

Characterisation of Supercritical Fluid Production in Taupo Volcanic Zone (TVZ) through Wellbore Modelling and Simulation

Julius Marvin Rivera

GNS Science, Private Bag 2000, Taupo 3352, New Zealand

j.rivera@gns.cri.nz

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ABSTRACT

Wellbore modelling was undertaken to estimate the potential production of a supercritical geothermal well in Taupo Volcanic Zone, New Zealand seeking to characterise fluid and energy flows from the reservoir to the surface. Well configurations with feed zone depths between 4500 to 6000 meters were simulated to extract supercritical fluid from the Taupo Volcanic Zone deeper metasedimentary formations. A bottom-up simulation approach using different feed zone parameters and casing sizes with the fluid thermodynamic properties computed up to the wellhead. The values computed at the surface characterised the well production potential including the mass flow rate, enthalpy, thermal power and exergetic power across a range of wellhead pressures. Sensitivity analysis shows that permeability directly affects the well output. However, a deeper and hotter well does not guarantee a higher production potential. It was also observed from the simulation that at the optimum wellhead pressure for energy delivery, supercritical fluid is unlikely to produce at the surface, but instead superheated steam is expected.

1. Introduction

Supercritical conditions present deep within the Taupo Volcanic Zone (TVZ) at temperatures greater than 400°C are a prospective renewable and low-carbon energy source yet to be harnessed (Carey et al., 2021, Chamberfort et al., 2022). Using supercritical geothermal energy is not a new concept having been researched in a number of countries: Iceland, Japan, USA. The birth for supercritical research and exploratory drilling started in Iceland through the Deep Vision project in 2000 (Friðleifsson et al., 2014). Research and drilling were driven from the theoretical wellbore assessment presented by Albertsson et al. (2003) where a 5 km well, with a diameter of 9 5/8", extracting 0.67 m³/s of fluid from the supercritical reservoir at temperature of 550°C and pressure

of 260 bar was simulated to produce superheated steam at a wellhead pressure of 195 bar and temperature of 500°C. The electrical output was assessed to be ~50MWe, an order of magnitude increase compared to the typical 5MWe output of an Icelandic steam well producing at a same volumetric flow rate with reservoir temperature of 235°C and pressure of 30 bar.

This paper reports assessments undertaken seeking to evaluate supercritical fluid production from wells in the TVZ. Theoretical wellbore modelling was conducted using a range of well and reservoir parameters to simulate fluid flow at the wellhead. The simulated results are presented including the computed thermal and exergetic power.

1.1 Thermal Power and Exergy

Thermal power, expressed as q , is the total thermal energy available from the geothermal fluid at the wellhead.

$$q = \dot{m} \times h$$

Where \dot{m} and h are the mass flow rate (kg/s), and enthalpy (kJ/kg) of the fluid, respectively.

Exergetic power, is the theoretical maximum work production, independent of any power cycle assumptions, computed at the wellhead conditions relative to the surroundings which are at the ambient dead state temperature conditions T_o (Degrees K).

$$\hat{W} = \dot{m} \times [h - h_o - T_o \times (s - s_o)]$$

Where \hat{W} , h_o , s , and s_o are respectively the; theoretical maximum work output (kJ/s), dead state enthalpy (kJ/kg), entropy of the fluid (kJ/kg-K), and dead state entropy (kJ/kg-K).

The exergy approach addresses the quality of the thermodynamic fluid conditions and is useful for computing and comparing the equivalent maximum mechanical work for simulated and actual production well data. Also using exergy analysis, it is possible to identify the wellhead conditions that produce the theoretical optimum work output from across a range of wellhead conditions. There are numerous publications that describe exergy in open geothermal system power production such as DiPippo (2016).

For the New Zealand situation, the exergy calculations have been made using production wellhead data computed using an ambient dead state temperature of 293.15 K (20°C) at which the dead state enthalpy and entropy are calculated.

2. Wellbore Modelling and Simulation

Wellbore simulation was undertaken to estimate the production potential from TVZ supercritical wells, characterising well performance at different wellhead conditions. The work described in this paper comes from the GNS Science report by Rivera and Carey (2023)

In that work the wellbore simulation code used was the GFlow wellbore simulator developed by GNS as described in Kato et al. (2015) which has supercritical capability. GFlow includes time-based heat loss calculations from the wellbore to the surrounding formations, gravity effects on the fluid delivered, fluid friction head loss calculations as the fluid ascends the wellbore and the slip between liquid and vapor phases.

The assumptions used in the wellbore simulation work are briefly described below.

