Supercritical Well Performance Simulation using GFlow Wellbore Simulator: A Case Study of Ultra-hot IDDP Wells in Iceland

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ABSTRACT

Wellbore modelling was undertaken to forecast production output of wells with feeds accessing supercritical fluids and to characterize the fluid flow and energy at the wellhead. This paper exhibits the use of the GFlow wellbore simulator developed by GNS Science and GERD to demonstrate its supercritical capability, handling high temperature and pressure fluid, for data calibration and well output estimation.

Data from IDDP wells drilled in Iceland were used to conduct wellbore calibration and output forecasting. Well flow testing data from IDDP-1 undertaken between 2010 and 2012, and well IDDP-2 injection test carried out in 2017 were investigated to determine the productivity and potential well output at the given reservoir conditions. The resulting flow conditions at the wellhead are then presented and analysed.

1. INTRODUCTION

The start of the Deep Vision project in 2000 led to the initiation of the deep drilling in Iceland, targeting the supercritical reservoir deeper than 3000 m to access heat and fluid with temperature and pressure of more than 374ºC and 220 bar, respectively. Two deep wells were already drilled, one in Krafla (IDDP-1) and another in Reykjanes area (deepening of RN-15), to gather geoscientific information on the deep formation and to investigate the economic feasibility of extracting fluid from the supercritical reservoir. The research and drilling of wells in Iceland are influenced by the theoretical simulation assessment done by Albertsson et al. (2003), which indicated a potential 50 MWe electrical output from a supercritical well, surpassing the 5 MWe output of a steam well in Iceland's geothermal field.

Wellbore modeling is done to numerically represent the flow of heat and mass within the wellbore from the reservoir to the surface. It has been an essential tool for calibration and forecasting, improving the match between the model and real-world condition. Calibration involved adjusting reservoir and well parameters to match physical data measured in the field. With an accurately modeled well, forecasting was then performed to estimate the well's output under specific well and reservoir conditions and to predict future performance.

Numerous wellbore simulators have been developed and are continuously being improved to adapt to technological progress and advance geothermal research. In this study, the GFlow wellbore simulator developed by GNS Science and GERD (Kato et al., 2015) was employed to calibrate the deep wells drilled in Iceland as this simulator can perform calculations at supercritical conditions. Furthermore, this simulator was utilised to estimate the potential production output of these wells.

2. GFLOW WELLBORE SIMULATOR

GFLOW is a simulator that models the steady flow of a multi-phase fluid in a geothermal well. The fluid can be a mixture of water, CO_2 and NaCl.

In GFLOW the conservation equations for momentum and energy are solved numerically. Using radial averaged variables such as pressure and temperature, the equations become.

$$\frac{dP}{dL} = g\rho_m \cos\alpha - \frac{f_m v_m^2 \rho_m}{2d} - \rho_m v_m \frac{dv_m}{dL} \qquad (1)$$

$$\frac{dH}{dL} = g\cos\alpha - v_m \frac{dv_m}{dL} - Q/w \qquad (2)$$

where L is the distance along the wellbore from the surface, P is the pressure, H is the fluid enthalpy, g denotes the gravitational constant, ρ_m is the fluid density, α is the angle of wellbore inclination, f_m the friction factor, v_m the mixture velocity, d the wellbore diameter, Q the heat exchange between the well and reservoir and w the mass flow rate. Details of these variables and equations can be found in Hasan and Kabir (2002).

The friction factor and the holdup (also pressure drop) correlation need to be chosen from a number of different models, e.g., Hasan & Kabir, 2010, Hasan & Kabir, 2002, Ansari et al., 1994, Aziz et al., 1972, Duns and Ros, 1963, and Orkiszewski, 1967. GFLOW implements many of these correlations, including the drift flux correlation, specifically developed to handle pressure drop calculation for a highly deviated well (Kato et al., 2015). Note that the holdup correlation is only required when two-phase conditions occur.

The mass flow rate is conserved in the wellbore, except at feedzones where mass can be exchanged with the reservoir. A linear relationship exists between the feed flow and the difference between the wellbore and reservoir pressures:

$$w = PI\left(\frac{k_{rl}\rho_l}{\mu_l} + \frac{k_{rv}\rho_v}{\mu_v}\right)(P - P_{reservoir})$$

where the subscripts l and v denote the liquid and vapour phases, k_r is the relative permeability and μ is the dynamic viscosity. The quantity PI (often called a productivity index) is a parameter that needs to be estimated during the model calibration.

