Thermodynamic Assessment of Near-Critical and Supercritical Geothermal Reservoir and Well Behaviours

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ABSTRACT

As the geothermal industry in New Zealand and elsewhere is exploring supercritical geothermal reservoirs, a question arises about how these wells will behave and what their potential output is. It is widely reported that drilling 4-5 km-deep wells in high-temperature conventional geothermal systems can encounter formations with a unique, discrete fracture network distribution and proximity to the brittle-ductile transitional zone, potentially limiting the reservoir rock permeability. At the same time, there will be high additional costs and technical challenges for drilling operations, casing, and cement integrity.

Therefore, it is important that these wells produce more power (MWe) than conventional wells to justify risk and investment. The power output from geothermal wells is the product of mass flow rate and fluid enthalpy. Therefore, the key target is to produce a high-enthalpy fluid. The enthalpy of supercritical fluid is highly dependent on temperature and pressure, and it is preferable to operate at a high reservoir temperature and low pressure. While the flow in geothermal wells is generally considered adiabatic, it is more polytropic near or above supercritical conditions.

This paper proposes a conceptual analytical thermodynamic framework for interpreting the depressurisation behaviour of supercritical fluids as a heat-supported polytropic process. Rather than providing a complete reservoir or wellbore simulation, the framework provides a general analytical description of how thermal support influences the thermodynamic pathway during depressurisation. The model does not explicitly resolve spatial and hydraulic behaviour of a geothermal reservoir and production well.

1. INTRODUCTION

Geothermal energy is a clean, constant, and renewable energy source that is increasingly vital as the world seeks to reduce greenhouse gas emissions and move toward a lower-carbon energy infrastructure (Feng et al., 2021; Xu et al., 2020). This energy is harnessed from the Earth's natural heat flow, which exists along a temperature gradient extending from the core to the surface (Suárez-Arriaga, 2019). While most developed geothermal systems currently operate at subcritical temperatures, there is a growing engineering interest in unconventional, very high-temperature resources found deep within the crust (Friðleifsson et al., 2014; Reinsch et al., 2017).

Geothermal energy is exploited through wellbores, which serve as the primary conduits for fluid transport. Geothermal production inherently involves pressure reduction; a pressure gradient, or drawdown, must be established to drive the geofluid from the high-pressure reservoir and through the wellbore toward the surface (DiPippo, 2016; Korzani et al., 2019).

This depressurisation causes profound changes in the fluid's thermophysical properties (Friðleifsson et al., 2014; Wang et al., 2023). In conventional liquid-dominated reservoirs, the reduction in pressure during ascent often causes the fluid to reach its saturation point and flash into a two-phase mixture of steam and water (DiPippo, 2016; Friðleifsson et al., 2014). Unlike the conventional geothermal reservoirs, supercritical systems operate at temperatures and pressures far above the critical point of water ($T > 373.946°C$, $P > 22.064$ MPa), where the distinction between liquid and vapour phases disappears, and properties such as density and viscosity vary sharply and non-linearly (Bell et al., 2014; Friðleifsson et al., 2020). These changes are critical because they dictate the fluid's mobility and its ability to transport heat through the wellbore.

In geothermal reservoir engineering, enthalpy is the key thermodynamic parameter that determines available energy. The total power output of a well fundamentally depends on the mass flow rate and the fluid's specific enthalpy (Suárez-Arriaga, 2019; Zarrouk & Moon, 2014). Enthalpy represents the heat extracted per unit mass during a process under constant pressure, and because supercritical water has significantly higher enthalpy than subcritical water or steam, it carries more energy per unit mass (Friðleifsson et al., 2014; Magnusdottir & Finsterle, 2015; Suárez-Arriaga, 2019).

Consequently, supercritical geothermal resources have much higher energy potential than conventional systems (Reinsch et al., 2017; Scott et al., 2017). Modelling and field data, such as those from the Iceland Deep Drilling Project (IDDP), suggest that a well producing from a supercritical reservoir can achieve a power output an order of magnitude greater than a conventional high-temperature well. For example, while standard geothermal wells typically produce 3–10 MWe, a single supercritical well could potentially generate 35–50 MWe (Feng et al., 2021; Friðleifsson et al., 2014, 2020).

Current geothermal reservoir studies are predominantly based on numerical simulation that predicts the thermodynamic state of the reservoir; they do not explicitly interpret the thermodynamic behaviour of water specifically during the depressurisation process (Feng et al., 2021). This paper proposes a conceptual thermodynamic interpretation of supercritical water during depressurisation. By establishing a theoretical framework based on a real-fluid polytropic

process, this study aims to evaluate the fluid's path-dependent evolution and its thermal interaction with the surrounding rock matrix.

1.1. Thermodynamic Behaviour of Water

Fluid movement in porous media occurs fundamentally because of a pressure gradient that drives the fluids from a high-pressure reservoir towards a low-pressure wellbore (Feng et al., 2021; Johansson et al., 2018). However, the physical response of a fluid to that pressure gradient depends critically on its compressibility and thermodynamic state (DiPippo, 2016).

Liquid water is nearly incompressible, particularly at subcritical temperatures (Suárez-Arriaga, 2019). When subjected to a pressure gradient, liquid water converts pressure energy primarily into fluid motion. With minimal density and volume changes, the flow remains largely isothermal (DiPippo, 2016). In contrast, supercritical water behaves fundamentally differently because of its high compressibility. A pressure gradient produces large volume expansion, significant density reduction, and intense cooling (Xu et al., 2020; Feng et al., 2021; Wang et al., 2023). In supercritical fluids, the pressure gradient acts not only as the hydraulic driving force for flow but also as the driving force for significant thermodynamic evolution of the fluid state.

