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Pressure transient analysis of geothermal wells: A framework for numerical modelling

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ABSTRACT

The need for numerical models for geothermal pressure transient analysis (PTA) is well recognised. Conventional PTA is based on analytical models which usually do not work for geothermal datasets, therefore PTA is under-utilised by the geothermal industry. A framework for numerical modelling is required to promote comparability of results and increase user-friendliness.

A framework is developed in this study using the TOUGH2 simulator and automated using PyTOUGH. A full justification of the grid design and model setup is given. A reference model is then created and subjected to a sensitivity analysis. The only parameter to which the model output is sensitive is the layer thickness of the model. The basic framework is equivalent to the analytical infinite uniform porous reservoir model. An equivalent to the analytical linear impermeable boundary model has also been developed.

The framework is then demonstrated by investigating the injection of cold water into a hot reservoir, a major issue for geothermal PTA. The tool is further demonstrated in a case study with datasets before and after deflagration of a well, and was found to produce superior results to the equivalent analytical analysis.

1. Introduction

Pressure transient analysis (PTA) of well testing data is a key tool for the oil and gas industry. Results from PTA are used as the basis for reservoir-scale models and the well-constrained values for permeability and skin are used to make important decisions such as whether to stimulate and by which method, and assess whether a well will produce at commercial levels. However PTA is currently under-utilised in the geothermal industry. The reason for this is because the conventional PTA is based on analytical models which do not often fit geothermal datasets [1]. Analytical PTA models were mainly developed for groundwater and oil and gas applications and there they work well in a relatively low temperature environment and simple reservoir structure. For geothermal wells however there are many factors which violate the assumptions behind the analytical models [2], including that geothermal reservoirs are non-isothermal, with non-uniform and non-linear fluid properties and non-horizontal flow. All factors are ultimately due to higher temperatures and larger more complex geothermal reservoirs [1,3,4]. The requirement for numerical models has been long recognised for PTA in complex systems such as geothermal [2,3,5–7].

These numerical models need to be consistent, user-friendly and produce comparable results in order to be widely applied by reservoir engineers working in the geothermal industry. For this purpose a framework has been developed based on TOUGH2 [8] and utilising the PyTOUGH scripting code [9]. A framework is user-friendly in the sense that important and time-consuming decisions regarding the model design have been made. Also PyTOUGH is considerably more user-friendly than running TOUGH2 directly as a single PyTOUGH script can be used to set up, run, invert and post-process the model results. Numerical model results can be sensitive to details of the grid design or other factors. Therefore sensitivity analysis of a model set up using the framework is included in this study. The numerical PTA results are graphically presented as a derivative plot [10] as this is very sensitive and reveals characteristic shapes for various model types and is a cornerstone for PTA [1].

The basic framework is the equivalent to the simple analytical infinite uniform porous reservoir model, with wellbore storage and

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skin. A wide variety of more complex analytical reservoir and boundary models are available, including a linear impermeable boundary model [11]. A numerical equivalent to this is possible by modifying the radial grid [12].

The numerical framework can be used for various applications including investigation of general issues faced by geothermal PTA, and well-specific case studies with field data. In this paper the framework is used to investigate the impact of cold water injection into a hot reservoir [13], and a case study with field data from before and after deflagration of a geothermal well [14].

2. Background

2.1. Numerical simulators

There are several geothermal simulators in use for solving the conservation equations of energy, mass, and also chemicals in multi-component, two-phase flow in porous and fractured rock. This includes: TOUGH2 [15], STAR [16], FEHM [17] and TETRAD [18]. All these simulators use the implicit Euler method for time stepping and upstream weighting of mobilities and enthalpy [19]. All have been used widely and successfully for both commercial and research geothermal reservoir simulation. They all share the same uncertainties and sources of error including: systematic errors and inconsistencies, uncertainty in model parameters, discretisation errors and measurement errors [19].

The TOUGH2 simulator was chosen for this study as it is the most widely used [15] and can be utilised via PyTOUGH scripts which greatly simplify the running of multiple models for parameter estimation and refinement. The version used in this study is AUTOUGH2 which was developed at the University of Auckland to have some features particularly useful for geothermal simulations [20].

