An Integrated Leapfrog/AUTOUGH2-SC Model Of The Menengai Geothermal Field

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ABSTRACT

The Menengai caldera is an ellipsoidal depression with minor and major axes measuring approximately 8 and 12 kilometres, respectively. The geothermal field is located near Nakuru along Kenya’s Rift Valley. A deep drilling program has been in place since early 2011, from exploration at the beginning to production drilling currently. This drilling programme has resulted in more than 52 deep geothermal wells within the caldera, aiming to characterise the deep reservoir properties, delimit the field extension, and provide steam for power development. The geoscientific, reservoir, and drilling data are continually reviewed and integrated to produce an updated geothermal model of the field. However, supercritical temperatures of above 370°C were encountered in some of the wells drilled in the Menengai geothermal field which pose a challenge in developing a numerical model of the field. The supercritical temperatures present difficulties for conventional reservoir simulators as a result of changes in the properties of water under these conditions. The supercritical state can be attributed to the complex nature of the system, which occurs in a particular zone with a deep vapour-dominated high-temperature reservoir just on top of the hot intrusion at temperatures higher than 300°C. This zone is disconnected from the shallower liquid-dominated reservoir (at temperatures ranging from about 130°C up to approximately 210°C) by a relatively thin impermeable layer. An integrated Leapfrog/AUTOUGH2-SC model of the Menengai geothermal field was developed with a new complete conceptual and natural state reservoir models. The findings demonstrate two primary heat sources for the Menengai caldera and the Ol’ Rongai field; it also indicates how major faults govern heat and fluid flow directions of the Menengai geothermal field. The reservoir model shows that the main feed zones are between ~1500 masl and about 500 masl and ~300 masl to -500 masl and the extent of the reservoir is around the summit of the caldera and towards the West of the caldera. The AUTOUGH2-SC model matched some wells with preliminary calibration signifying that it is the ideal tool for reservoir modelling of the Menengai geothermal field.
1. Introduction

Various conceptual and numerical model simulations of the Menengai geothermal system have been developed (Ezekiel et al., 2013, O’Sullivan et al., 2015; Montegrossi et al., 2015; and Mibei et al., 2016). These models relied on the limited data that had been acquired at the time when fewer wells had been drilled, and parts of the field had not been investigated due to the inaccessibility of the terrain. Models constructed during the early stages of exploration drilling and geoscientific studies are a little different from the ones set up during production drilling. The drilling of a successful well (MW-18A) at the northeast of the caldera has raised interest regarding the extent of the heat source in the field, which had previously been thought to be confined to the centre of the caldera. Recent work done by Kanda et al., 2019, suggests that there is a more significant heat source at Ol’ Rongai than had previously been thought. The evidence of a shallow high-density body is mirrored by the presence of fumarolic activity, which appears to be controlled by NNE and NE trending faults.

Supercritical temperatures have been recorded in some wells such as MW-01, MW-04, MW-06, and MW-21. They present difficulties for conventional reservoir simulators as a result of changes in the properties of water under these conditions. During discharge testing (Sekento 2012), MW-04 fluid entries were observed from overlying layers and temperatures of above 390 °C. They were measured after 11 days of flow testing and about one month after the end of drilling. Pressures of up to 140bars were recorded during shut-in. At flowing conditions, bottom-hole pressure was found to be approximately 20 bars. An earlier numerical model developed by Kipyego et al., 2013, highlighted the structural control and the reservoir characteristics of the field. Still, it could not handle the supercritical temperatures recorded at depths below 3200m (O’Sullivan et al., 2015). A new model was developed using the University of Auckland’s supercritical version of the TOUGH2 simulator (O’Sullivan, 2015). The results indicated that the supercritical model achieves a significantly better match than the previous model, thereby eliminating the artificially low permeability needed at the bottom of the model to replicate high temperatures (O’Sullivan et al., 2015).

With such supercritical conditions, detailed conceptual and numerical models are necessary to assess the heat transfer along with the fluid thermodynamics at the wellbore. This modelling process provides production scenarios and forecasts that are as accurate as possible. This paper aims to present a new approach to geothermal modelling of the Menengai field by tightly coupling the Leapfrog geological conceptual model with the TOUGH2-SC reservoir model. The tight coupling of the two models ensures uniformity between the geological and reservoir models and provides a means for automatically setting up and updating reservoir model parameters. This integration facilitates the mechanism of using newly acquired field data to update the conceptual model as well as assigning the changes to the reservoir model. It also allows the reservoir modelling process to proceed quickly.
2. Conceptual model representation

A representation of the Menengai geothermal field conceptual model is generated through a 3-D Leapfrog geological model. Geological well logs data are used to generate a clear lithostratigraphic view of the geothermal system. Downhole reservoir temperature well logs in conjunction with the gravity data, Kanda et al. (2019), are used to generate the heat source depth and the extent of the magmatic heat source.

The model depicts surface geology of the Menengai caldera and Ol’ rongai field (post-caldera volcanics) very well and presents the upper pre-caldera volcanics intrusion on the southern part
of the caldera. As shown in figure 1 below, Syn-caldera volcanics are widely distributed outside the caldera confirming with Lagat et al. (2010) how the regional surface geology is spread. The lowest lithostratigraphic sequence of the geological model is the Lower pre-caldera volcanics (average thickness of 3600m) with 2 (two) Magmatic heat-source intrusion bodies. On top of the Lower pre-caldera volcanics, are the Upper pre-caldera volcanics (average thickness of 1100m) where most of the total drilled depths of the wells are located, and they host some minor Magmatic Heat-source intrusions. The Syn-caldera (average thickness of 300m outside the caldera and 700m inside the caldera) volcanics lie beneath the Post-caldera volcanics (average thickness of 550m).