Figure 1 presents the variation of constant-pressure heat capacity (C_p) near the critical region, exhibiting strong non-linear behaviour as critical conditions are approached, indicating that enormous quantities of thermal energy can be absorbed with only small temperature changes. Simultaneously, fluid compressibility increases substantially, and density becomes highly pressure dependent. These strong property variations imply that thermodynamic parameters commonly treated as constants for ideal gases cannot be assumed uniform for supercritical geothermal fluids. Instead, these must be continuously evaluated throughout depressurisation. Consequently, the thermodynamic path itself evolves as fluid properties change.

$$\gamma = \frac{C_P}{C_v} \tag{1}$$

γ is the heat-capacity ratio shown in Figure 2.

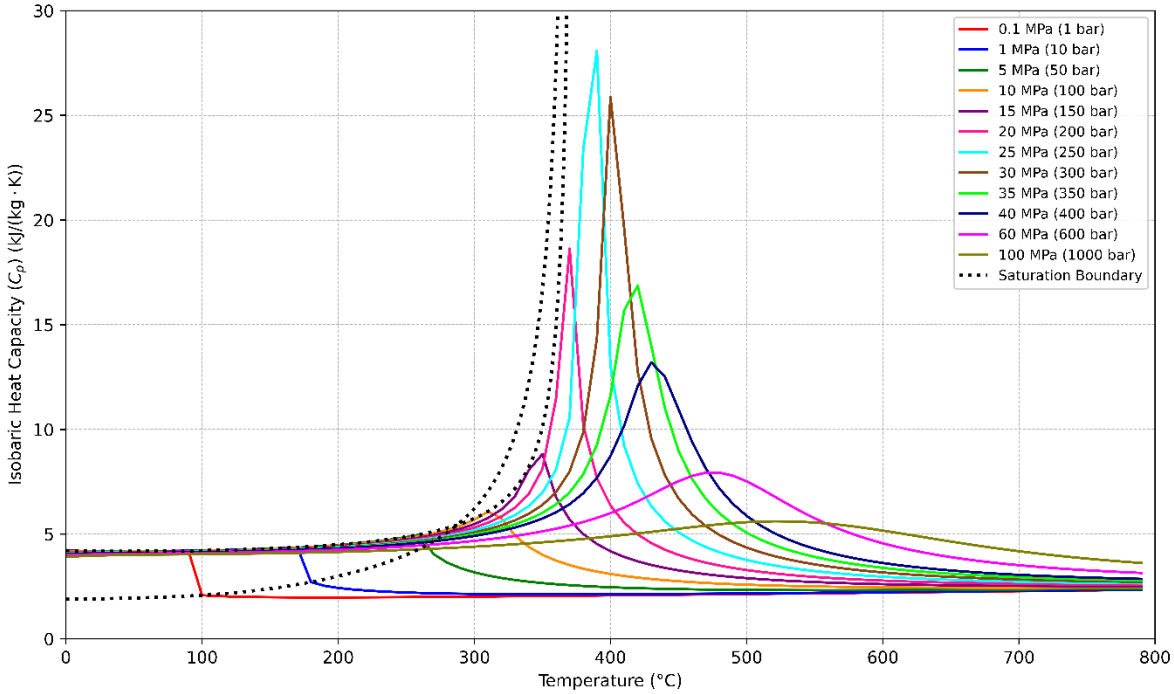


Figure 1: Isobaric Heat Capacity (C_P) of water as a function of temperature for constant-pressure lines (Bell et al., 2014).

2. PROPOSED HYPOTHESIS IN RELEVANCE TO SUPERCRITICAL GEOTHERMAL SYSTEMS

In supercritical geothermal systems, depressurisation occurs within the reservoir as fluid flows towards the production well (DiPippo, 2016; Korzani et al., 2019). Owing to its high compressibility, supercritical water undergoes significant volumetric expansion during pressure reduction. The expansion work is supplied by the fluid's internal energy, resulting in substantial expansion cooling. This behaviour is strongly influenced by the thermal expansion coefficient (α), which increases sharply near the critical point, making the cooling effect considerably greater than that observed in nearly incompressible subcritical liquid water (Friðleifsson et al., 2014; Scott et al., 2017; Xu et al., 2020).

As this rapid cooling occurs, a temperature difference may develop between the fluid and the surrounding hotter rock. This localised thermal gradient allows the reservoir rock matrix to act as a distributed thermal buffer, transferring heat back into the expanding fluid (Magnusdottir & Finsterle, 2015). This mechanism is physically robust because the rock matrix stores the vast majority, approximately 95% to 99.92%, of the total thermal energy in supercritical systems (Suárez-Arriaga, 2019).

