Using T2well For Simulating Coupled Wellbore-Reservoir Simulations

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ABSTRACT

Geothermal modelling plays a crucial role in the successful development of geothermal fields. It aids in the planning of resource utilization, as well as the assessment and management of geothermal fluid production to achieve optimal performance. An important application of a wellbore/reservoir model is conducting future scenario simulations to make accurate forecasts using a well-calibrated reservoir model. To accurately simulate the future performance of geothermal wells, it is crucial to understand the coupling requirements to effectively integrate wellbore and reservoir simulators. T2Well is a simulator for non-isothermal and multiphase fluid flow that can model tightly coupled wellbore-reservoir flow. T2Well extends the capabilities of the numerical reservoir simulator TOUGH2 by integrating a wellbore sub-domain into the numerical grid, allowing it to compute flow in both the wellbore and the reservoir concurrently and efficiently. However, it appears that there are no published examples where T2WELL has been applied to a full-scale convective 3D geothermal model.

This paper presents a 3D coupled wellbore-reservoir model developed following geothermal reservoir modelling best practices. We utilized T2Well with a pure water equation of state, EOS1, to fulfil the necessary model setup requirements for a hot, convective geothermal system with reservoir temperatures ranging from 250°C to 270°C. The initial conditions for the fully coupled wellbore-reservoir simulation are based on the results of the natural state simulation of a synthetic geothermal field. The model was then used to simulate transient, late transient, and pseudo-steady state production phases for a geothermal well over a one year period.

1. INTRODUCTION

Geothermal modelling is important for planning the development of geothermal energy resources and evaluating and managing the production of geothermal fluids to ensure optimal performance. We discuss geothermal wellbore simulation and geothermal reservoir simulation in this work. Geothermal wellbore simulators solve equations that describe the conservation of mass, momentum and energy for a two-phase fluid within a well (Tonkin et al., 2021). Geothermal reservoir simulators solve equations describing the conservation of mass and energy for two-phase flow in a porous media (O'Sullivan et al., 2023). As one might expect, the dynamics of a geothermal wellbore and the reservoir are closely linked. For example, production through the well will cause reservoir conditions to change, which, in turn, will cause production from the well to change.

Coupled simulations, where both the reservoir and the well are represented numerically, are required to model the dynamics of the combined system. Coupled simulations are invaluable for accurately simulating forecasts of production from a geothermal field and also aid in accurately simulating the future performance of geothermal wells using production history data derived from field surveys.

There are multiple ways in which simulators can be coupled. The following four categories, ordered in terms of increasing numerical complexity, can be used to broadly classify different methods of coupling numerical simulators:

- Indirect coupling involves running wellbore (or reservoir) simulations for a wide range of scenarios before the main reservoir simulation work.
- In explicit coupling, the wellbore and reservoir are treated as different domains, which are solved using different numerical simulators. The wellbore simulator is run at the beginning of each timestep of the reservoir simulation to calculate the flows to the wells.
- Semi-implicit coupling methods treat the well and reservoir as separate computational domains that are solved using different numerical simulators. However, unlike explicit coupling, information is passed between the two simulators multiple times during a single timestep to iteratively converge a shared calculation of flow variables.
- Fully-implicit coupling methods treat the well and reservoir as a single computational domain. The conservation equations describing mass, momentum and energy transfer in both the well and the reservoir are solved simultaneously for each time step. Fully implicit couplings of the wellbore and reservoir have been presented by Pan et al. (2011) and Korzani et al. (2019).

In the past, wellbore and reservoir simulations have been treated independently in modelling studies. The behaviour of the wells has mostly been approximated by deliverability models (e.g., Yeh et al., 2015). For some of the deliverability models, parameters such as the cutoff pressure, are calculated by running wellbore simulations before commencing the reservoir simulation.

Several researchers have explored the integration of a geothermal reservoir simulator with a wellbore simulator. Hadgu et al. (1993) explicitly coupled TOUGH (Pruess, 1987) with the steady-state wellbore simulator WFSA

