areas of engineering and scientific research, such as reservoir engineering for estimation of hydrocarbon recovery factors and well completion and production logging [1–4] studies of groundwater and aquifer potential (casing cements, completion design, fluid flow; evaluation of fractures); evaluation of thermal conductivity of the formation [5–7], overpressuring detection of zones [8], exploration for energy minerals (petroleum and coal) [3], paleoclimatology [9], and studies of the Earth's evolution [10], among others.

Although UFT are disturbed during the drilling of wellbores, they can be estimated using information obtained during drilling stoppages, after circulation stops and the well returns to thermal equilibrium. UFTs in wellbores can be inferred from temperature logging [11], empirical correlations [12] or analysis of fluid inclusions [13]. Also UFTs can be obtained by numerical simulation based on logged temperatures, which can be monitored during well drilling. Numerical simulation usually requires information such as drilling fluid composition, inlet fluid temperatures, fluid circulation rate and circulation losses, well geometry characteristics, geothermal gradient (the initial condition to start the simulation, which represents the UFT) and thermophysical properties.

Drilling of a wellbore is essentially a transient process due to circulation (cooling) and shut-in (heating) processes. During the drilling process the formation temperature is perturbed from the original condition (UFT), which is unknown. Thus, the inverse heat transfer problem determines the UFT, knowing directly measured quantities such as the logged temperatures or bottom-hole temperature (BHT), which is the temperature measured at the bottom of the well during routine geophysical logging. This is a typical inverse problem where initial temperatures should be estimated from final time temperatures. In contrast to the direct problem which consists of computing the consequences (BHT) of given causes (UFT), the inverse problem is associated with the reversal of the cause-effect sequence and consists of finding the unknown causes (UFT) of known consequences (BHT). As a result the transient disturbance associated with the recirculation of drilling mud, BHT is generally lower than real UFT [22].

The specific problem being studied in the present paper is the estimation of the UFT of a fully transient and a two-dimensional heat transfer with convective and conductive mechanisms from BHT measurements. The solution of this inverse problem is not straightforward due to their ill-posed, implying that small perturbations in the observed functions may result into large changes in the corresponding solutions. The ill-posed requires numerical techniques to stabilize the results of calculations through algorithms such as least-squares method [14,15] and the conjugate gradient method [16]. These inverse algorithms are iterative and therefore

* Corresponding author. Fax: 52 55 5804 4900.
E-mail address: gepe@xanum.uam.mx (G. Espinosa-Paredes).

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require repeated computation of governing equations before obtaining estimations.

In contrast with the typical methods to solve the inverse heat transfer problem, we propose a feedback control scheme to reduce the estimation error between logged and simulated temperatures for a best estimate of the UFT. The oil well FE-1227 from the Gulf of Mexico maritime zone and the well CP-0512 from Cerro Prieto Mexican geothermal field were used to show how the UFT can be found by means of a suitable feedback control.

2. Analysis

The circulation process in a wellbore is similar to a heat exchange system. In such process, fluid moves downward inside the drill pipe and upward through the annulus between the inner and outer pipes. Thus, the system acts as a counterflow heat exchanger from which there is an additional heat exchange to the rock outside the drill hole. Fluid enters the drill pipe at the top, flows down and exits the pipe at the bottom. There followed, it enters the annulus and flows upwards.

In order to describe the physical process of the heat transfer in the system, a simplified scheme of the physical well drilling system was considered as is illustrated in Fig. 1. Here, the radii correspond to each of the physical regions in which the well was considered, according with the main heat transfer process. Four regions were considered in the heat transfer analysis:

- *Region 1:* Drill pipe ($0 \leqslant r < r_1$).
- *Region 2:* Drill pipe wall ($r_1 \leqslant r < r_2$).
- *Region 3:* Annular region ($r_2 \leqslant r < r_3$).
- *Region 4:* Formation.

The fluid temperature in the wellbore depends upon a number of different thermal processes involving conductive and convective mechanisms in the system well-formation, as is illustrated in Fig. 1. Brief descriptions of the thermal processes in each region are given as follows:

- *Region 1:* The fluid enters the drill pipe with flow velocity v_{z1} at a specified temperature (T_{in}). As the fluid passes down the pipe in the *z* direction, its temperature (T_1) is determined by the rate of heat convection down the drilling pipe and heat exchange with the metallic pipe wall.
- *Region 2:* The drill pipe wall temperature (T_2) is determined by the rate of heat convection between the wall and flow down the drill pipe and up in the annulus as well as conduction in the pipe wall.
- *Region 3:* The circulation process requires that the fluid temperature at the exit of the drill pipe to be the same as the fluid temperature at the entrance of the annulus. In this region, the temperature (T_3) is determined by the rate of heat convection up the annulus, the rate of heat exchange between the annulus and the drill pipe wall, and the rate of heat exchange between the wall of the well and the annulus fluid whose flow velocity is $v_{z,3}$.
- *Region 4:* Corresponds to the heat transfer in the formation or cement, here T_4 is used to represent the temperature in this region. The well-formation interface is considered as a porous medium through which fluid may be lost or gained by the well.

3. Direct problem formulation

The mathematical model consists of a set of partial differential equations describing the two-dimensional transient temperature field $T(z,r,t)$. The fundamental assumptions of the model include the following: cylindrical geometry, isotropic rock formation, constant physical properties, negligible viscous dissipation and thermal expansion effects and incompressible fluid. Additionally, we considered that when the flow is stopped an axial-symmetric heat conduction situation prevails, i.e., the system well-formation tends to thermal equilibrium. During the drilling process the formation is disturbed thermally and is necessary to consider transient convective heat transfer due to circulation losses to the rock surrounding a well. Under these conditions, the governing equations and initial and boundary conditions for each region are

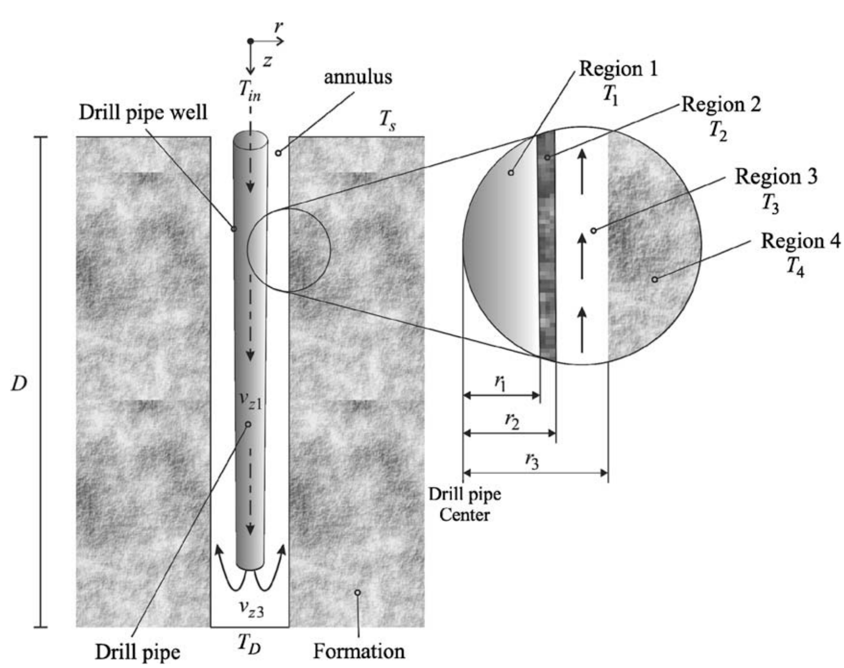

Fig. 1. Drilling process in oil (or geothermal) well.