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Interpretation of production tests in geothermal wells with T2Well-EWASG

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ABSTRACT

In the geothermal sector, being able to simulate production tests by combining surface and downhole measurements can be extremely useful, improving data interpretation and reducing the impact of unavailable field data. This is possible with T2Well, a coupled wellbore-reservoir simulator. We plugged the EWASG equation of state for high enthalpy geothermal reservoirs into T2Well and extended the function to analytically compute the heat exchange between wellbore and formation at the short times. Changes to the analytical heat exchange function were verified by comparison with wellbore-formation heat exchange numerically simulated. T2Well-EWASG was validated by reproducing the flowing pressure and temperature logs taken from literature, and by using the software for the interpretation of a short production test. Simulation results indicate that T2Well-EWASG can be effectively used to improve the interpretation of production tests performed in geothermal wells.

1. Introduction

Numerical modelling of geothermal reservoirs is an essential tool to optimize georesource characterization and exploitation. Determining the hydraulic properties and thermodynamic conditions of a reservoir is an important aspect of the simulation process since these features are key to resource assessment and forecasting behaviour-under-exploitation scenarios. Production tests allow determination of a well's deliverability curve in terms of flow rate and enthalpy vs wellhead pressure (WHP). The flowing P & T (pressure and temperature) logs allow evaluation of feedzone location and thermodynamic characteristics. Finally, pressure transient recording, i.e. wellbore pressure changes due to controlled production or injection operations, evidence main hydrological parameters of the reservoir area drained by the well, such as: formation permeability-thickness, formation storage coefficient, skin and wellbore storage coefficients (Axelsson, 2013). Production tests duration is often limited, however, by environmental constraints such as the disposal of extracted brines, and downhole measurements are limited by safety and cost considerations such as the need for expensive tools in elevated temperature, high production wells. In this context, the possibility to reproduce via simulation the whole production test, including surface and downhole measurements, is extremely useful to improve data interpretation. In particular, coupled simulation of both wellbore and reservoir transient fluid flows allowing matching of the output production curve, flowing logs, and downhole pressure transients, should provide a more reliable evaluation of reservoir properties. This can be done by using a coupled wellbore-reservoir numerical simulator such as T2Well (Oldenburg and Pan, 2013) and coupling it to a suitable equation of state (EOS) module for high enthalpy geothermal fluid mixtures of water, salts and non-condensable gases.

TOUGH2 (Pruess et al., 1999) is a numerical simulator for non-isothermal flows of multicomponent, multiphase fluids in one, two, and three-dimensional porous and fractured media. As well as an academic tool, TOUGH2 is also widely used for industrial applications and by government organizations (Finsterle et al., 2014).

Numerous researchers have investigated coupling TOUGH2 with a wellbore simulator. Hadgu et al. (1995) coupled TOUGH2 with the steady-state wellbore simulator WFSA used as a TOUGH2 subroutine. Bhat et al. (2005) coupled TOUGH2 with the steady-state wellbore simulator HOLA (Björnsson, 1987), designed for the modelling of single and two-phase flow of pure water in wellbores with a multi-feedzone. Tokita et al. (2005) coupled TOUGH2 with a multi-feedzone wellbore simulator called MULFEWS (Tokita and Itoi, 2004) and with a two-phase pipeline network simulator. Gudmndsdottir et al. (2012) developed a coupled wellbore-reservoir simulator using TOUGH2 and FloWell, which is a system designed to model liquid, two-phase and superheated steam steady-state flow in geothermal wells (Gudmndsdottir et al., 2012; Gudmndsdottir and Jonsson, 2015).

With the aim of accurately simulating coupled wellbore-reservoir

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flows under transient conditions, Pan and Oldenburg (2013) developed T2Well as an extension of TOUGH2. T2Well can model non-isothermal, two-phase coupled wellbore-reservoir flow for generic multi-component mixtures by using a suitable EOS module.

In this study, the T2Well wellbore-reservoir numerical simulator was coupled to the EWASG EOS module developed for high enthalpy geothermal reservoirs containing 3-component mixtures of water, NaCl and a non-condensable gas (NCG) (Battistelli et al., 1997; Battistelli, 2012). In addition, improvements were made to the analytical computation of heat exchange between the well and the surrounding formations at the short times. T2Well-EWASG was verified by comparing the results of the modified analytical wellbore-formation heat exchange function with wellbore-formation heat exchange numerically simulated. T2Well-EWASG was validated by reproducing two published flowing P & T logs recorded in wells producing brine with remarkable amounts of CO_2 and a short production test, the latter performed in a recently drilled exploration well in the Wotten Waven field, Commonwealth of Dominica. All the experimental data are related to reservoir containing NaCl and CO_2. The new T2Well-EWASG can be used for the interpretation of well tests by combining surface and downhole measurements and to simulate the exploitation of high enthalpy geothermal systems.