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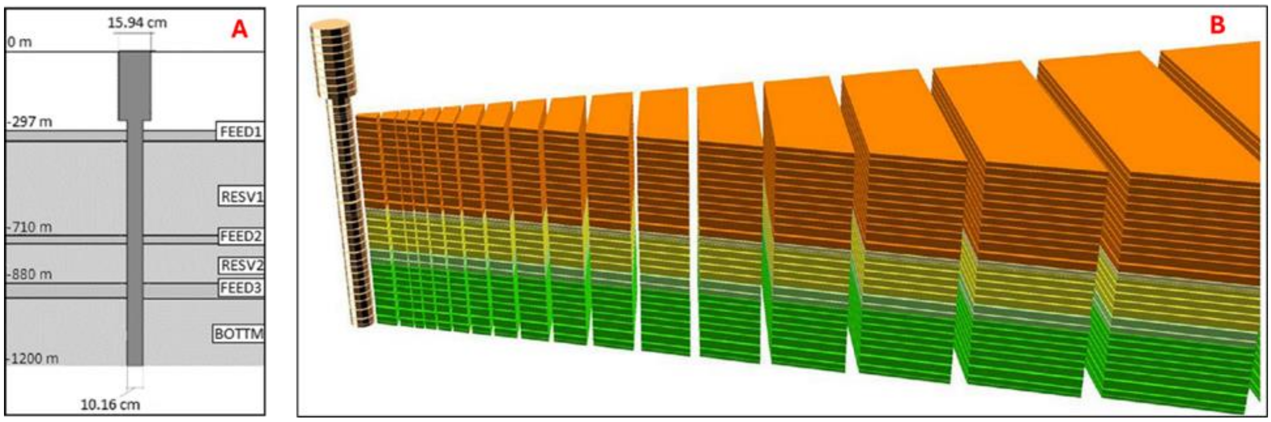

Figure 1: Conceptual model (A) and vertical cross-section of WW-01 wellbore-reservoir model (Vasini et al., 2018)

(Hadgu and Freeston, 1990) using a bridging function named COUPLE, which facilitated the exchange of information between the simulators. Bhat et al. (2005) performed an explicit coupling of TOUGH2 (Pruess et al., 1999) with the HOLA wellbore simulator (Bjornsson, 1987) by integrating HOLA as a subroutine within TOUGH2. Gudmundsdottir (2012) utilized TOUGH2 and the steady-state wellbore simulator FloWell (Gudmundsdottir et al., 2012; Gudmundsdottir and Jonsson, 2015) to create a linked wellbore-reservoir simulator using the DELV type generator in TOUGH2. Franz & Clearwater (2021) note that the geothermal reservoir simulator, Volsung, is capable of running coupled reservoir-wellbore simulations using their steady-state wellbore simulator called Gudrun, but the method used for coupling is unclear. However, it appears that there are no published examples where T2WELL has been applied to a full-scale convective 3D geothermal model.

The literature indicates that it is possible to use scripts to implement explicit coupling methods, converting the feedzone conditions to well production forecasts using a wellbore model at each reservoir simulation time step. However, these methods can suffer from convergence issues and can result in long simulation times. Conversely, fully-coupled methods can present difficulties with meshing, especially for deviated wells, and convergence issues associated with flow within the well can be challenging to manage. Running coupled simulations for geothermal systems with many wells presents additional challenges with both approaches. Therefore, it is important to understand the requirements for coupled wellbore and reservoir simulation.

The long-term goal of this research is to develop and efficient coupling method that is suitable for simulating reservoirs with many wells, which is typical in commercial geothermal systems. It is, therefore, important to understand the how different coupling methods perform numerically and the ability for different coupling methods to accurately simulate the combined dynamics of both systems. The research discussed in this paper investigates a fully coupled wellbore-reservoir simulation with one vertical production well, referred to as WELL-1. In the future, this model will be used as a base-case when comparing different types of coupling.

In this work, we present an integrated wellbore-reservoir simulation applied to a full-scale 3D geothermal model using T2WELL (Pan and Oldenburg, 2014). We discuss the T2WELL simulator further in Section 2. In Section 3, we discuss the setup of the 3D reservoir model, which follows the modelling framework developed by the Geothermal Institute (Nugraha et al., 2022; O'Sullivan et al., 2023). The initial conditions for the fully coupled wellbore-reservoir simulation are based on the results from the natural state simulation of a synthetic geothermal field. In Sections 4 and 5, we discuss the natural state and production simulation results. These simulations use the pure water equation of state, EOS1, to simulate production from a hot, convective geothermal system with temperatures in the upflow ranging from 250°C to 270°C. Simulation results are visualized using TIM (Yeh et al., 2013).