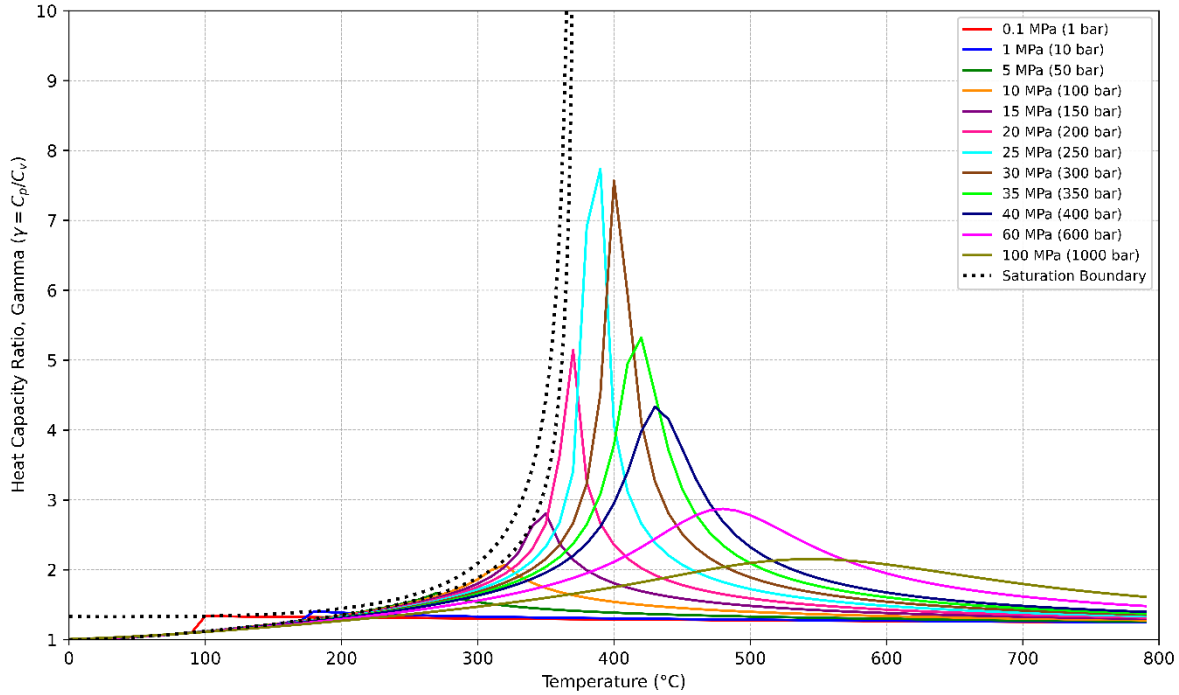


Figure 2: Heat capacity ratio (γ) of water as a function of temperature for constant-pressure lines (Bell et al., 2014).

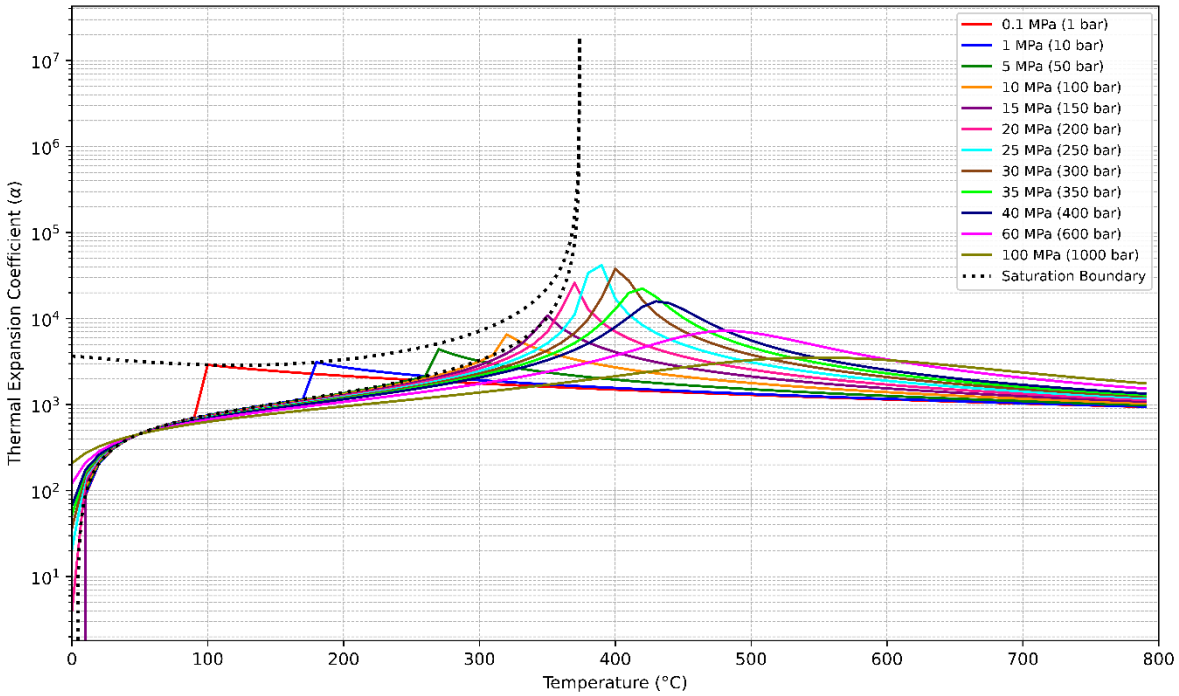


Figure 3: Thermal expansion Coefficient (α) of water as a function of temperature for constant-pressure lines (Bell et al., 2014).

If thermal energy is supplied from the surrounding rock, the thermodynamic path during depressurisation may differ from the conventional adiabatic interpretation, which assumes no heat exchange and results in maximum temperature decline . (Friðleifsson et al., 2014; Scott et al., 2017) Instead, the trajectory follows a heat-supported polytropic process where the degree of enthalpy preservation depends on the thermal support and the location of the pressure drop (Reinsch et al., 2017; Korzani et al., 2019). This forms the hypothesis that thermal support may influence the thermodynamic pathway followed by the supercritical fluid and is illustrated in Figure 4 .

