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Analysis for formation thermal properties of water injection well from temperature data

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ABSTRACT

Formation thermal properties are important parameters for evaluating thermal recovery. This study uses a special layered inversion method appropriate to water injection well to estimate the formation thermal properties profiles from temperature log data. The proposed method is based on the water temperature model. Therefore, a novel heat transfer model for water injection well was built firstly to get the temperature model. Then sensitivity analysis was conducted to investigate the correlation between the thermal properties and water temperature, determining estimation sequence. With applying the inversion method to predict the formation thermal properties of three water injection wells, the thermal properties profiles which reflect the differences in physical properties of geological formations were obtained. The sensitivity analysis concludes that heat capacity showed stronger correlation with temperature than thermal conductivity, which is contrary to steam injection well sensitivity result. Based on the sensitivity analysis, heat capacity is estimated firstly bringing higher precision for water injection well thermal properties estimation. And the prediction precision of heat capacity is higher than that of thermal conductivity, also demonstrating the accordance of the proposed method for water injection well. Above all, thermal properties acquired by the layered inversion method show depth-variant in whole formation.

1. Introduction

Water injection for heavy oil production plays a significant role in thermal recovery projects. Especially, in water injection well, the heat transfer from the wellbore to the formation is an important factor that needs to be carefully taken into consideration. Reliable assessment of the thermal properties (thermal conductivity and heat capacity) of geological formations is of great importance for evaluating the heat transfer performance of water injection projects. As there are few in situ values, the thermal properties of geological formations are conventionally obtained by laboratory measurements. There are various experimental methods for thermal properties measurement which have been summarized for core analysis [1–3], including the divided-bar steady-state measurements and the needle-probe transient measurements. In addition, one of the most advanced lab measurements by optical scanning was developed by Popov et al. [4,5]. However, although the sample was obtained from real cores in a certain depth, the most thermal conductivity values of samples were obtained under room temperature and atmospheric conditions [4,6,7], which is different from in situ situations and would inevitably bring out deviations to the measurement results. Although some studies were tried to minimize the measurement deviation by improving the simulated conditions [7,8], the in situ conditions still have been difficult to be realized easily in laboratory. Furthermore, it is also impossible to obtain enough samples for laboratory measurements with the high cost of drilling [9].

In situ field measurements [10–15] are able to overcome the sampling difficulties and situation difference in laboratory measurements. However, the measurement accuracy are confined to certain factors, including the hole size and shape of core, water convection, time needed for measurements and so forth [6,16]. Another technique for thermal properties testing is the well-log correlation method [17–21]. Log data can not only prevent biased sampling in a situation without complete coring sequence, but also overcome the difficulties with regard to in situ measurements. Generally, well-log correlation method to compute the thermal conductivity can be classified into two main categories [22]. The first approach computes thermal conductivity form one or more

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Nomenclature

Variables

A_k	uncertainty parameters, $k = 1, 2, 3$
a	geothermal gradient, K/m
C_e	volumetric heat capacity of layer i, J/(m^3 K), $=(\rho c)_e$
C_J	Joule–Thompson coefficient, K/Pa
C_w	volumetric heat capacity of the wellbore, J/(m^3 K), $=(\rho c)_w$
c_p	heat capacity of tubing fluid (water), kJ/kg
c_{pa}	heat capacity of annulus fluid, kJ/kg
h_c	convective heat transfer coefficient for annulus fluid, W/(m^2 K)
h_f	forced-convection heat transfer coefficient for tubing fluid, W/(m^2 K)
h_r	radiation heat transfer coefficient for annulus, W/(m^2 K)
j	variable denoting random values of uncertainty parameter
M	number of formation layers
N	sample size
P	water pressure, Pa
$PRCC$	Spearman's partial rank correlation coefficient
Q	heat flux to formation over unit depth dz, W/m
$R(x_j)$	rank of random values of uncertainty parameter
$R(y_j)$	rank of simulated T_i
r_{ci}	inside radius of casing, m
r_{co}	outside radius of casing, m
r_h	wellbore outside radius, m
r_{ti}	inside radius of tubing, m
r_{to}	outside radius of tubing, m
T_{ei}	original formation temperature, K
T_{es}	surface formation temperature, K
T_h	wellbore/formation interface temperature, K
T_w	water temperature, K
T_{wi}	water temperature at z_i, K
U_{to}	overall heat-transfer coefficient, W/(m^2 K)
v	injection velocity of water, m/s
V	specific volume of water, m^3/kg
w	mass flow rate of injected water, kg/s
z	well depth, m
z_i	measured depth, m