Figure 2: Leapfrog lithological structure of the Menengai geothermal field with inferred Magma bodies.

There are two dense bodies which interpreted as heat sources for the system. In comparison to the previous conceptual model by Mibe et al., (2016), which had only one dense body inside the caldera, the new model has two dense bodies. They are located inside the caldera and at the Ol’rongai area. The magmatic heat source in the main caldera is confined within the caldera wall. Upflow zones are in the centre of the caldera and in the North of the caldera at Ol’rongai field (Figure 2). The magma heats the lower pre-caldera volcanics which consequently heats the upper pre-caldera, syn-caldera and post-caldera volcanics through permeable rocks and the fault structures that develop in this area to become a reservoir in the geothermal system.
3. TOUGH2 model generation

After developing a conceptual model, a TOUGH2 model input file is created directly from the Leapfrog model, as shown in Figure 3. The topography of the TOUGH2 model is correctly transferred on to the grid, and the geological structures are automatically assigned. The grid can be rotated and oriented to align with the faults by use of Leapfrog software. The Leapfrog model can accommodate uneven grid spacing that allows a highly refined grid to be assigned closer to drilled wells and the centre of the system (Popineau et al., 2018). Figure 4 shows how a TOUGH2 reservoir model of Menengai geothermal is generated with the faults overlaid. TOUGH2 model blocks that are intersected by the faults are identified then assigned different properties manually. The software TIM is used to make the TOUGH2 model.
In Figure 4 above, the outputs from both the Menengai geothermal field conceptual and natural state numerical models can be represented in a high-resolution 3D visualization. The structures created for both the geological conceptual model and the natural state numerical models of the Menengai geothermal field remain consistent and are precisely documented. The setup time and effort for the natural state reservoir model of the Menengai geothermal field was significantly reduced, enabling more work to be done in the model with more accurate output. With this, new data acquired from the Menengai geothermal field can be easily updated in the conceptual model as well as assigning those changes accurately to the natural state reservoir model. Additionally, specialists from different geothermal disciplines can be able to interact and communicate on the same platform, thus aiding the modification or upgrading of the model.

4. TOUGH2 model calibration and presentation of results

Following the generation of a Leapfrog geological model, PyTOUGH scripts are used to generate the model specifications. There are three crucial strong points in using PyTOUGH scripts for generating the model parameters. Foremost, using scripts makes it a trivial task to regenerate model parameters for a TOUGH2 model that has had its structure updated using Leapfrog. Furthermore, PyTOUGH scripts simplify the calibration process and are essential records of the calibration history (Croucher, 2012, 2016). Lastly, PyTOUGH scripts significantly minimise the chance of introducing errors when assigning model parameters to complex simulations. As an alternative, without requiring scripts, TIM can be used to visualise 2D plan views or slices of reservoir parameters assigned to the blocks. It provides a powerful tool during the calibration process, by allowing manual changes of model parameters and providing a general overview of them at the same time.
The AUTOUGH2-SC is used to run the model and a few adjustments done to achieve realistic results. The surface temperatures in the model are shown in Figure 5 below. The heat zone is concentrated in the centre of the caldera and the NE at Ol’Rongai fumaroles, and these are the outflows of the system.

Figure 6: The surface temperature for the field.
The model temperature profiles for wells MW-01, MW-04, MW-06 and the shallow part of MW-09 match the field data well. The excellent match is attributed to the supercritical feature of the AUTOUGH2-SC.

For MW-02, the model matches well at the shallow elevations up to ~1350 masl by capturing the conductive part of at this point. It, however, does not wholly capture the cold inflow part of the well. Concerning MW-03, the model does not capture the cold inflow shallow parts of the well. The steeper conductive gradient below 200 masl is matched very well with temperatures increasing to above 300°C. Though the model for MW-05A takes the same pattern in a mirror-like form, the model temperatures are high as to those of the measured ones. A few adjustments need to be made to the model to eliminate this temperature difference. Concerning MW-08, the model gives a poor match. This disparity can be attributed to the location of the well where it is out of the main heat zone of the Menengai caldera.

5. Conclusions

Integrating the Leapfrog Geothermal conceptual model with an AUTOUGH2-SC model allows us to generate a more accurate model, easily visualise model outputs, and compare model outputs directly with field and well data. This makes modelling effortless and expedites the dissemination of AUTOUGH2-SC model to a broader team of engineers and geoscientists using a single source of information. These meaningful benefits provide detailed information from the geothermal modelling process for the management to make informed decisions about the field.

The use of AUTOUGH2-SC in the natural state modelling of the Menengai geothermal field is essential, and this is demonstrated by the output of well plots of MW-01, MW-04, and MW-06. MW-04 & MW-06 recorded fresh glassy, quenched cuttings at depths, (Mbia et al., 2015), implying the wells were drilled through a magma-containing domain and recording supercritical temperatures. The AUTOUGH2-SC can match these wells with preliminary calibration signifying that it is the ideal tool for reservoir modelling of the Menengai geothermal field.
REFERENCES


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