- The fluid is assumed to be pure water.
- Thermal losses through heat transfer from wellbore to the formation are accounted for with the TVZ formation properties coming from Mielke et al., (2016) (presented in Table 1) and the flow duration at which the heat transfer is calculated set at 10^7 seconds (about 115 days).
- The casing roughness was set at 0.5 mm (5×10^{-4} m) and the slotted / perforated liner roughness set to 0 m as is the convention for wellbore simulation.
- The results described in this paper are for a well with a 6000m deep feedzone.

Table 1: Formation properties used in the calculation of wellbore to formation heat transfer.

Formation Property	Value
Density	2700 kg/m ³
Thermal conductivity	2.0 W/m-K
Specific heat	800 J/kg-K

Details of the fluid state condition, wellbore configurations, and reservoir parameters used in the simulations are described in detail in Rivera and Carey (2023) and summarized in the sections that follow.

2.1 Pressure and Temperature Profile

The temperature profiles in the wellbore models came from profile similar to the Rotokowa area, where the highest bottomhole temperature in TVZ has to date been measured (Carey, et al., 2021). A shallower cooler zone is inferred from the surface down to 100 m with a temperature of about 20°C to that depth. Below this depth, a thermal gradient of ~150°C/km has been assumed in the formation down to the top metasedimentary (greywacke) basement, which is inferred down to ~1950 mVD. The temperature in the greywacke is then projected to increase between 37.5 to 50°C/km which is the basis of the three temperature cases simulated, reaching 450°C, 500°C and 600°C at 6000 m as shown in Figure 1.

The reservoir pressure is hydrostatic from the surface and is calculated using the overlying density of the static fluid column as a function of temperature. The three pressure profiles that correspond to the three temperature cases are shown in Figure 1. The pressures at the 6000 m feed zone depth together with the fluid density are tabulated in Table 2. The fluid density, along with the feedzone pressure, reduce substantially with increasing temperature.

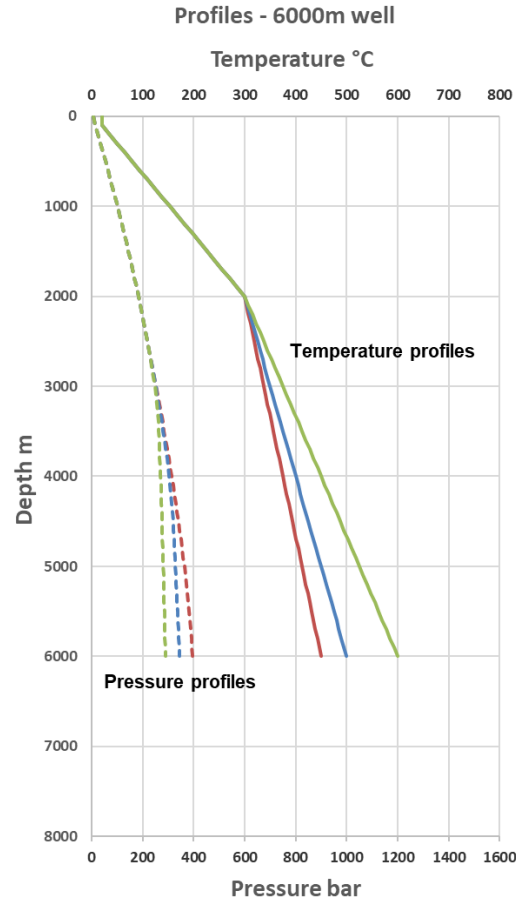


Figure 1: Temperature and pressure profiles for three different simulation cases – 450°C in red, 500°C in blue, and 600°C in green, at 6000 m depth.

Table 2: Temperature, pressure and density at 6000 m and naming nomenclature.

Nomenclature	Temperature (°C)	Pressure (bar)	Density (kg/m ³)
PT-1	450	395.9	264.7
PT-2	500	344.1	140.6
PT-3	600	289.3	83.7

2.2 Casing Configuration

A range of well sizes (WS) were reported in Rivera and Carey (2023) from narrow diameter, more suitable for measurement, sampling and monitoring, through to possible production well casing options. In this paper the results for a well with the 9 5/8" diameter casing set at 3500 m and a 7" diameter production casing set from there to 100m above the 6000m feed zone are presented. The lower 100 m is slotted / perforated liner of 7" diameter.

2.3 Feed Productivity

In wellbore simulation, productivity index (in m^3) represents the ability of the reservoir to deliver fluid to a wellbore as it flows through the permeable zones in the formation. For existing wells in the TVZ drilled shallow than ~ 3500 m, a range of values from 1×10^{-12} to $5 \times 10^{-11} \text{ m}^3$ has been assessed. As no wells have been deeper than this there is no measured productivity data from deeper in the TVZ and so the productivity of the deeper metasedimentary formations is assumed in the range computed from the existing wells. There is however an expectation that the deeper wells might have productivities lower in the range (Watanabe et al., 2020).