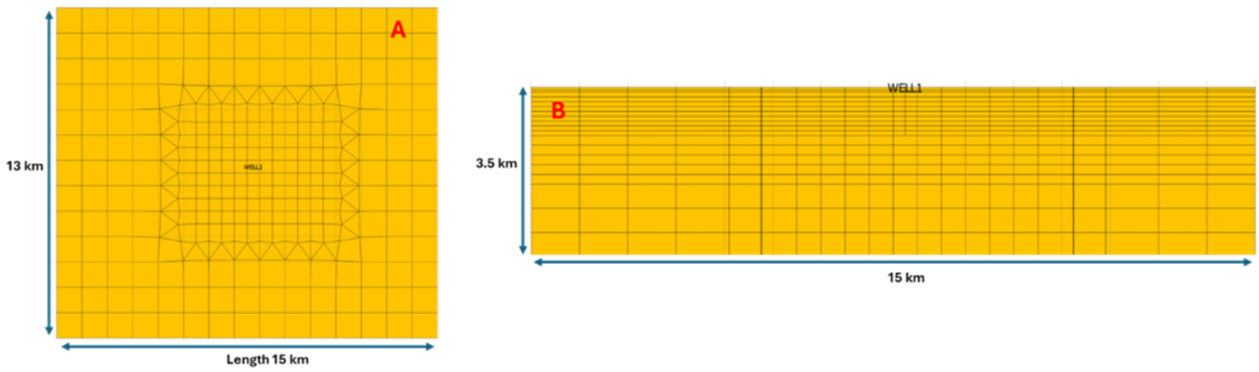

Figure 2: Top surface's plan view (A) and vertical cross-section (B) of the TOUGH2 model grid

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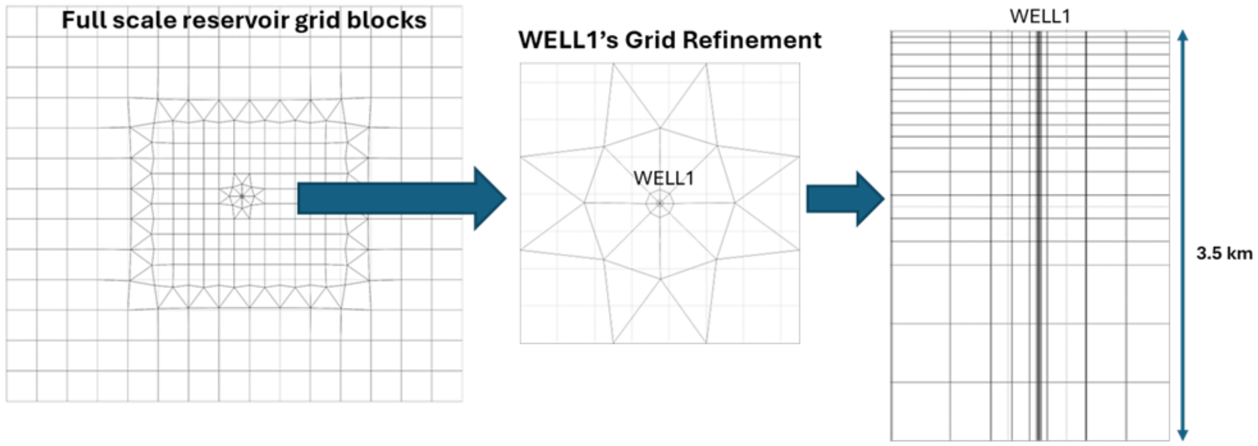

Figure 3: Local grid refinement surrounding the wellbore area WELL1 using optimized triangular refinement

2. T2WELL SIMULATOR

T2Well is a fully coupled simulator for non-isothermal and multiphase fluid flow, capable of modelling coupled wellbore-reservoir flow (Pan et al., 2011). T2Well extends the numerical reservoir simulator TOUGH2 (Pruess et al., 1999; Finsterle et al., 2014) by incorporating a wellbore sub-domain within the numerical grid. This integration enables concurrent and efficient flow computation in the wellbore and the reservoir. The Drift Flux Model (Shi et al., 2005) is used to represent phase slip in the well. This empirical model is applicable across a wide range of flow regimes, without resorting to approximations such as single-phase flow, using a productivity index, or assuming quasi-steady state wellbore flow (Pan and Oldenburg, 2014).

T2Well is available commercially as a coupled wellbore-reservoir simulator for CO_2 and variable salinity water mixtures (Pan et al., 2011). In this context, T2Well was utilized with the equation of state, ECO2N, to simulate CO_2 injection and leakage behavior via wellbores.

Furthermore, T2Well has been applied in studies involving Enhanced Geothermal Systems (EGS) simulations with ECO2H (Pan et al., 2015), energy storage applications of compressed air with EOS7C (Oldenburg and Pan, 2013) and modelling the Macondo well blowout with EOIL (Oldenburg et al., 2011).

