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Development and Application of Enhancements to the iTOUGH2 Simulator for Geothermal Reservoir Management

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ABSTRACT

An essential aspect of sustainable operation and management of a modern-day geothermal field is a state-of-the-art numerical reservoir model. A field-wide conceptual model of the reservoir, based on all available and applicable production and geoscience data, is used to construct a numerical model. iTOUGH2 is a simulation-optimization framework widely used in numerous engineering and academic disciplines and is based on the successful TOUGH2 non-isothermal, multiphase flow and transport simulator. In this case, the focus is on applications related to geothermal reservoir engineering and groundwater hydrology. iTOUGH2 is highly flexible, incorporating an ever-increasing arsenal of methods for model parameter estimation, local and global sensitivity analyses, data-worth and error propagation analysis. To meet increasing demands set by the industry for detailed numerical modeling, the iTOUGH2 platform is under continuous development. The ability to incorporate proper physics into the simulator will clearly aid in the model calibration and result in more realistic future production scenarios of interest to the geothermal field operator. This paper discusses the development of several recent enhancements to the iTOUGH2 platform and demonstrates how they can be applied. This includes: (1) A full 2D tensorial anisotropic scheme (supporting irregularly structured, non-rectangular meshes with sloped layers); (2) coupling of the FLOWELL wellbore simulator with iTOUGH2 to enable the direct use of wellhead production data for model calibration and predictions. The FLOWELL simulator can model liquid, two-phase and superheated steam flow and can be applied to directional wells with many feedzones and various well segments with different diameters and friction factors; and (3) a module for two-phase simulation of water and multiple tracers, which allows for simultaneous calibration of multiple tracer returns with other transient data such a pressure decline and temperature/enthalpy changes. Included in the new tracer module is preferential phase partition, tracer adsorption to the rock matrix and time/temperature dependent degradation to daughter species. The enhancements will be described and demonstrated through various examples of modeling geothermal areas in Iceland and others.

1. INTRODUCTION

Simulations are used in the geothermal industry to assist with the planning of geothermal projects. Typical questions asked of geothermal modelers include: how much power can we extract from a geothermal field? For how long? With how many wells? When and how often will make-up wells be required? Where should the wells be drilled? How deep should the wells be? How much steam will they produce? How fast will the pressure decline? Should the brine be re-injected to support the pressure and where?

At the same time, the methods employed to monitor the wellfields are improving. The recording of pressure response has become systematic. Tracer Flowing Testing (TFT) provides estimation of flow rates and enthalpies. The use of tracers to identify pathways inside the reservoir is becoming more common. PTS (Pressure-Temperature-Spinner) probes provide information about the wells and theirs feedzones. To combine all these data, physically more realistic models are required.

In this article, we discuss three new iTOUGH2 modules developed to improve the quality of geothermal models. First, a two-dimensional anisotropic module for iTOUGH2 is presented, with an example that shows how the module can be used to analyze a well test performed in an anisotropic reservoir. The second section presents the different features and capabilities of iTOUGH2-FLOWELL, a wellbore simulator integrated into iTOUGH2. The section ends with an example of how iTOUGH2-FLOWELL can be used to find the major feedzones in a well. The last section briefly discusses the functionalities introduced by the new equation-of-state module EOS1nt, which allows for the simulation of multiple tracers. The tracers are modeled to have the same physical properties as water but can preferentially partition into the liquid or steam phase, decay into daughter components and adsorb into the rock matrix.

2. 2D TENSORIAL ANISOTROPIC SCHEME, iTOUGH2-ANISO

Before the development of iTOUGH2-ANISO the only way to simulate anisotropy in iTOUGH2 was to use a rectangular mesh where the connections were aligned with the principal axes. Besides putting a limit on the structure of the mesh this also meant that the principal axes could not be adjusted without regenerating the mesh. This limitation led to the development of an anisotropic scheme which was originally an extension module for TOUGH2 (Arnaldsson, Berthet, Kjaran, & Sigurðsson, 2014). Recently, the module was adapted and incorporated into iTOUGH2, so that the parameters describing the permeability tensor could be adjusted when performing inversions (Berthet, Sigurðson, Kjaran, & Arnaldsson, 2018).