Greek letters

α_e	thermal diffusivity of formation, m^2/s
λ_{cas}	thermal conductivity of the casing wall, W/(m K)
λ_{cem}	thermal conductivity of the cement, W/(m K)
λ_e	thermal conductivity of formation, W/(m K)
λ_{tub}	thermal conductivity of the tubing wall, W/(m K)
ρ_a	density of the annulus fluid, kg/m^3
ρ_w	density of water, kg/m^3
ω	ratio of formation heat capacity and wellbore heat capacity ($=C_i/C_w$)
τ	injection time (h)

logging measurements or some derived properties by empirical relationships [17–19,23]. However, some factors may introduce the uncertainty in the estimated result of thermal conductivity, such as the uncertainties existing in relationship between the thermal conductivity and density [17]. For the second approach, the major mineral components of rocks are identified and their volumetric fractions are derived from regular logging data. Based on the composition and the known values of thermal conductivity of the components, the thermal conductivity can be computed by assuming appropriate mixing laws [20,21,24,25]. However, there are some unavoidable uncertainties associated with the estimated results, such as the uncertainties in the well-logs and that regarding the reference values assigned to minerals [9,17]. Another technique for estimating thermal conductivity is the temperature-gradient logs method [6,7], which is based on the Fourier law of heat conduction. However, this method requires the measured thermal conductivities of at least one of the major rock types encountered in the formation, which are usually obtained from laboratory measurements on cutting samples.

As for water injection well, Nowak [26] used the temperature surveys to estimate water injectivity profiles and location of water-intake strata, and analyzed the general characteristics and heat flow of temperature logging in water injection well. Smith and Steffens [27] studied on some factors affecting on temperature profiles in water injection wells, such as thermal conductivities of cement and formation rock, water leakoff, reservoir temperature and so on. The thermal properties of formation show great influence on water temperature in water injection well by affecting formation heat transfer [28,29]. These studies may make advantage for estimating formation thermal properties by temperature log data for water injection well.

Moreover, due to the difficulties in achieving in situ values, the thermal properties of geological formations are usually assumed to be depth-invariant in thermal design and numerical simulations [30–35]. Although some new measurements for vertical variations in formation thermal properties have been developed [17–19,36], in some cases, the formations locating at different geologic regions and depths even use the same value of thermal conductivity or volumetric heat capacity [30–35,37–39], which are called typical values [37]. In fact, estimation of some important geological and production parameters by the inversion of field data has been developed sequentially, such as inversion of field data in fault tectonics for the regional stress [40], estimation of ocean-bottom properties by acoustic field data inversion [41], soil hydraulic and dielectric parameters estimation through GPR and hydrological data inversion [42], and so on. Cheng [43] presented a layer inversion method for estimating the spatial distributions of formation thermal properties by temperature logs for steam injection well. However, there are many distinct differences in heat transfer and fluid flow model between the water injection well and steam injection well [44,45], such as, different injection conditions between the two types of well, stream condensation during steam injection and no phase change in wellbore during the water injection, single-phase flow for water injection but multiphase flow for steam injection and so on. Especially, the inversion method is based on injection well heat transfer model. Therefore, the presented method for steam injection well may be applied to water injection well thermal properties estimation with incomplete feasibility.

In order to explore the thermal properties predictions for water injection wells and expand the presented inversion method application, this paper firstly built a heat transfer model appropriate to water injection well to obtain the water temperature model, and sensitivity analysis was used to study correlation between the thermal properties and water temperature, showing the difference between the two kinds of injection wells. Based on