Vasini et al. (2018) used T2Well and the EWASG equation of state to interpret a short period of a production experiment in a high-enthalpy geothermal reservoir. The T2Well-EWASG was validated through a fully coupled wellbore-reservoir simulation using their wellbore-reservoir model including a well called WW-01 (Figure 1). This model excluded the cap-rock and thus, the heat exchange between the wellbore and the cap-rock (area above -297 mRL) was simulated using Ramey's heat loss function (Ramey 1962), which is available in T2Well. In subsequent work, Battistelli et al. (2020) integrated the new EOS2H module, suitable for subcritical and steam-like supercritical H2O-CO2 mixtures, into T2Well, the same version used by Vasini et al. (2018). The T2Well-EOS2H code was validated through simulations conducted with various supercritical reservoir simulators and steady-state subcritical and supercritical wellbore flow simulations. Battistelli et al. (2020) compared T2Well-EOS2H to T2Well-EWASG by modelling steady-state wellbore flow in two geothermal wells, W2 and KD13, also referencing literature (Barelli et al., 1982; James, 1975) cited by Vasini et al. (2018).

3. 3D NUMERICAL MODEL DEVELOPMENT

The TOUGH2 model grid developed for this study (Figure 2) spans an area of 15 km x 13 km. It features large blocks of area 1 km x 1 km and is refined in the main upflow zone to blocks of area 500 m x 500 m. The depth of the model grid extends to 3.5 km, with vertical thicknesses ranging from 500 m for the three bottom layers to 50 m near the surface. The total number of blocks for this model is 6,580. This setup was conducted following best practices in constructing the 3D numerical model (Nugraha et al., 2022; O'Sullivan et al., 2023) to facilitate the simulation of a convective hot geothermal system.

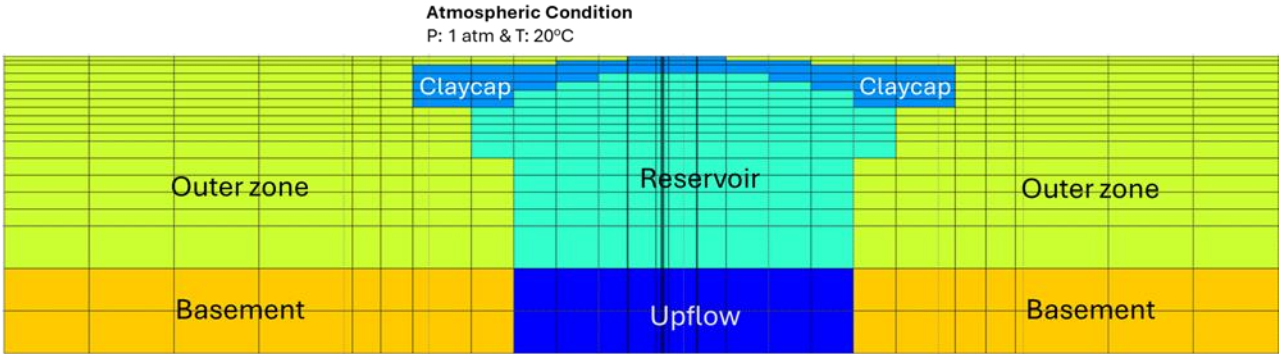

Figure 4: Rock type distribution within the TOUGH2 model and top boundary conditions set up

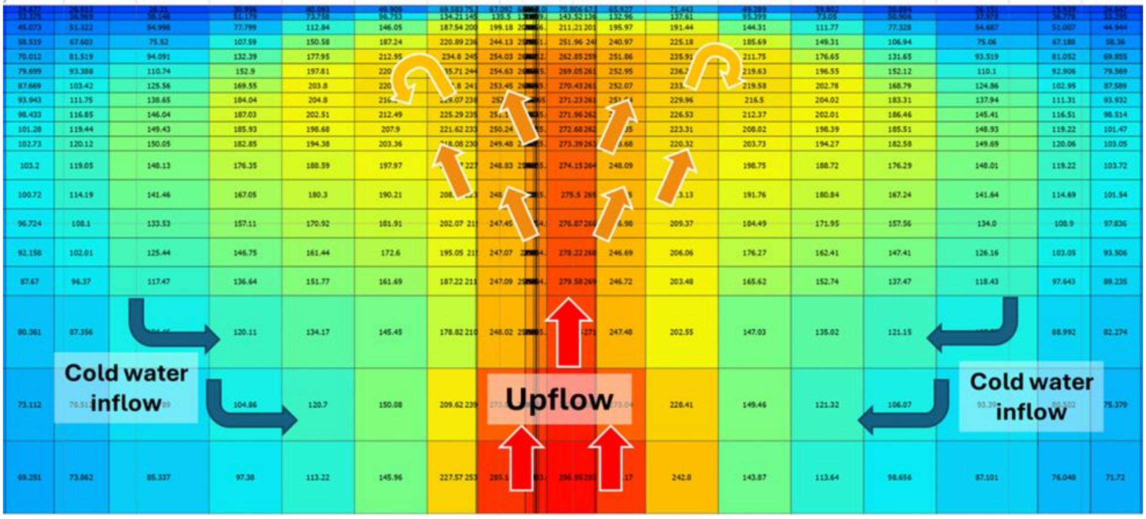

Figure 5: Simulated natural state temperature distribution in the synthetic geothermal model