An example of an inversion, using iTOUGH2-ANISO, is presented here. The example demonstrates how the software can be used to analyze the data of a well test performed in an anisotropic aquifer. In the example, a well named W_0 discharges for over 24 hours at a rate of 80 kg/s. The well is straight and 1000 m deep. The top 500 m of the well crosses an impermeable caprock. Below the caprock, the permeable reservoir extends from 500 m to a depth beyond the bottom of the well at 1000 m. In order to estimate the reservoir's permeability, the pressure in two observation wells (W_1 and W_2) is recorded every 30 seconds. The pressure response in the wells clearly indicates that the reservoir is anisotropic, but the orientation of the principal axes is not known. If they were known, then a rectangular mesh aligned with the axes and regular iTOUGH2 could be used. Instead, a hexagonal mesh is created, and a model is constructed to run iTOUGH2-ANISO. The inversion input file for the model includes the data from the observation wells, and specifies five adjustable parameters: the porosity, the vertical permeability, two horizontal permeabilities, and an angle. The angle corresponds to the angle between the anisotropy first principal axis and the abscissa. The parameter is specific to iTOUGH2-ANISO.

The results of the inversion are shown in Figure 1 and Figure 2. For comparison, another inversion was performed using iTOUGH2, with the regular finite volume scheme. In the case of regular iTOUGH2, the inversion does not converge to a good solution despite being able to adjust four parameters. This happens because the program is not able to change the direction of the anisotropy. When iTOUGH2-ANISO is used, the inversion algorithm is able to converge to the solution by adjusting the principal angle.

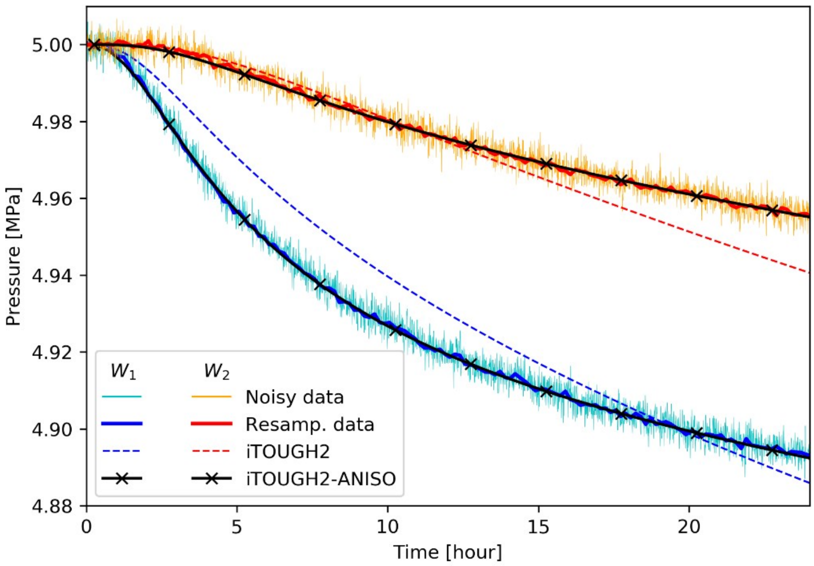

Figure 1. Pressure in observation wells W_1 and W_2. The figure shows the "measured" noisy data, and the results of two inversions, one performed with regular iTOUGH2, and a second performed with iTOUGH2-ANISO.