PyTOUGH is a library for the Python scripting code, developed for the automation of TOUGH2 simulations [9]. PyTOUGH allows easy and automated modification and running of TOUGH2 input files and extraction of results from TOUGH2 output files, a previously onerous task.

As the inverse modelling code iTOUGH2 [21] is not integrated with PyTOUGH each model parameter will be tested individually in a manual sensitivity analysis.

2.2. Previous numerical geothermal PTA studies

A small number of case studies have been published using numerical simulation for geothermal PTA. Nakao and Ishido (1998) used the STAR simulator to model permeability change with cold water injection for a well in Yutsubo Geothermal Field, Japan [7]. Villacorte and OSullivan (2011) investigated the same issue using both TOUGH2 and FEHM simulators with datasets from two unidentified wells [22]. The Yutsubo dataset was revisited by Riffault (2014) using TOUGH2 and PyTOUGH and a new relationship developed for the relationship of porosity and permeability to pressure and temperature [23]. Other studies use TOUGH2 to simulate field datasets and obtain estimated reservoir parameters for the Philippines [24,25] and New Zealand [26,27].

In all these studies significant time and effort has been used to match field data from one or two wells. The resulting model designs are specialised and specific to a single well or dataset, often with multiple layers and rock types to reflect the lithology [1].

All grid designs are radial, but beyond that there are significant differences in features such as the presence of a skin zone and its width, reservoir thickness, number of blocks and radial spacing. In all of these studies was not possible for the reader to re-create these models, or to apply them to other datasets. Without this imperative there is no full description of the model design or reasoning, and no consistency between different studies. Hence an industry-based reservoir engineer cannot use any of these studies as a framework for modelling a new geothermal PTA dataset. Even if enough information was given for a framework, it would depend on which study it was based.

The exception to the case studies above is the work of O'Sullivan (1987) and O'Sullivan et al. (2005), which explored geothermal PTA more generally. First O'Sullivan (1987) used MULKOM, the predecessor of TOUGH2, for the simulation of geothermal drawdown/buildup and injection tests including the effects of phase changes [6]. Later O'Sullivan et al. (2005) developed AWTAS, the first and only software for geothermal PTA based on numerical models [3], see Section 2.3.

2.3. Automated Well Test Analysis System (AWTAS)

In 2005 a study was published on the development of AWTAS (Automated Well Test Analysis System) [3]. It is the first and only geothermal well test analysis software to be developed which calculates the model response numerically rather than analytically, important as geothermal conditions violate the assumptions on which analytical models are based. The objective of AWTAS was to create something accessible and user-friendly, by means of a graphical interface with a range of TOUGH2 models already set up and with non-linear regression capability. These models include homogeneous porous layer, fractional dimension, skin, wellbore storage, leaky aquifer and various other models to represent different reservoir types.

In theory AWTAS fits the requirements of the geothermal industry for numerical PTA. Unfortunately AWTAS was never widely utilised as it was developed for a private client and the user interface was written in a programming code which is now obsolete. It is also widely considered to have been superceded by PyTOUGH. AWTAS has been used for a small number of academic studies [28,22].

2.4. Summary of background

An industry-based geothermal reservoir engineer with a PTA dataset needs a method for numerical simulation of the dataset as analytical methods are inapplicable. A framework is required to guide on the model design but published geothermal numerical PTA studies are not a good resource for this as the models are complex and highly specialised to a particular well or dataset and are therefore not suitable for other wells. Further, there is insufficient information published to reproduce the model setup, and the background reasoning is not included. The only work done that would in theory give the industry a tool to use is the AWTAS software with its built-in numerical modelling capability. The gap that AWTAS was created to fill unfortunately still exists as AWTAS is not widely accessible by industry. The creation of a framework based on TOUGH2 and PyTOUGH aims to fill this gap as both are widely used and freely available.

3. Design of numerical framework

3.1. General grid setup

The general setup is a single-layer radial grid model with three main components: a central well block, adjacent skin zone and reservoir zone beyond this (Fig. 1). The radius of the well block is the actual well radius and the skin zone then extends out to 5 m. The radial extent of the model is 20 km which is far beyond the likely radial extent of the pressure changes induced in geothermal