2. T2Well

T2Well extends the existing numerical reservoir simulator TOUGH2 by introducing a special wellbore sub-domain in the numerical grid. Wellbore flow is simulated by solving the one-dimensional momentum equation. In the case of two-phase wellbore flow, the Drift Flux Model (Shi et al., 2005; Zuber and Findlay, 1965) combines two momentum equations of two phases to create a single momentum equation of the mixture. Like TOUGH2, T2Well can be used with different EOS to describe different fluid mixtures. Thus far, T2Well has been used with ECO2N (Pruess, 2005) for applications related to CO_2 sequestration, with ECO2H (Pan et al., 2011, 2015) for enhanced geothermal system simulations, with EOS7C (Oldenburg and Pan, 2013) for applications related to compressed air energy storage, and with EOIL to model Macondo well blowout (Oldenburg et al., 2011). The heat exchanges between wellbore and the surrounding formation can be numerically simulated, or optionally calculated with Ramey's analytical method (Ramey, 1962) or Zhang's convolution method (Zhang et al., 2011). Details of T2Well characteristics and numerical formulation can be found in Pan and Oldenburg (2013).

3. EWASG EOS module

EWASG (Equation-of-state for WAter, Salt and Gas) is a TOUGH2 EOS module developed primarily to model hydrothermal systems containing dissolved solids and one non-condensable gas (NCG) such as CO_2, CH_4, H_2S, H_2 or N_2 (Battistelli et al., 1997). EWASG can handle phase equilibria and fluid property calculations up to 350 °C and 100 MPa for H_2O-NaCl-NCG mixtures found in low and high enthalpy geothermal reservoirs, with the limitation of low to moderate NCG partial pressures. Compared to the version included in TOUGH2V.2.0 (Pruess et al., 1999), the EWASG version, jointed to T2Well, implements several major improvements (Battistelli et al., 2012), namely:

- IAPWS-IF97 correlations for pure water and steam (IAPWS, 1997; Croucher and O'Sullivan, 2008) and a more recent formulation for water and steam viscosity (IAPWS, 2008).
- An internally consistent H_2O-NaCl EOS package derived from the work of Driesner and Heinrich (2007) and Driesner (2007) to effectively covering the entire P-T-X area of interest (T = 0-350 °C; P = 0-100 MPa; NaCl mass fraction = 0-1);
- A more consistent approach to vapour pressure lowering (VPL) and water adsorption, including the dependency of capillary pressure on temperature and salt concentration.
- Enhanced, albeit still simplified, modelling of NaCl partitioning in the gas phase to improve transitions phase from two-phase to single gas phase and vice versa.

EWASG has subsequently been coupled with other simulators belonging to the TOUGH2 family of codes (Battistelli, 2012), such as iTOUGH2 (Finsterle, 2007) and TOUGH-MP (Zhang et al., 2008). EWASG was also used as the starting point for the development of new TOUGH2 EOS modules such as ECO2 and ECO2N. Its correlations for brine properties have been included in other TOUGH2 EOS modules such as EOSM, TMVOC V.2.0 (Battistelli, 2008) and TMGAS (Battistelli and Marcolini, 2009).

4. Modification of the analytical calculation of heat exchange between wellbore and formation

The availability of analytical computational methods to calculate wellbore-formation heat exchange allows substantial simplification of grid discretization, thereby reducing both the complexity of the numerical model and computational time. However, both methods implemented in the original version of T2Well have some limitations. Ramey's (1962) method works effectively only for times longer than approximately a week, and so is not suitable for the study of short transient phenomena. Zhang's et al. (2011) method, on the other hand, uses a simplified wellbore design, assuming there is no thermal resistance related to well completion. To overcome these limitations, the Ramey analytical function for heat exchange between wellbore and formation was modified by introducing the Chiu and Thakur (1991) time function. As suggested by Ramey (1962), thermal resistance of the wellbore completion was also taken into account with the introduction of this author's expression for wellbore heat conduction rate:

$$dq = \frac{2\pi\, r_1\, U\, (T_1 - T_E)}{r_1\, U\, f(t_D) + k_T}\, dZ \tag{1}$$

Where: r_1 is the wellbore radius (m), $f(t_D)$ the time function, $t_D = \frac{\alpha t}{r_2^2}$ the dimensionless time, $\alpha = \frac{k_T}{\rho c}$, c the specific heat, ρ the density of the formation and r_2 the well completion radius, T_1 the wellbore temperature, T_E the formation temperature, k_T the thermal conductivity of the formation, dZ differential element of depth, and U the over-all heat transfer coefficient of well completion as defined by Willhite (1967).

Moreover, the following time function by Chiu and Thakur (1991) was added to T2Well:

$$f(t_D) = 0.982 \ln(1 + 1.81 t_D) \tag{2}$$

which is in good agreement with the exact solution of Carslaw and Jaeger (1959) for all the times, as shown in Fig. 1.

Willhite (1967) provides the general expression for computation of the overall heat transfer coefficient (U) which is carried out considering wellbore completion as a series of thermal resistors for radial heat transfer. Starting from the Willhite's expression, and assuming that the inner casing wall is in thermal equilibrium with the flowing fluid and that the casing resistors are negligible, in the case of a single cemented annulus the fluid produced flows in the production casing and U is given by:

$$U = \frac{k_{cem}}{r_1 \ln \frac{r_2}{r_1}} \tag{3}$$

where r_1 is the wellbore radius, r_2 the completion radius and k_{cem} the thermal conductivity of the wellbore completion.

5. Verification and validation of T2Well-EWASG

The modifications made to T2Well-EWASG, were tested to verify the new analytical equation for the heat flux with and without the wellbore