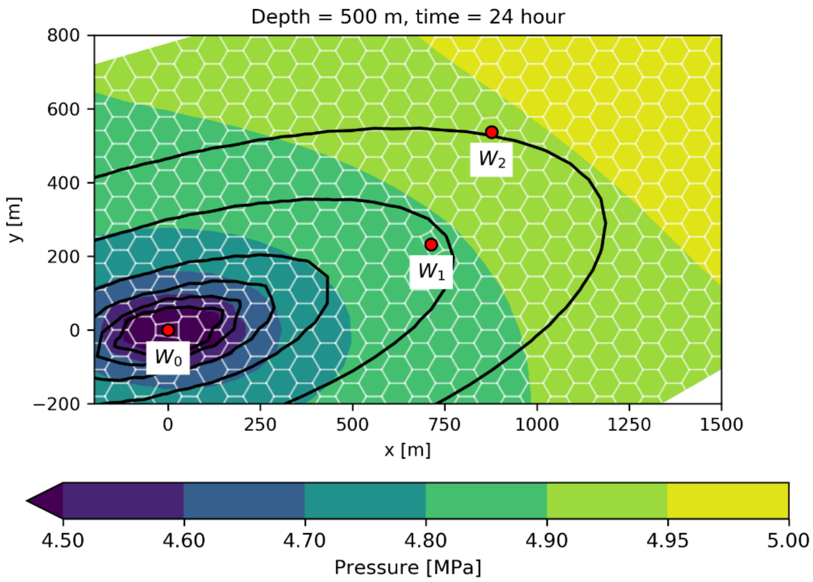

Figure 2. Pressure calculated at the end of the inversions. The colored zones show the result of the iTOUGH2-ANISO inversion. The black lines show the result of the inversion with regular iTOUGH2. The red dot indicates the positions of the wells. The hexagonal mesh is shown in white.

3. INTEGRATED WELLBORE SIMULATOR, iTOUGH2-FLOWELL

The FLOWELL simulator began as a master project at the University of Iceland (Guðmundsdóttir H. , A Coupled Wellbore-Reservoir Simulator utilizing Measured Wellhead Conditions, 2012; Gudmundsdottir, Jonsson, & Palsson, 2013). The first version of the simulator was implemented in Matlab and coupled to iTOUGH2 through the PEST interface. Since then, the simulator has been re-implemented in Fortran and integrated into iTOUGH2 (Guðmundsdóttir, Jónsson, Berthet, Arnaldsson, & Finsterle, 2018). The current combined wellbore-reservoir simulator (iTOUGH2-FLOWELL) has the following capabilities. It can model wells discharging liquid, two-phase fluid, or pure steam. The simulator can handle straight and deviated wells, multiple diameters, and wells with more than one feedzone. The wellbore simulator relies on a friction model, a correction (or correlation) model, and a void fraction model. Many different versions of these models exist in the engineering literature, and several of those were implemented in the simulator: Blasius, Swamee and Jain, Serghides, Friedel, Beattie, Chisholm, Gunn, Lockhart and Martinelli, Bankoff, Chawla, Muller-Steinhagen and Heck, Zivi, Chisholm, Premoli, Rouhani and Axelsson, Jonsson. The simulator is set up to handle both production and injection. The simulator has two modes: a passive mode, where the user provides a flow rate for each feedzone, and the simulator computes the state of the fluid at the wellhead (pressure, temperature, enthalpy, etc.); and an active mode, where the user specifies a flow rate and minimum well-head pressure, and the simulator computes the flow rate in each feedzone.

Interface

To run FLOWELL, a FLOWE block is added to the forward input file. The interface is designed to provide a backward compatibility with older models running regular iTOUGH2. Thus, the FLOWE block is used to provide additional information about wells whose feedzones are already listed in the GENER block (Figure 3). In the GENER block, the feedzones are either specified to be 'MASS' or 'DELV'. The FLOWE block contains information about the wells (such as length, diameter, casing and liner roughness, inclination), the feedzones (productivity index or mass rate), the minimum wellhead pressure for production, and parameters to select the friction, correlation, and void fraction models. In all those cases, different parameters can be specified for different sections of the well.