The planned production well (WELL1) is positioned at the center of the main upflow area. We refined the grid blocks surrounding the wellbore area through four stages of an optimized triangular scheme (Figure 3). This refinement was implemented to enable the representation of the radial flow of hot fluids during production scenario simulations and to ensure numerical accuracy by maintaining orthogonal connections among the refined blocks. As a result of this wellbore refinement, the total number of model grid blocks increased to 7,380. As outlined in the previous chapter, T2Well is an extension of TOUGH2, equipped to conduct fully integrated wellbore-reservoir simulations. However, T2Well lacks the capabilities and computational efficiency of AUTOUGH2 (Yeh et al., 2012) for running a 3D model effectively. To ensure that the simulation process ran efficiently within a reasonable time frame, we aimed to keep the total number of model grid blocks under 10,000.

4. NATURAL STATE MODEL SETUP AND SIMULATION

4.1 Natural State Model Setup

Before utilizing the TOUGH2 model for natural state simulation, we categorized the model grid blocks into five distinct rock types, which represent the typical components of a convective geothermal system. As illustrated in Figure 4 below, we designated the two bottom layers of the model as Basement (B0001), characterized by tight permeability. Adjacent to this, in the middle area of these two layers lies the Upflow (U0001), with higher vertical permeability to facilitate the upward flux of hot water to the reservoir zone. The Reservoir (R0001), located beneath the Clay-cap, exhibits high permeabilities in the X, Y, and Z directions, simulating the fractured zone. Above the reservoir zone and near the surface, the Clay-cap (R00A1) is allocated very tight permeability, which is characteristic of an alteration zone. Surrounding the Reservoir zone, the Outer zone (O0001) is has the permeability characteristics typical of volcanic rock. Detailed parameters of these five rock types are presented in Table 1.

Table 1: Detailed parameters of the designated rock types

	Name	DROK	POR	PER(1)	PER(2)	PER(3)	CWET	SPHT	FREQUENCY
1	0ATM1	2500	0.1	1.000000e-15	1.000000e-15	1.000000e-15	2.5	1000	368
2	O0001	2500	0.1	1.000000e-15	1.000000e-15	1.000000e-15	2.5	1000	4001
3	R00A1	2500	0.1	1.000000e-16	1.000000e-16	1.000000e-16	2.5	1000	785
4	B0001	2500	0.1	1.000000e-15	1.000000e-15	1.000000e-15	2.5	1000	538
5	R0001	2500	0.1	3.000000e-14	3.000000e-14	7.000000e-15	2.5	1000	1476
6	U0001	2500	0.1	1.000000e-15	1.000000e-15	5.000000e-15	2.5	1000	200

4.2 Boundary Condition Setup

Top boundary: At the top of the model, general atmospheric conditions are assigned at the top surface blocks with a pressure of 1 atm and ambient temperature of 20°C. The equation of state, EOS1, is used in this model to describe