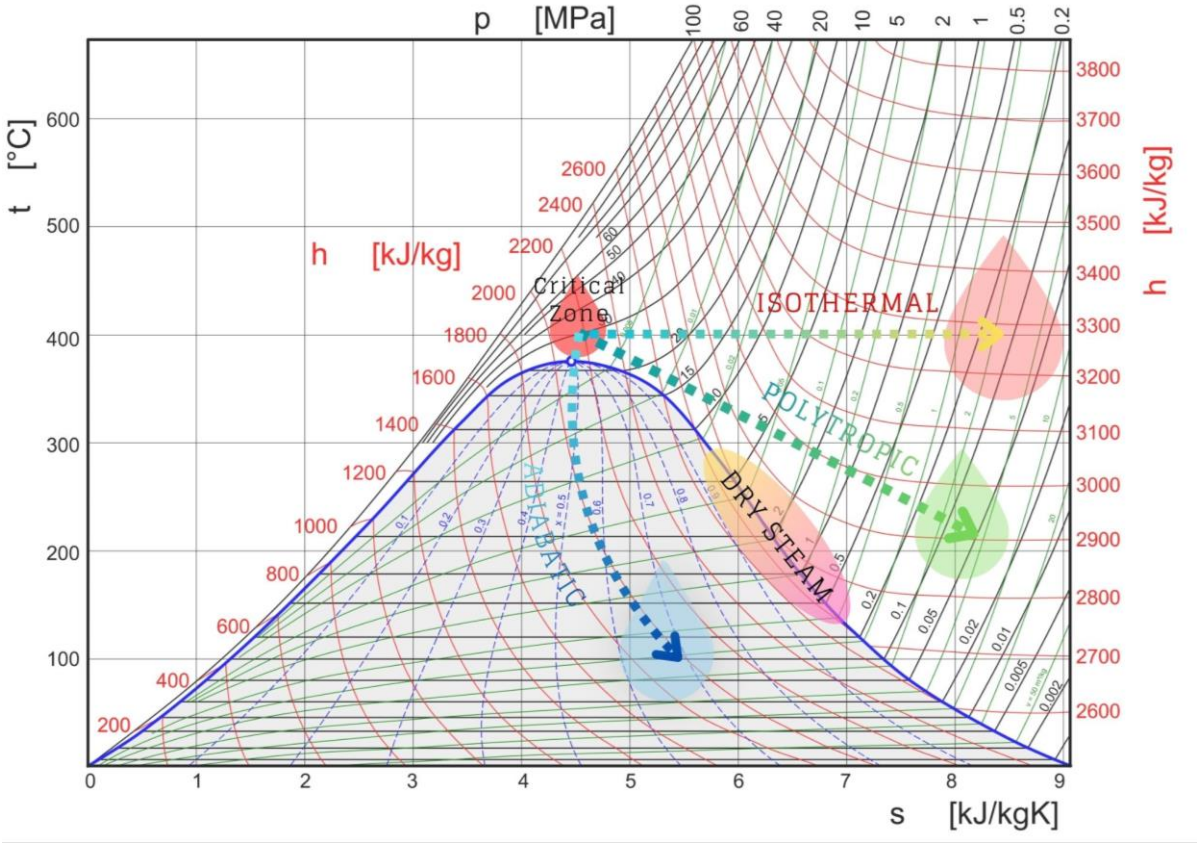


Figure 4: Illustrative Temperature-Entropy (T-s) diagram showing adiabatic, intermediate polytropic, and isothermal depressurisation pathways from an initial supercritical state, highlighting the effects of varying thermal support during fluid expansion (modified after (Kaboldy, 2020)).

3. THERMODYNAMIC FRAMEWORK FOR INTERPRETATION OF THE BEHAVIOUR OF SUPERCRITICAL FLUID UNDER DEPRESSURISATION

The proposed framework interprets the migration and production of supercritical fluids as a path-dependent polytropic process. Unlike conventional ideal-gas models, this framework accounts for the simultaneous, non-linear variations of fluid properties with temperature (T), pressure (P), and volume (V) that occur as a real fluid decompresses while maintaining thermal contact with a surrounding rock matrix of constant heat capacity (C_r). This approach evaluates the fluid's thermodynamic trajectory between the idealised adiabatic (no heat exchange) and isothermal (constant temperature) limits.

The thermodynamic behaviour is described using the derived governing relationship for a single-phase supercritical fluid.

$$\frac{dT}{dP} = \frac{\alpha\, v\, T}{C_P + C_r\, \omega} \qquad (2)$$

Eq. 2 describes the fundamental thermodynamic interaction between expansion cooling and the combined heat associated with the system. It isolates the exact temperature change (dT) relative to the pressure drop (dP) from its initial state of temperature (T_i) and pressure (P_i), effectively linking the fluid's thermophysical properties such as the thermal expansion coefficient (α) and specific volume (v), with the external thermal support provided by the reservoir rock matrix.

In the proposed relationship, ω is a dimensionless lumped parameter that represents the degree of thermal support provided by the reservoir rock to the expanding geofluid. ω effectively envelopes several complex physical characteristics of the reservoir that dictate heat transfer efficiency: permeability controls the fluid's residence time, where lower permeability restricts migration and increases the duration of fluid-rock interaction (Xu et al., 2020; Feng et al., 2021). Porosity, fracture density, and specific surface area define the geometric architecture of the flow, with denser fracture networks providing greater contact area for energy transfer (Suárez-Arriaga, 2019; Mahmoodpour et al., 2022). Thus, greater thermal support may improve enthalpy preservation while simultaneously limiting fluid mobility.

Finally, the thermal conductivity of the rock matrix determines how efficiently the formation acts as a distributed thermal buffer to replenish the internal energy lost by the fluid during substantial expansion cooling (Suárez-Arriaga, 2019; Mahmoodpour et al., 2022; Wang et al., 2023).

The specific heat capacity of the rock (C_r) is a fundamental property that allows the reservoir to function as a distributed thermal buffer. This is critical because, in supercritical geothermal systems, the rock stores the vast majority of the thermal energy (Suárez-Arriaga, 2019). By combining these hydraulic and thermal factors into a single value ω, determines the fluid's thermodynamic trajectory, shifting it from a cooling-prone adiabatic path towards a high-enthalpy, near-isothermal pathway as thermal support increases.

