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A Time-Convolution Approach to Evaluate Heat Exchange Between Wellbore and Formation

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For geothermal and geological CO_2 storage projects, the targeted formation is typically deeper than 1000 meters. This great injection depth requires that the heat exchange between the wellbore and its surrounding formation is accounted for when accurate predictions of downhole or wellhead temperature conditions are essential. One way to calculate this heat exchange is to fully discretize and numerically model the two-dimensional radial formation that surrounds the wellbore. However, since only the energy equation needs to be solved, i.e., there is no fluid exchange between the cased wellbore and the formation, this approach is computationally ineffective. In this work, we propose a time-convolution method, where only the wellbore is fully discretized, and heat exchange between the wellbore and the formation is calculated using analytical solutions of radial conductive heat flow, which was based on approximate solutions provided by Carslaw and Jaeger (1959) for heat conduction between a wellbore and surrounding formation due to a temperature different of ΔT, where heat flux q can be calculated for small values of t_d as

$$q = \frac{k\Delta T}{r_0}\left\{(\pi t_d)^{-0.5} + \frac{1}{2} - \frac{1}{4}(\frac{1}{\pi})^{0.5} + \frac{1}{8}t_d - \ldots\right\} \quad (1)$$

and for large values of t_d as

$$q = \frac{2k\Delta T}{r_0}\left\{\frac{1}{2\ln(4t_d) - 2\gamma} - \frac{\gamma}{[\ln(4t_d) - 2\gamma]^2} - \ldots\right\} \quad (2)$$

Here, k is heat conductivity, r_0 is the wellbore radius, t_d is the dimensionless time defined as $t_d = \alpha t / r_0^2$, where α is the thermal diffusivity, and γ =0.57722 is Euler's constant.

In our calculation, the time-dependent temperature evolution in the wellbore is calculated numerically using a wellbore simulator for non-isothermal, multiphase fluid mixtures. At each time step, radial heat transfer across the wellbore-formation interface is calculated by superposition of the analytical solutions (Equation 1 or 2) of heat flow for the temperature differences between subsequent time steps. This coupling scheme is implemented in the TOUGH2 suite of reservoir simulators.

To verify the proposed semi-analytical method and to demonstrate its applicability, we present examples and compare them to full numerical solutions.

Reference

Carslaw, H.S. and Jaeger, J.C., 1959. Conduction of Heat in Solids. Oxford Univ. Press, 2nd ed.