The assumed productivity index for what has been described as the base case model has been assumed to be $1 \times 10^{-12} \text{ m}^3$ with one order of magnitude higher (PI-1) and lower (PI-3) indices used for sensitivity testing (Table 3).

Table 3: Feedzone productivity index data.

Productivity Identifier (PI)	Productivity Index (m^3)
PI-1	10^{-11}
PI-2	10^{-12}
PI-3	10^{-13}

3. Wellbore Modelling Results

The simulation was undertaken using combinations of the reservoir parameters. A base well model was developed with a feed zone depth of 6000 m, a feed temperature of 500°C , and a productivity index of $1 \times 10^{-12} \text{ m}^3$. Some results are presented in the sections that follow with the detailed discussion of the sensitivity testing and the results presented in Rivera and Carey (2023).

3.1 Well Output at Different Pressure and Temperature Profiles

This section presents results for the effect of feedzone temperature on the well output. Each of the temperature cases (plotted as curves in Figure 2) has a different hydrostatic pressure profile which translates to ~ 100 bar pressure difference at the 6000 m feed-point as identified in Table 2.

As shown in Figure 2 (left side), there is a decrease in simulated mass flow rate with the increase in feedzone temperature. This is because of the reduced pressure at the higher temperatures.

Enthalpy (Figure 2 right side) is increasing with increasing temperature as more heat is present in the fluid due to higher feedzone temperature.

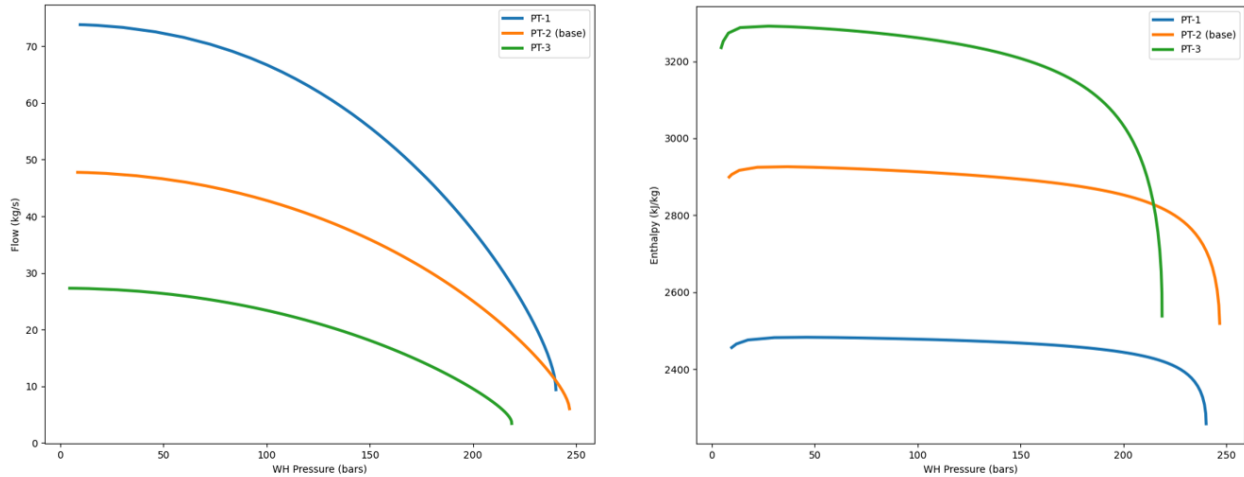


Figure 2: Mass flow rate (kg/s) and enthalpy (kJ/kg) plotted across the range of wellhead pressures for the different feed temperature curves (blue 450, orange 500, green 600)

Figure 3 shows the thermal (left) and exergetic power (right) calculated from the wellhead output data for the three feed zone temperatures. Interestingly the higher reservoir temperature produces lower thermal and exergetic power which identifies that the feedzone pressure is the more dominant controlling variable than the temperature in the simulated output.

A balance between the reservoir temperature and downhole pressure conditions needs to be considered in thinking about well depth and the temperature conditions that might be encountered relative to optimising the power output that might be produced.