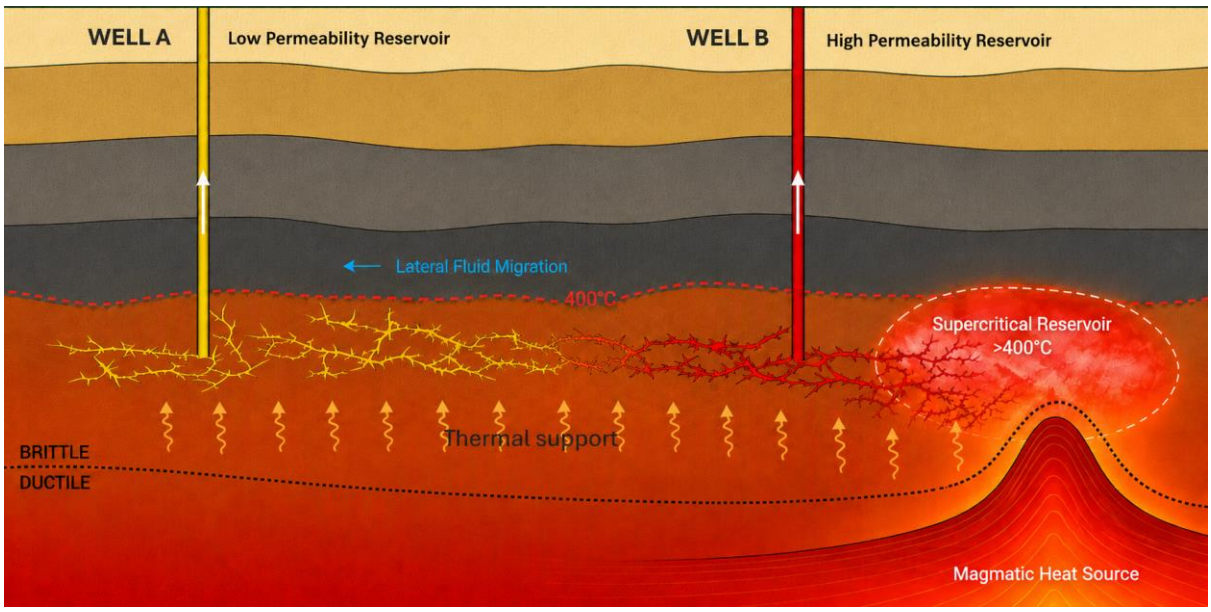


Figure 5: Conceptual illustration of a supercritical geothermal reservoir above a magmatic heat source. Well B is located near the reservoir and exhibits high permeability, whereas Well A is situated farther from the reservoir and has lower permeability. Fluid migration laterally through interconnected fracture networks allows conductive heat transfer from the surrounding rock and provides thermal support.

In the present framework, the wellbore pathway is treated as the adiabatic limit. Under the steady-flow approximation adopted for wellbore ascent, with heat transfer and shaft work neglected, this adiabatic pathway is treated as approximately isenthalpic. In contrast, the reservoir pathway includes heat transfer from the surrounding formation and is therefore represented by a heat-supported polytropic.

3.1. Interpretation of thermal support (ω)

Thermal support modifies the fluid's path-dependent evolution during production:

Adiabatic Limit ($\omega = 0$): Without thermal support, expansion cooling is uncompensated, leading to maximum temperature decline and the likely collapse of the fluid into a low-energy, two-phase mixture of liquid and steam.

Thermally Supported Pathway (Polytropic): As ω increases, the trajectory shifts away from the adiabatic limit toward a near-isothermal pathway. This intermediate state is best described as a quasi-polytropic process.

In this preliminary framework, $\omega = 0$ represents the adiabatic limit, while ω = 10, 20 and 30 represent progressively stronger levels of effective fluid–rock thermal support. These values are used as sensitivity parameters rather than directly measured reservoir properties.

3.2. Computational procedure for the framework

Based on the theoretical framework, a lumped-parameter thermodynamic model is developed to simulate the trajectory of a single-phase supercritical fluid. Rather than spatially discretising the reservoir, the model evaluates the thermodynamic state of fluid at successive equilibrium pressures along the depressurisation pathway (Grant & Bixley, 2011). The framework begins by specifying the initial reservoir pressure (P_i), temperature (T_i), thermal support parameter (ω), and the target wellhead (WH) and well bottom (WB) pressures. Depressurisation is simulated using incremental pressure reductions (dP). At each pressure step, real-fluid thermodynamic properties are obtained from the CoolProp library using the IAPWS formulation for water (Bell et al., 2014). The governing thermodynamic relationship (Eq.2) is solved to update the fluid temperature (T_i+dT), enthalpy (h). The procedure is repeated until the specified well bottom pressure is reached or the fluid enters two-phase, after which the calculations terminate, and the resulting temperature, enthalpy, and thermodynamic trajectories are evaluated.

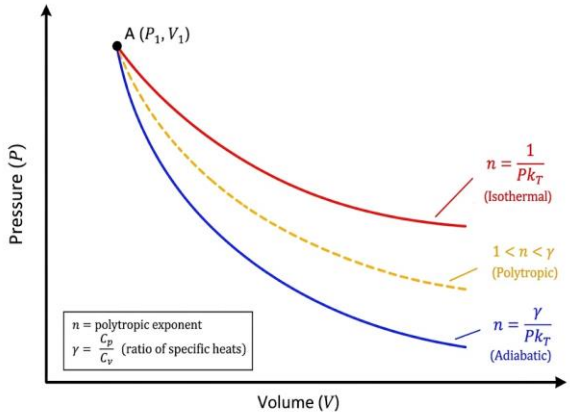


Figure 6: Pressure-volume (*P-V*) diagram showing the idealised isothermal, polytropic and adiabatic depressurisation path and their corresponding exponent limits.

4. RESULTS AND DISCUSSIONS

The proposed framework was applied to investigate the thermodynamic behaviour of supercritical water during depressurisation under different levels of thermal support (ω). The results are presented in Figure 7 to Figure 10 illustrating how thermal support influences temperature evolution,

enthalpy preservation and the resulting thermodynamic pathway.

The flow inside the geothermal well is considered 100% adiabatic (constant enthalpy), with no thermal losses or pressure drop (friction, or acceleration) within the wellbore as the geothermal fluid travels up the well to the surface. This is not entirely accurate, as there will be approximately 50-100 kJ/kg of enthalpy loss in conventional two-phase geothermal wells (Zarrouk & McLean, 2019). A numerical wellbore simulation using supercritical thermophysical water properties will be needed to accurately predict deviations from adiabatic conditions. However, the assumption is valid for this level of assessment. The prescribed pressure reduction from well-bottom to wellhead is retained.