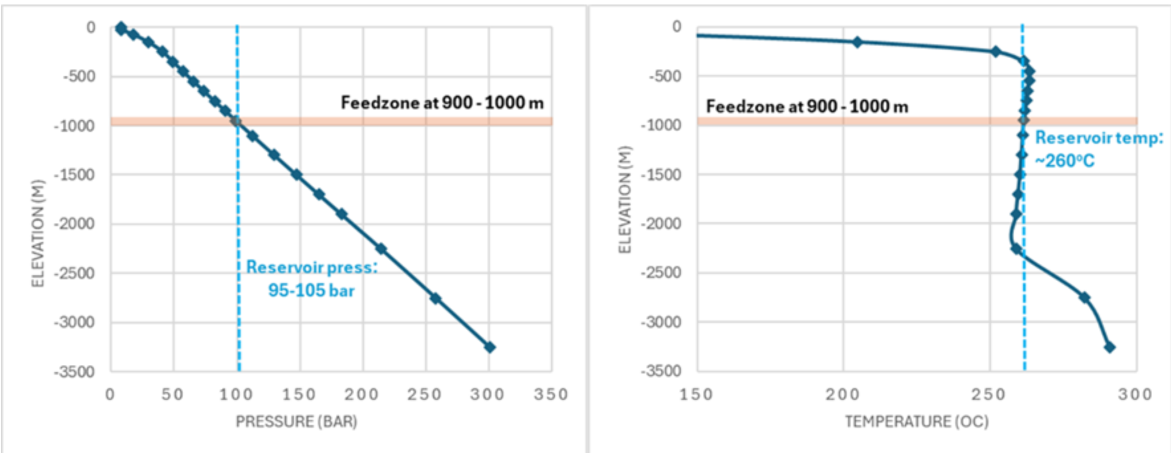

Figure 6: The profiles of static pressure (left) and temperature (right) at the location of WELL1

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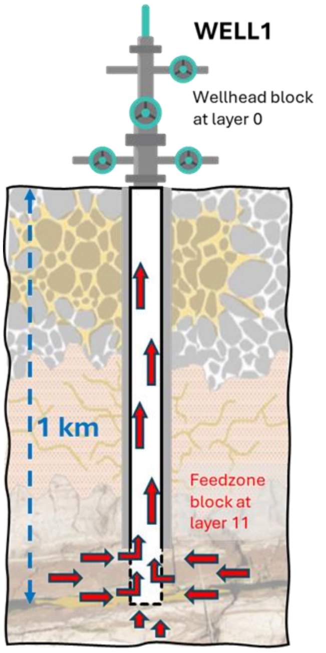

Wellbore Parameters

Parameter(s)	Value	Note
Length	1000 m	Vertical Wellbore
Diameter	9-5/8 inch	Production Casing
Wellhead Pressure	6.5 bar	
Atmospheric Temp	20°C	
Feedzone Depth	900 m - 1000 m	Single feedzone
Pipe Roughness	0.046 mm	Steel Pipe

Figure 7: Conceptual design (left) and wellbore parameters (right) of WELL1

pure water in its liquid, vapor, and two-phase states, and to simulate a convective hot geothermal system.

Side boundary: The side boundaries are presumed to be no-flow boundaries, i.e., no heat or mass entering or exiting the system. The side boundaries are far away (3 - 4 km) from the geothermal reservoir area.

Base boundary: The upflow of the geothermal system is represented by a hot water flux in the Upflow zone blocks, with a total constant mass input of 66.81 kg/s and an enthalpy ranging from 1,200 to 1,300 kJ/kg.

4.3 Natural State Simulation

The natural state model was simulated for a period of 3.17 x 10^6 years to achieve steady-state conditions. The simulation results (Figure 5) illustrate the temperature distribution within the reservoir zone, exhibiting a gradient from approximately 270°C in the deeper regions to about 250°C in the upper areas of the reservoir. The dynamics of the hot fluids are characterized by their upward movement from the Upflow blocks, facilitated by the permeable lithologies assigned within the 3D model. As the hot fluid rises, thermal mixing occurs with recharge water, forming a characteristic convective plume of a liquid-dominated geothermal system. Subsequently, the hot fluids are redirected horizontally toward the periphery of the Reservoir zone, guided by the overlying profile of the Clay cap.

Over time, as the fluids traverse horizontally, they begin to cool and descend toward the deeper segments of the reservoir model. A cyclical process ensues where the cooling fluids mix anew with rising hot fluids from the Upflow blocks, effectively replenishing the Reservoir zone. Figure 6 depicts the static pressure and temperature at the location of WELL1, which is designated as the production target zone for the subsequent tightly coupled wellbore-reservoir simulation.

5. TIGHTLY COUPLED WELLBORE – RESERVOIR MODEL SETUP AND SIMULATION

5.1 Production Model Setup

WELL1 was designated as the production well in the production model by integrating specific wellbore parameters into the Natural State model. The conceptual design of WELL1, as depicted in Figure 7, targets the upper part of the reservoir at a depth of 1,000 meters. For WELL1, a 9 5/8 inch production casing is employed. The bottom block of WELL1, located at layer 11, is designated as the feedzone and has a thickness of 100 meters. A pipe roughness value of 0.046 mm was selected for this model, reflecting the typical roughness associated with steel pipes. Furthermore, wellhead parameters are specified in the surface block (layer 0) of WELL1, maintaining a constant pressure of 6.5 bar.