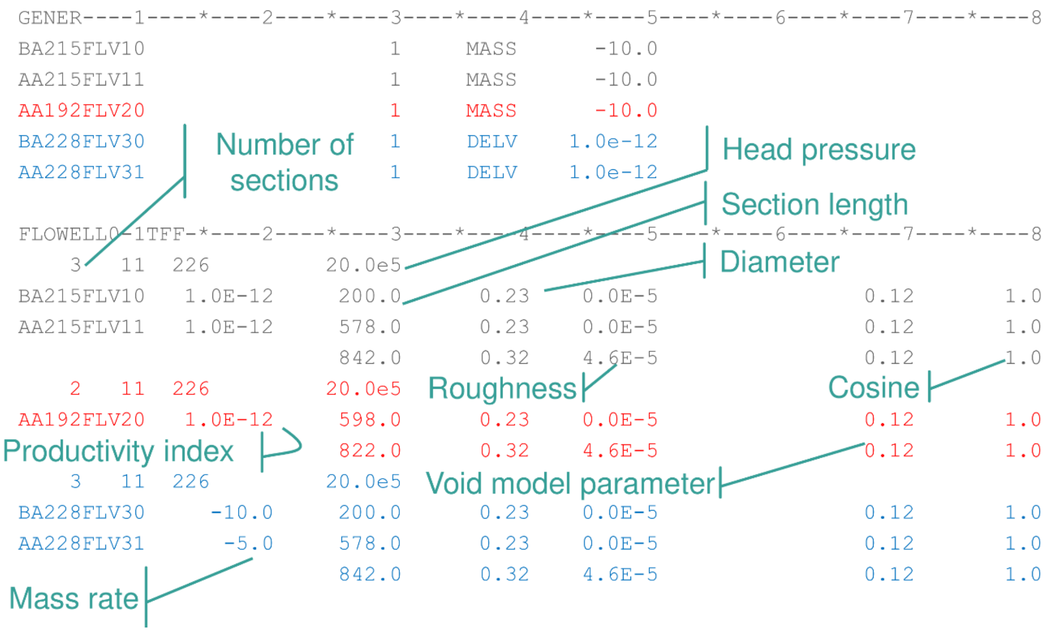

Figure 3. Example of iTOUGH2-FLOWELL input. The wells have a typical casing-liner setup (casing from surface down to around 800 m and liner below). Well FLV1 and FLV3 have two feedzones each, while FLV2 has one.

Time-series of the variables calculated by FLOWELL can be generated by listing them in the OUTPU block (Finsterle, Enhancements to the TOUGH2 Simulator Integrated in iTOUGH2, 2018). The time-series of the listed parameters will be added to the GOFT and fi_gener.csv output files generated by iTOUGH2.

Features

Production

FLOWELL has two operational modes: passive and active. In the passive mode, FLOWELL does not interfere with the reservoir simulation. The wellbore simulator reads the feedzone rates calculated by the reservoir simulation and computes the state of the fluid at the wellhead. In the active mode, the program runs an iterative procedure to find the flow rate in each feedzone that correspond to a set of constraints specified by the user. For production, these constraints are a maximum flow rate, and a minimum wellhead pressure. The user specifies a maximum flow rate for the well a maximum flow rate and a minimum wellhead pressure. If the wellhead pressure is above the minimum at the maximum flow rate, then the well produces at the maximum rate. If the wellhead pressure is found to be below the allowed minimum, the program adjusts the flow rate to keep the pressure at the minimum. The feedzone rates calculated by the iterative procedure are then used in the reservoir simulation.

Figure 4 shows an example of a simulation where the active mode of FLOWELL was used. In the example, a well named FLV10 has two feedzones. The user specified a maximum flow rate of 20 kg/s, and a minimum pressure of 20 bar. For the first year and a half, the pressure is above 20 bar (green dash-dotted line) and the well produces 20 kg/s (red dash line). When the pressure reaches 20 bar, the iterative procedure in FLOWELL reduces the flow rate to keep the pressure at 20 bar. Regardless of whether the well produces at constant rate or constant pressure, the contribution of each feedzone to the total flow from the wellhead is constantly changing. This can be seen in Figure 4where the blue solid line shows the flow from the bottom feed zone while the red dotted line shows the total flow from the well.