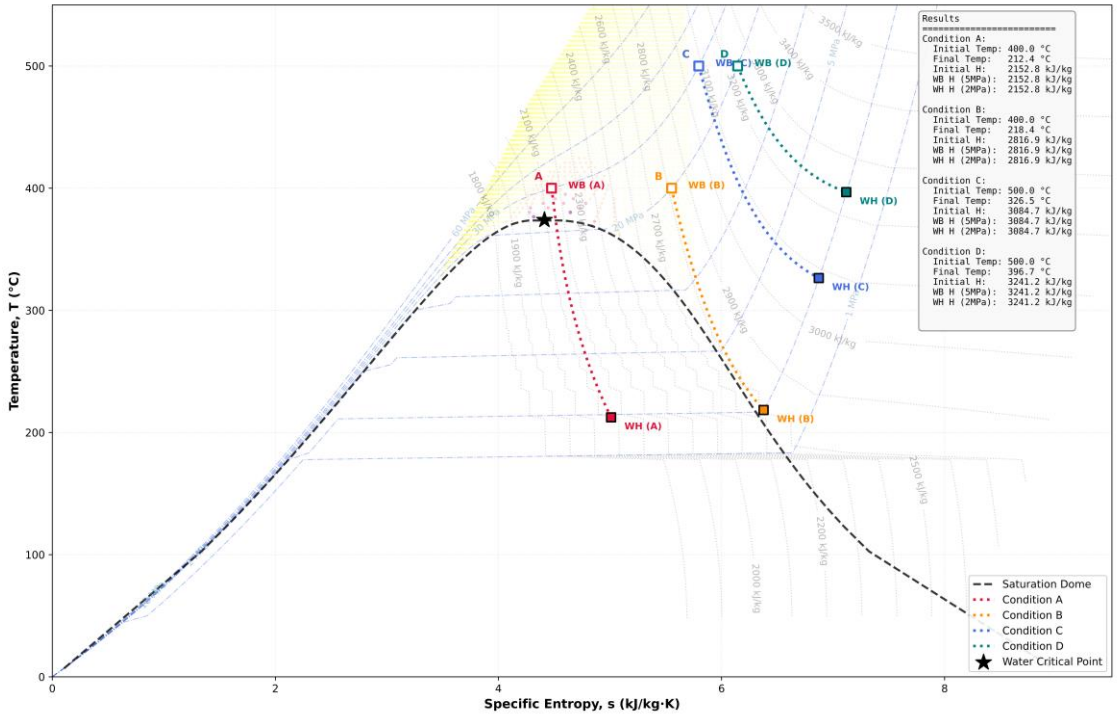


Figure 7: Temperature-entropy (*T-s*) depressurisation trajectories for the adiabatic limit (ω = 0), representing a highly permeable reservoir analogous to Well B. Limited fluid-rock interaction provides no thermal support, resulting in maximum cooling during drawdown.

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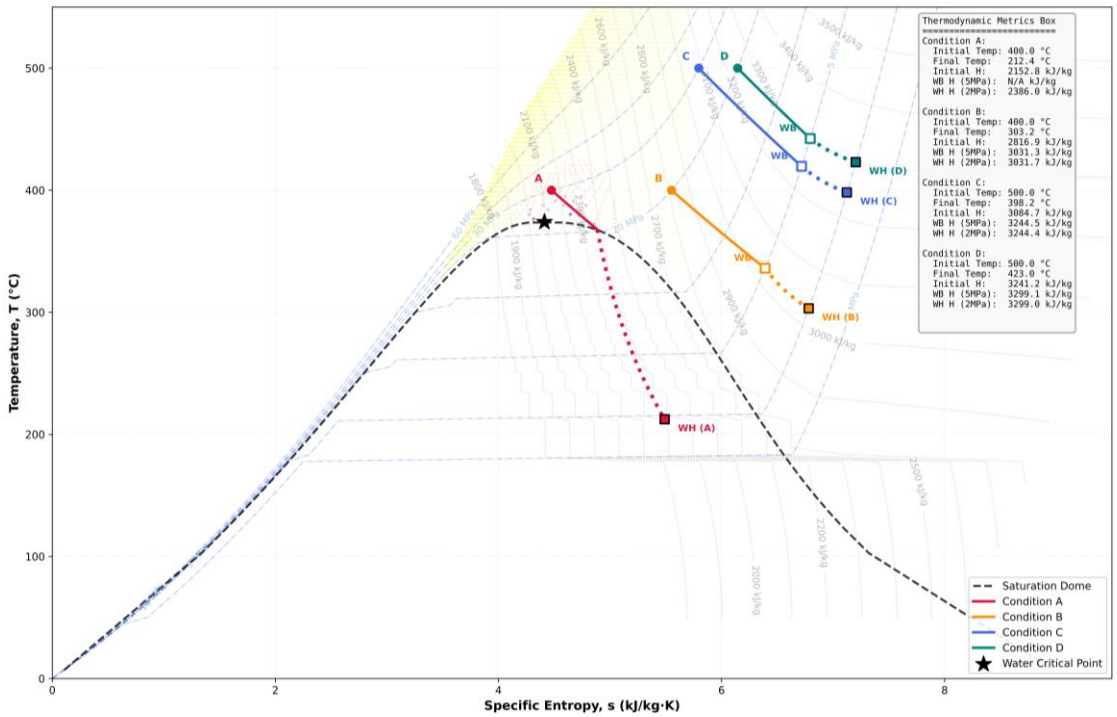


Figure 8: Temperature-entropy (*T-s*) depressurisation trajectories for moderate thermal support (ω = 10), representing intermediate fluid-rock interaction. Heat supplied from the surrounding rock formation partially compensates for expansion cooling, preserving enthalpy and reducing the tendency for phase transition during drawdown.