5.2 Tightly Coupled Wellbore-Reservoir Simulation

The production scenario was conducted over 3.156 x 10^7 seconds (approximately one year). Figure 8 illustrates the simulation results across this one-year production period. Initially, WELL1 exhibited a high flow rate of 271.56 kg/s. This high flow rate is caused by the low flowing bottom hole pressure (Pwf) during the earliest transient period. Meanwhile, the reservoir pressure (Pr) remains in its natural state. Consequently, the drawdown pressure is at its maximum, resulting in a high production flow rate. This rate rapidly decreased to 123.49 kg/s after just 132 seconds of production and diminished further to 42.19 kg/s after two hours. Beyond this point, the flow rate stabilized at an average of 40.85 kg/s throughout the remainder of the year.

Concurrently, the enthalpy profile of the produced fluids remained almost constant. The initial enthalpy was simulated at 1,148 kJ/kg, which only slightly decreased to 1,118 kJ/kg by the end of the year. This tightly coupled wellbore-reservoir simulation effectively captured the three distinct production phases of WELL1: transient, late transient, and pseudo-steady state conditions.

Furthermore, we can observe the detailed parameters of the fluids produced from this simulation, such as pressure, temperature, enthalpy, and mass flow profiles along the wellbore, as shown in Figure 9 to Figure 12. The enthalpy profile slightly changes along the wellbore due to the thermal exchange between the wellbore blocks and the surrounding formations via conductive heat flow. This phenomenon is also in line with the temperature profile of the hot fluids along the wellbore, where the temperature decreases from 212°C in the feedzone to 164°C in the wellhead. The pressure along the wellbore varies from 19.2 bar in the feedzone to 6.5 bar at the wellhead due to hydrostatic effects and the flow restriction inside the wellbore. From all those parameters, we can conclude that the produced hot fluid is already two-phase when entering the wellbore through the feedzone, and it is expanding more due to the pressure decline while flowing upward to the surface, increasing the fraction of steam (Figure 13).

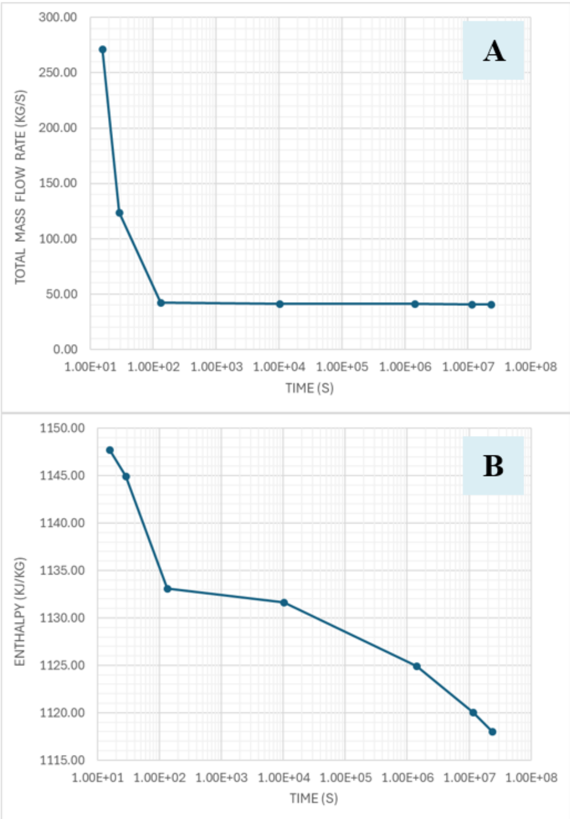

Figure 8: Simulation results for 1 year production period: (A) Total Mass Flow Rate in kg/s and (B) Enthalpy in kJ/kg