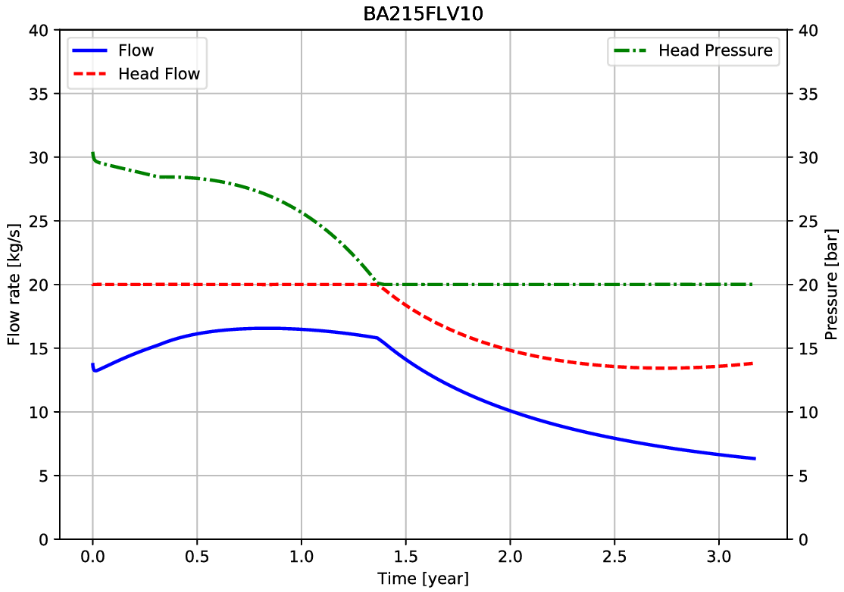

Figure 4. Example showing how iTOUGH2-FLOWELL operates. When the head pressure is above 20 bar, the well produces at 20 kg/s. When the pressure reaches 20 bar, the flow rate is reduced to keep the pressure at 20 bar. The blue solid line shows the flow rate from one of the feedzones.

Injection

FLOWELL also works for injection. For injection, the input is the same as for production, except that the minimum pressure becomes a maximum. This prevents the unrealistic scenario where a constant flow rate could be injected into a well with an ever-increasing pressure. When the head pressure is below the maximum, the injection is performed at the user-specified maximum rate. When the pressure reaches the maximum, FLOWELL reduces the injection rate to keep the pressure at its maximum.

Figure 5 shows an example of an injection scenario. The user specified an injection rate of 25 kg/s and a maximum wellhead pressure of 10 bar. First, the liquid is injected into a two-phase reservoir. The steam condenses, and after a while, the pressure drops to zero. The zero pressure indicates that the water-head is below the surface. After five months, the vacuum created by the condensation of the steam is filled, and the pressure increases again. When the pressure reaches 10 bar, the program reduces the injection rate to keep the pressure at the maximum. In the five months during which the pressure is zero, the injection is performed at the maximum injection rate of 25 kg/s.

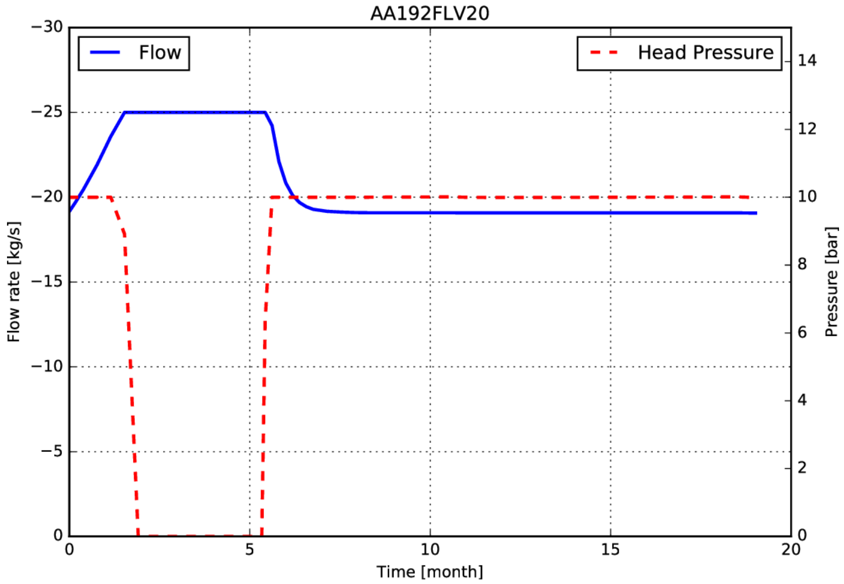

Figure 5. An example of FLOWELL injection simulation. While the pressure is below 10 bar, the injection is performed at 25 kg/s. When the pressure reaches 10 bar, the injection rate is reduced to keep the pressure at the maximum.