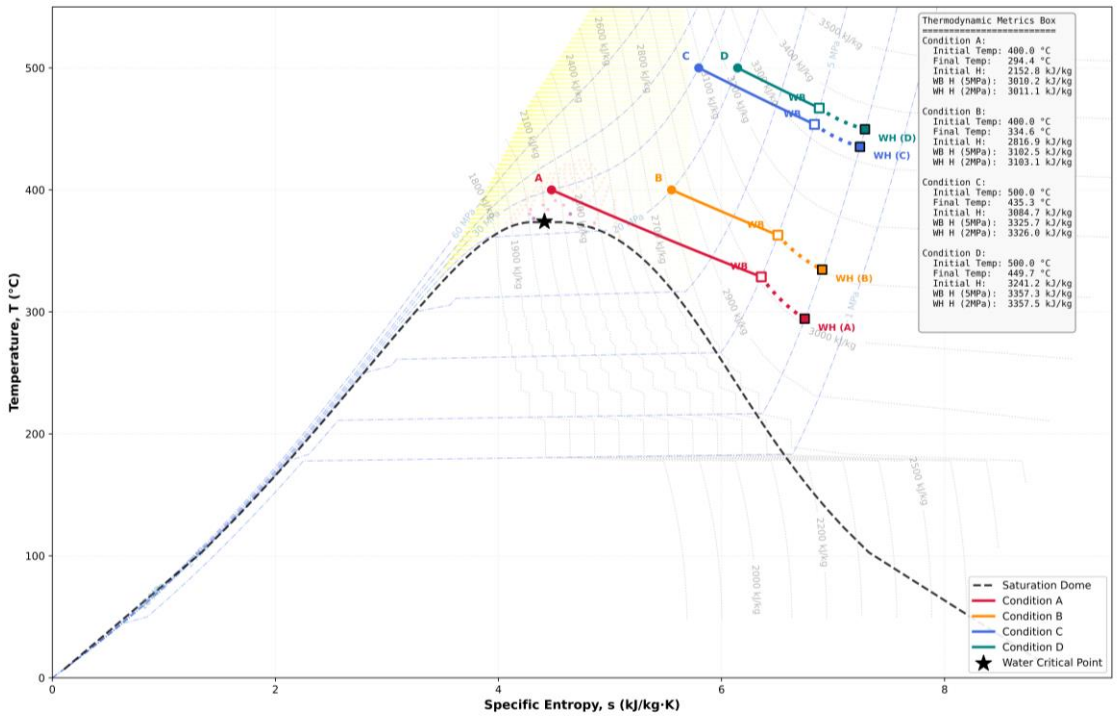


Figure 9: Temperature-entropy (*T-s*) depressurisation trajectories for ω = 20 analogous to Well A with low permeability. Strong thermal support from the surrounding rock preserves fluid enthalpy and shifts the thermodynamic trajectory towards polytropic behavior, allowing all the conditions to remain within the superheated steam region during drawdown.

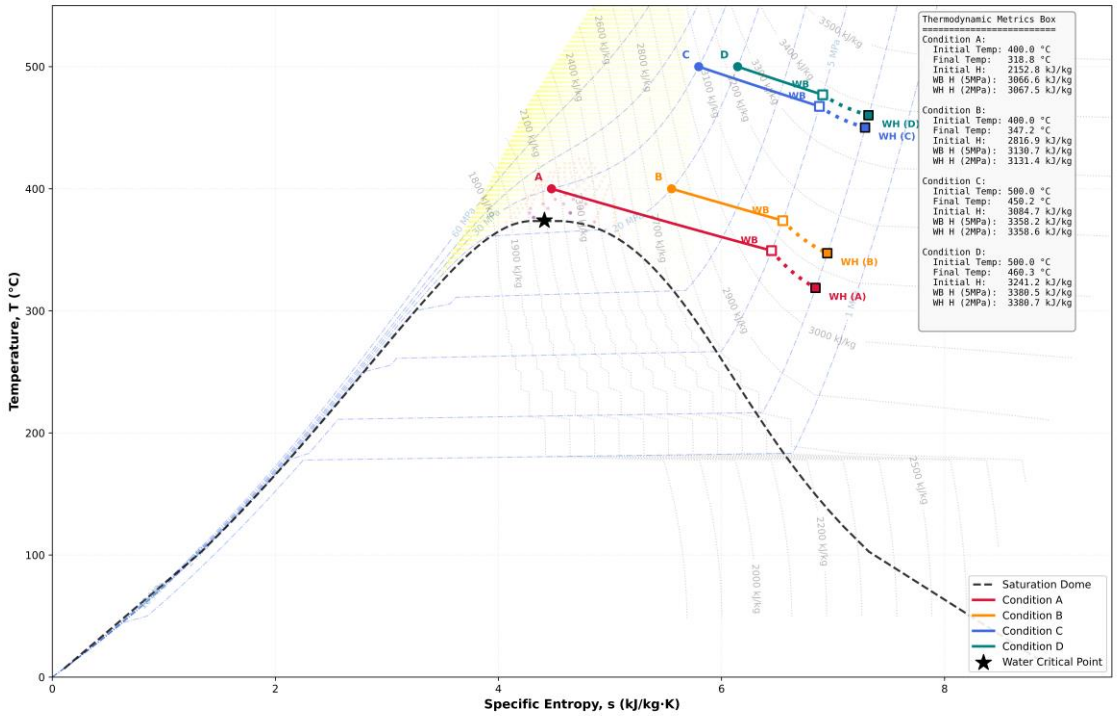


Figure 10: Temperature-entropy (*T-s*) depressurisation trajectories for ω = 30, analogous to an extremely low-permeability well. The surrounding rock acts as an effective thermal buffer, shifting the fluid pathway towards near-isothermal behaviour and maintaining single-phase high-enthalpy superheated conditions throughout drawdown.