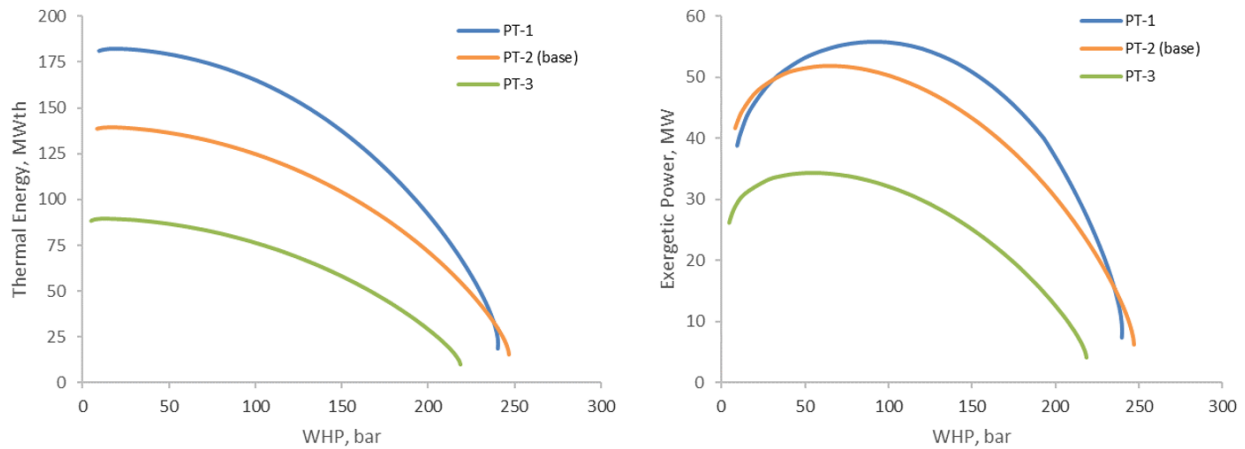


Figure 3: Thermal and exergetic power across a range of wellhead pressures at different feed temperatures

3.2 Well Output at Different Feed Productivity Indices

The effect of changing the productivity index of the well-on-well output is clearly evident. A magnitude increase in the productivity index increases the mass flow rate by 80%. Conversely, a decrease of about 100% in the mass flow rate output is observed with the magnitude decrease in

productivity index. It also noted that a higher maximum discharge pressure can be expected at the greater productivity index. The plot of these results can be found in Rivera and Carey (2023).

Thermal and exergetic power vary by an order of magnitude across the two orders of magnitude change in productivity indices evaluated in the wellbore modelling ((Figure 4).

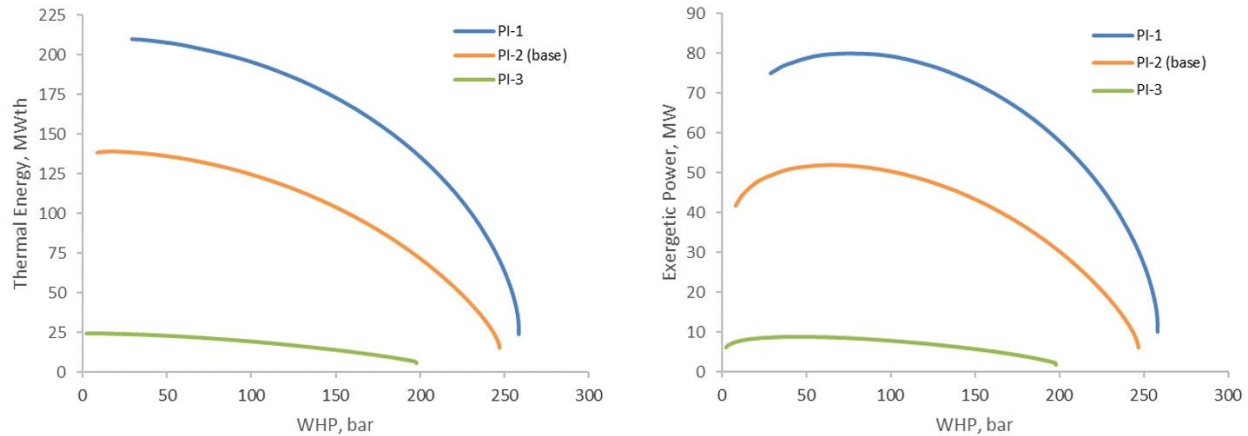


Figure45: Thermal and exergetic power across a range of wellhead pressures at the three different productivity indices (blue PI-1 greater, orange PI-2 intermediate – base, green PI-3 lower)

4. Conclusion

The GNS Science developed GFlow wellbore simulator has been used to simulation well outputs from supercritical reservoir conditions in the TVZ, New Zealand. A selection of results from Rivera and Carey (2023) are presented in this paper.

Fluid density controls the in-situ reservoir pressure conditions that has a significant effect on the well output, a hotter feedzone may not be better for energy production, and this should be considered when targeting well drilling for supercritical production.

The productivity index of a feedzone has a significant effect on the output of the well.

The thermal and exergetic power calculations shows that operating wellhead pressure at 120 bar and below is advantageous for production.

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