Model calibration

FLOWELL can be used to calibrate a combined reservoir-wellbore model. Wellhead and down-hole measurements can be added to the inversion input file, as data to match. The following data can be specified: wellhead enthalpy, wellhead pressure, bottom-hole (feed-zone) pressure, wellhead temperature, and steam quality. The parameters controlling the wellbore simulator can be used as adjustable parameters during an optimization. The following parameters can be specified: friction factor, correction factor, void fraction, and productivity index.

Example

The program is mainly intended for coupled reservoir-wellbore simulations, but it can also be used to optimize a standalone wellbore model. In the example below, iTOUGH2-FLOWELL was used to study the feedzones in a well. The well was less than a year old when this work was performed, and downhole data were available. The pressure and temperature had been monitored while the well was recovering from the cooling induced by the drilling. At the end of the recovery period, a discharge test was performed; the downhole pressure and temperature were recorded while the well was discharging, along with the wellhead flow rate and flowing enthalpy. The temperature and pressure measured during the recovery phase were used to construct a simple reservoir model. The model was made of a column of forty-eight elements, representing the formation, which were assigned pressures and temperatures based on the measurements. The downhole pressure, downhole temperature, wellhead flow rate and flowing enthalpy measured during the discharge test were added to the inversion input file as observation data for the calibration. The wellbore model was constructed based on the characteristics of the well, and the presumed location of the feedzones. Spinner data were not available when this work was performed; therefore, the feedzones' locations were estimated from the steps and changes observed in the vertical temperature profile (Egilson, 2017). Feedzones were assumed to be located at 1980 m, 1775 m, and 1460 m. On the interval from 1200 m to the end of the casing at 910 m, the more gradual change in temperature suggested a continuum of smaller feedzones. In the model, the continuum of small feedzones was simulated by adding a small feedzone every 50 m. The well flow rate and flowing enthalpy during the test were measured at 6.4 kg/s and 945 kJ/kg. These were also added to the inversion file as parameters to match.

The result of the inversion is shown in Figure 6. The inversion indicates that of the total discharge rate, 32%, 26%, and 24% came from the feedzones at 1980 m, 1775 m and 1460 m depth, respectively. The well was tested again later with a spinner. From the spinner data, it was estimated that 25%, 30%, and 30% of the total flow came out of the respective feedzones (Guðmundsdóttir V. , 2018).