The thermodynamic properties of the fluid are required to undertake the calculations involved. These properties are calculated by combining formulations for pure water (IAPWS-IF97, 2007), NaCl solutions (Driesner et al., 2007a and 2007b) and CO_2 mixtures (Mao et al., 2010). The IAPWS97 formulation for water allows temperatures up to 800°C with pressures up to 1000 bar to be considered and also temperatures up to 1000°C with pressures up to 500 bar. For single-phase fluids, the variables used were pressure, temperature, NaCl and CO_2 mass fractions. From these variables a pseudo-partial pressure for CO_2 was calculated and the fluid phase was tested. The various thermodynamics properties were then calculated for the appropriate mixture of components.

For sub-critical two-phase fluids the variables were pressure, temperature, NaCl mass fractions and vapour volume fraction. From these variables, the CO_2 partial pressure was calculated as the difference between the pressure value and the saturation pressure of a brine solution at the given temperature. Then the properties of liquid and vapour phases were calculated using the appropriate mixture of components.

Equations (1) and (2) are solved using a Runge-Kutta method of the 4th and 5th order (Butcher, 1996). This allows integrating both up and down the wellbore, so both production and injection can be modelled.

3. SUPERCRITICAL WELLBORE SIMULATION

This study utilises a standard approach for wellbore modeling and simulation, which is commonly used in other research works. The initial step involves developing a wellbore conceptual model based on data obtained from the well and reservoir. Key information such as well tracks, wellhead parameters, and feedzone parameters are identified.

The GFlow simulator offers three solving capabilities: solving from the bottom using feedzone parameters, solving from the wellhead considering surface conditions, and generating output curves to estimate flow at various wellhead pressures.

Certain assumptions were made during the wellbore simulation, which are as follows, unless explicitly stated in the case study:

- The fluid is considered to be pure water.
- Thermal losses through heat transfer from the wellbore to the formation are accounted for using the approach from Hasan and Kabir 2002., With thermal conductivity of 2.56 W/m-K and heat capacity of 800 kJ/kg. The heat transfer timescale is set at 10^7 seconds (about 115 days).
- The casing roughness was set to 0.5 mm and the slotted/ perforated liner roughness set to 0 m as the convention for wellbore simulation.

Details of the fluid state condition, wellbore configurations, and reservoir parameters used in the simulations are described in the sections of the case study that follows.

4. WELLBORE SIMULATION CASE STUDY

4.1 Well IDDP-1

The first well IDDP-1 of the Iceland Deep Drilling Project was successfully drilled in 2009. Its primary objective was to explore supercritical fluid conditions in the Krafla field at a depth of 4500 m. However, while drilling, a layer of magma was unexpectedly encountered at a shallower depth, causing the drilling operation to stop at a vertical depth of only 2096 m. Consequently, the actual depth reached fell significantly short of the intended target, and despite encountering high temperatures, the pressure remained insufficient to attain supercritical conditions.

The well was completed with a 9 5/8" production casing to 1949 m and a 9 5/8" slotted liner down to the 2077 m, which was integrally connected to the production casing as shown in Figure 1. Details are presented in Friðleifsson et al. (2015) and Pálsson et al. (2014).

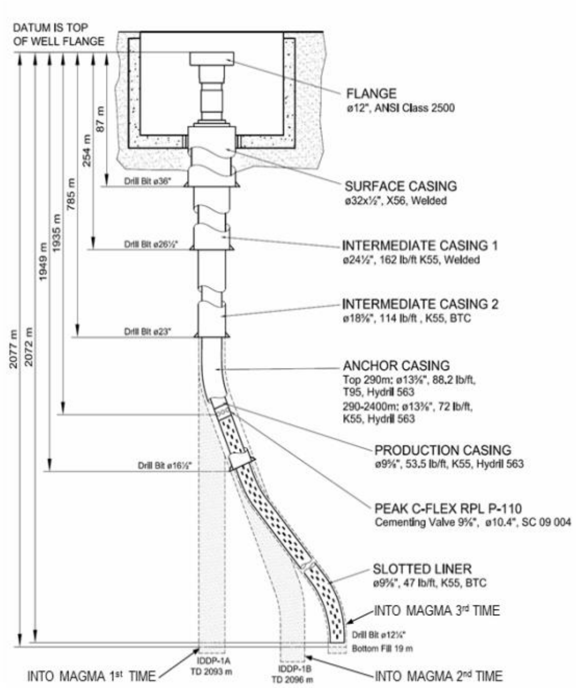

Figure 1: IDDP-1 well casing profile drawing (as built) (Friðleifsson et al. 2015).