Table 1: Initial reservoir conditions and final wellhead thermodynamic properties predicted by the real fluid polytropic model at a fixed wellhead pressure (WHP) of 2 MPa. Increasing the rock-to-fluid mass interaction ratio enhances thermal support (ω > 0), resulting in higher wellhead temperatures and enthalpies.

Cond-itions	Initial *T* (°C), *P* (MPa), *h* (kJ/kg)	Final (ω =0, WHP = 2 MPa)		Final (ω =10, WHP = 2 MPa)		Final (ω =20, WHP = 2 MPa)		Final (ω = 30, WHP = 2 MPa)	
		T (°C)	*h* (kJ/kg)	*T* (°C)	*h* (kJ/kg)	*T* (°C)	*h* (kJ/kg)	*T* (°C)	*h* (kJ/kg)
A	400, 30, 2152.8	212.4	2152.8	212.4	2386.0	294.4	3011.1	318.8	3067.5
B	400, 20, 2816.9	218.4	2816.9	303.2	3031.7	334.6	3103.1	347.2	3131.4
C	500, 30, 3084.7	326.5	3084.7	398.2	3244.4	435.3	3326.0	450.2	3358.6
D	500, 20, 3241.2	396.7	3241.2	423.0	3299.0	449.7	3357.5	460.3	3380.7

The results obtained using the proposed framework Table 1 are consistent with the developed hypothesis. As thermal support increases, the framework predicts a progressive reduction in expansion cooling, accompanied by greater enthalpy retention and a corresponding shift in the thermodynamic pathway. These trends indicate that, when thermal support is available during depressurisation, the thermodynamic behaviour of supercritical water may differ from the conventional adiabatic interpretation.

Figure 7 & 8 and Table 1 clearly show that for the 400 °C initial condition and high pressure (> 30 MPa), the high-permeability case with limited thermal support undergoes greater cooling during depressurisation and approaches the two-phase region, which would require conventional steam–water separation before power conversion. In contrast, the low-permeability case, represented by greater thermal support in the present framework (Figure 9 & 10), maintains a higher-temperature, higher-enthalpy fluid at the same initial temperature and pressure (Table 1), reducing the tendency towards phase separation. However, greater thermal support does not necessarily translate into higher power output, as increased fluid–rock interaction may be accompanied by reduced fluid mobility and mass flow. Similarly, the higher-pressure cases exhibit greater cooling under adiabatic depressurisation because of the larger pressure reduction to the specified wellhead condition. Thus, the results demonstrate that initial thermodynamic conditions and the

degree of thermal support strongly influence the temperature and enthalpy retained during depressurisation, rather than establishing an optimum reservoir pressure or permeability. Well A, analogous to a lower-permeability pathway, may enhance fluid enthalpy retention through greater thermal support; however, the resulting production performance depends on the balance between enthalpy, mass flow rate, and power-conversion efficiency.

The proposed framework is limited to the thermodynamic evolution of supercritical water during depressurisation. It does not explicitly resolve spatial fluid flow, heat transport, or coupled reservoir processes and is therefore not intended to represent the complete behaviour of a geothermal reservoir or production well. Instead, the framework provides a thermodynamic basis for evaluating how thermal support modifies the depressurisation pathway and the resulting temperature and enthalpy of the fluid.

5. SIGNIFICANCE OF THIS HYPOTHESIS

Enthalpy preservation is the primary engineering objective in supercritical geothermal production, aimed at maintaining the geofluid in a high-energy, single-phase state as it migrates from the reservoir toward the wellhead (Magnusdottir & Finsterle, 2015; Friðleifsson et al., 2020). It is fundamentally challenged by the depressurisation process required to drive fluid flow from the deep reservoir (DiPippo, 2016; Friðleifsson et al., 2020). If the production follows an adiabatic trajectory (no heat exchange), the fluid may "collapse" or condense into a lower-energy, two-phase mixture (Friðleifsson et al., 2014; Scott et al., 2015). Such phase separation is detrimental because it reduces fluid mobility due to relative permeability effects and lowers the accessible energy contained in the pore space (Scott et al., 2015, 2017; Friðleifsson et al., 2020).

To achieve effective enthalpy preservation, the fluid must receive thermal support from the surrounding reservoir rock matrix (Scott et al., 2017; Friðleifsson et al., 2020). The rock functions as a distributed thermal buffer, transferring heat back into the expanding fluid to partially or fully offset the energy consumed by expansion work (Suárez-Arriaga, 2019). In systems where intrusions are deep enough to maintain high pressures, heat transfer is maximised through condensation-driven advection, which can be hundreds of times more efficient than conduction alone (Scott et al., 2017). By preserving single-phase high wellhead enthalpy, operators maximise exergy (available power) while avoiding operational hazards such as silica scaling, corrosion, and reduced well productivity associated with two-phase flow (Reinsch et al., 2017; Suárez-Arriaga, 2019; Friðleifsson et al., 2020).

The results of this analytical framework demonstrate that the thermodynamic pathway followed during production is controlled not only by the magnitude of the pressure reduction but also by the location where it occurs.

6. CONCLUSIONS AND SCOPE FOR FUTURE STUDY

This study presented a conceptual analytical thermodynamic framework to investigate the depressurisation behaviour of supercritical fluid under varying levels of thermal support. The framework provides a thermodynamic interpretation of how thermal support may influence the evolution of temperature and enthalpy, and the thermodynamic pathway during pressure reduction, offering a contrasting perspective to the conventional adiabatic interpretation and complementing rather than replacing existing geothermal reservoir simulation approaches. The lumped approximation of fluid–rock interaction makes it suitable for assessing limiting thermodynamic pathways, while detailed prediction of reservoir and well performance requires further coupling with spatially resolved reservoir and wellbore models. By varying the parameters associated with the thermal support parameter (ω), the thermodynamic behaviour predicted by the framework will be compared with coupled numerical simulation results. This comparison will be used to estimate the reservoir parameters associated with the thermal support parameter (ω) and the possible mass flow rate from the well for different values of ω.

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