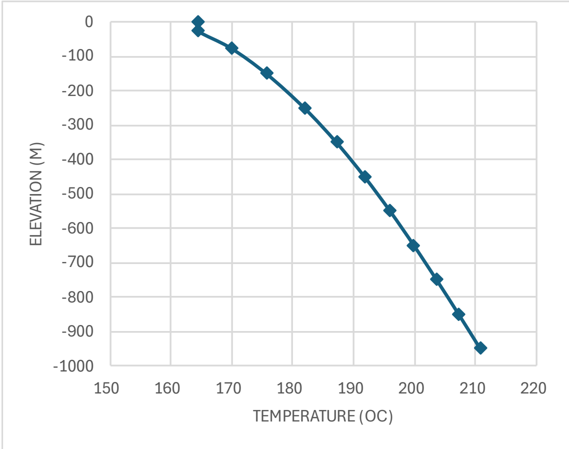

Figure 9: Pseudo steady-state downhole temperature

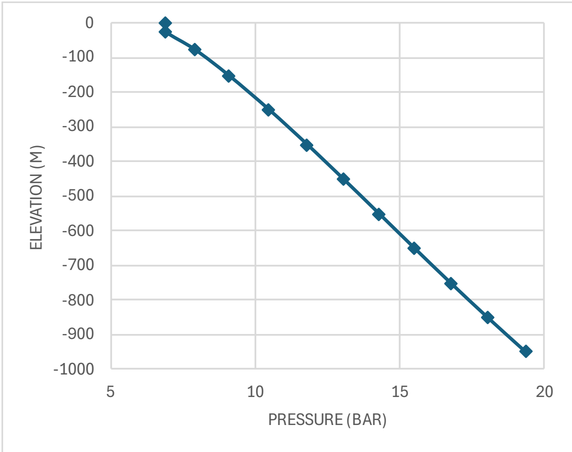

Figure 10: Pseudo steady-state downhole pressure

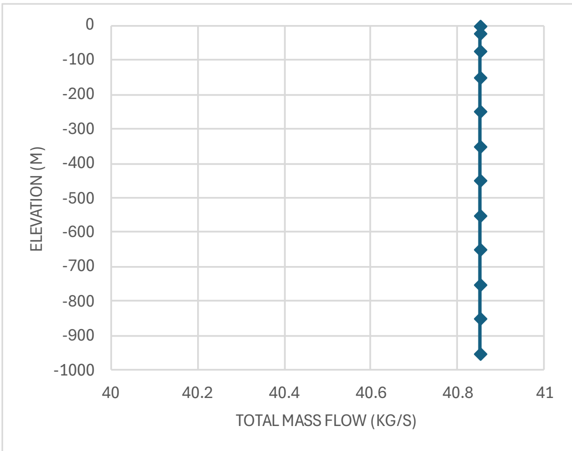

Figure 11: Pseudo steady-state downhole mass flow

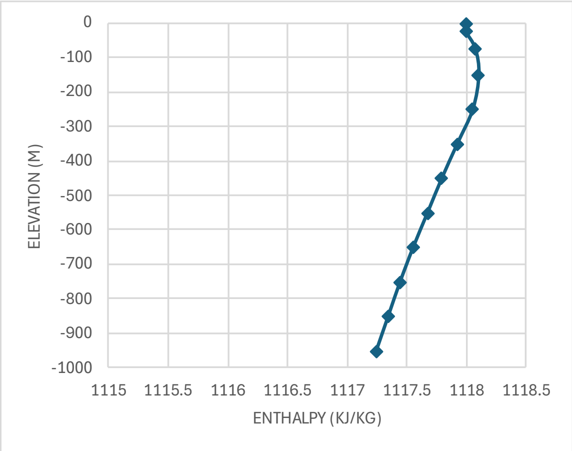

Figure 12: Pseudo steady-state downhole enthalpy

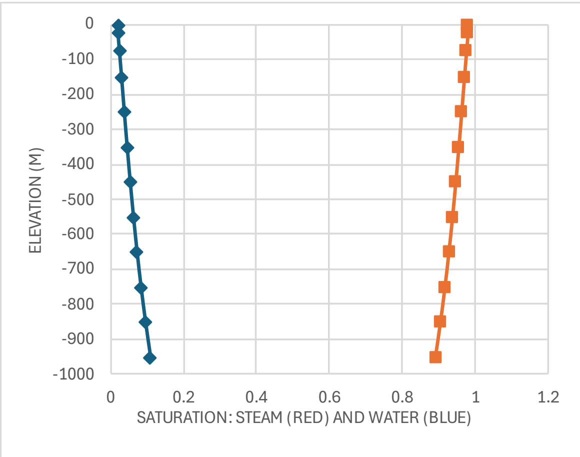

Figure 13: Saturation profile of vapor (Red) and liquid (Blue)

6. CONCLUSION

In this project we successfully developed a full-scale 3D geothermal model for tightly coupled wellbore-reservoir simulations. A fully integrated wellbore-reservoir simulation has been carried out, yielding interesting simulation results. Through this fully integrated simulation using the T2WELL simulator, we were able to observe the typical behavior of a geothermal production well. T2WELL effectively simulated the three distinct production phases of WELL1: transient, late transient, and pseudo-steady state conditions.

The authors are planning further research to conduct various wellbore-reservoir coupling simulations using T2Well. These studies will explore how minimizing the reservoir grid meshes attached to the wellbore model impacts the simulation results and will compare these results with those from the tightly coupled simulation described in this paper. The goal is to ensure that the simulation outcomes from other coupling methods are comparable in quality to those obtained from the fully coupled full-scale 3D reservoir model.

To our knowledge this the first implicitly coupled wellbore and reservoir simulation for a full-scale, hot geothermal system.

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