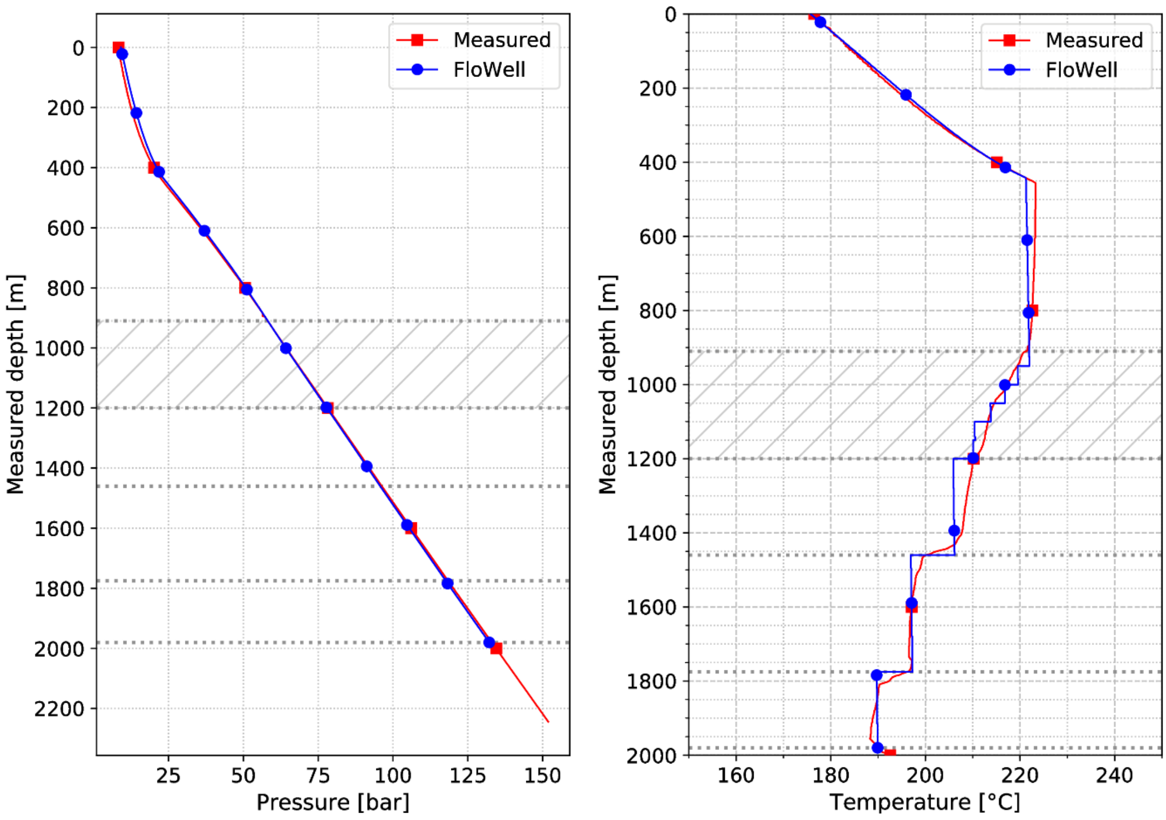

Figure 6. Comparison between the measured and calculated, pressure and temperature in well ÞG-15. The discharge rate is 6.4 kg/s. The horizontal dotted lines and hatched area show the location of the feedzones.

4. TRACER MODELLING

In recent years, it has become increasingly common to test geothermal reservoirs with tracers in order to understand the pathways and to better be able to predict the effect of brine re-injection. The tracers used are often phase specific, and, because their dispersion through the reservoir often last for months, it is common to begin another test with a new tracer, while the previous tracers are still present. Some of the liquid tracers commonly used are naphthalene-sulfonic and -disulfonic acids (1-NS; 2-NS; 2,6-NDS; 2,7-NDS; 1,5-NDS; 1,6-NDS), which, although fairly stable at geothermal temperature, tend to decay and can transition into one another. This has led to the development of a new module EOS1nT (Finsterle, iTOUGH2-ESO1nT: A Nonisothermal Two-Phase Flow Simulator for Water and Multiple Tracers. User's Guide., 2017). The original equation-of-state module EOS1 from TOUGH2 allowed for two types of waters (water, water with tracer). The new module can simulate many tracers. The phase partitioning of a tracer can be adjusted by specifying a Henry constant. Temperature-dependent degradation and transition between tracers can also be modelled by the new EOS.

Below is an example of a multi-tracer test. A tracer (2,7-NDS) was injected in a well in August 2013. The tracer was detected in a nearby well after a few weeks, and the concentration peaked after 120 days (Figure 7). Five months later, another tracer (2-NS) was injected in another well. The tracer was detected in a nearby well after a few weeks (Figure 8). It is easy to see from the figures that the tracers linger for several years after the test, thus the necessity for different tracers, and the need for being able to model multiple tracers simultaneously. In the second test (Figure 8), a residual concentration of 2-NS was observed before the tracer was injected. This is likely a leftover from the first test because 2,7-NDS, when decaying, can transition through 2-NS. This effect was not modelled in the example.

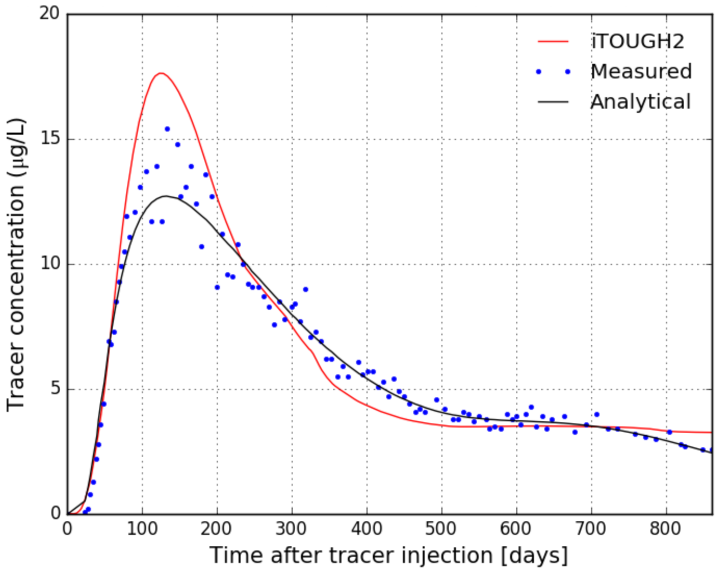

Figure 7. Concentration of 2,7-naphtalene disulfonic acid. The tracer was injected in August 2013.

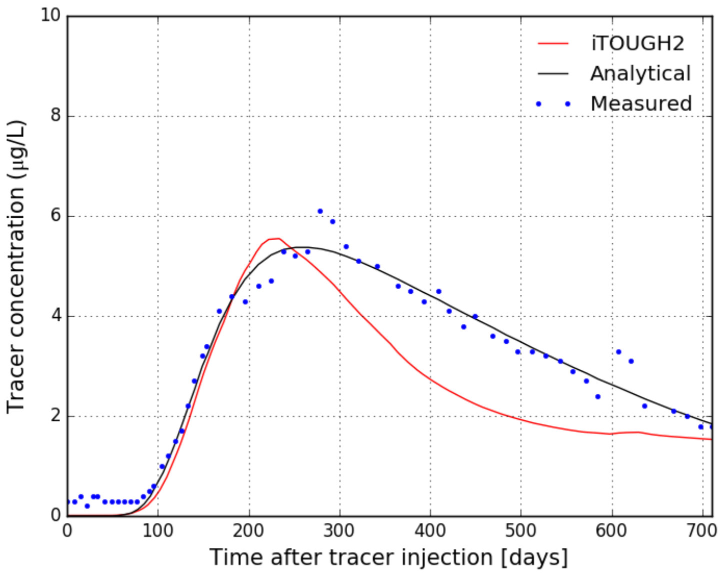

Figure 8. Concentration of 2-naphtalene sulfonic acid. The tracer was injected in January 2014.

5. CONCLUSIONS

Three new iTOUGH2 modules have been presented in this article. These modules and iTOUGH2 in general are under constant development to improve the computational efficiency, the usability of the software, or to add new features. The anisotropy module provides a new solution to handle the anisotropy which allows more flexibility: using rectangular elements and aligning the mesh with the anisotropy axes is no longer needed. Since anisotropy can have a significant effect on the flow in a rock matrix, accounting for it is crucial in the accurate modelling of geothermal reservoirs. Coupled reservoir-wellbore simulations, a frequently requested feature from the geothermal industry, can be performed with iTOUGH2-FLOWELL. Production at constant wellhead pressure can be simulated for a greater variety of wells: deviated wells, casing-liner wells with a variable diameter, and multiple feedzones. Simulating production at a constant wellhead pressure makes it possible to run long term scenarios where the geothermal reservoir reaches its limit for sustainable utilization. Data collected at the wellheads can also be used to calibrate both the wellbore and reservoir models. At last multiple tracers can be modelled in a single forward run as well as their decay into daughter components. This feature is essential when multiple coincidental tracer tests are increasingly being used to draw conclusions about the connections in geothermal reservoirs. All these developments allow for more data from different sources to be used simultaneously to calibrate models, thus improving the quality and reliability of the models.

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