After undergoing a continuous heating for more than seven months, the well was discharged intermittently between March 2010 and July 2012 as part of five discharge testing phases. Initially, the discharge exhibited subcritical two-phase behavior transitioning to superheated steam after flowing for a period of 17 days. The highest recorded mass flow rate was approximately 50 kg/s, with an enthalpy approaching 3200 kJ/kg. During 2011, the discharge from the well was measured under various wellhead opening conditions, enabling the development of a bore output curve.

4.1.1 IDDP-1 Wellbore Model

The wellbore model was constructed based on the information on the well configuration and reservoir condition discussed in Friðleifsson et al. (2015) and Ingason et al. (2014). A detailed discussion of the simulation and results are presented in Rivera and Carey (2023).

The well model set the feedzone at a vertical depth of 2100 m, with a reservoir pressure of 180 bar and a temperature of 470°C. A 9 5/8" casing was set from the feedzone to the wellhead with a roughness of 0.5 mm. Thermal energy loss from the wellbore to the formation was accounted for, with a formation temperature profile taken to be boiling-point-for-depth from the surface down to 2100 m.

4.1.2 IDDP-1 Discharge Test Calibration

A bottom-up simulation was conducted using GFlow to match the discharge data of the well (Ingason et al., 2014). A reservoir to well productivity index of 2.9×10^{-12} m^3 was selected to achieve the best wellbore model match as shown in Figure 2 and Figure 3. This productivity index is comparable to the productivity indices calculated from the production of subcritical Icelandic wells (Rutagarama, 2012).

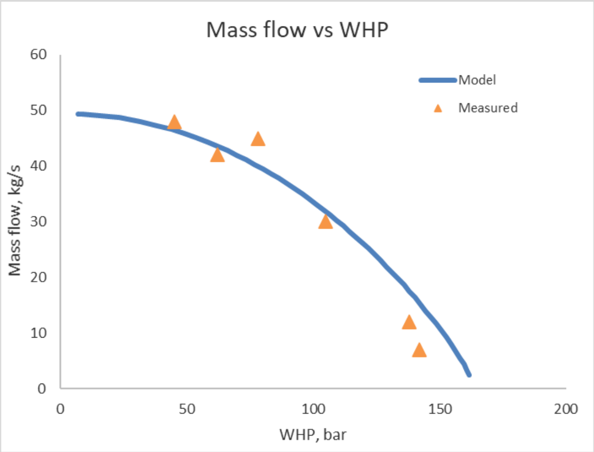

Figure 2: Simulated IDDP-1 mass flow rate (blue curve) compared to measured data (triangles)

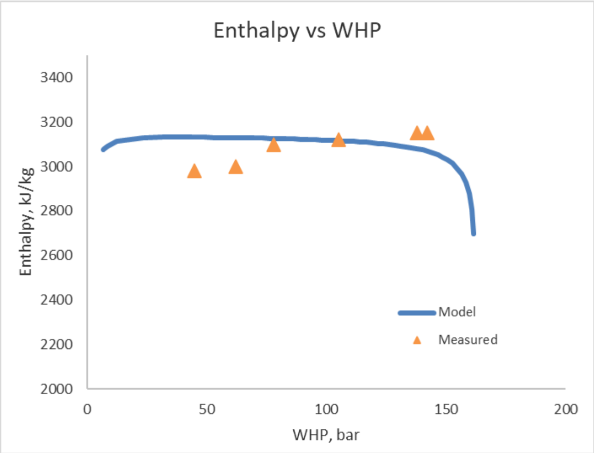

Figure 3: Simulated IDDP-1 enthalpy (blue curve) compared to measured data (triangles)

Figure 4 illustrates the wellhead velocity profile calculated by GFlow under various wellhead conditions. A noticeable observation is that as the wellhead pressure decreases, the fluid velocity increases. This velocity factor becomes crucial in determining the minimum viable operating wellhead pressure due to the potential erosion risks if any particulate matter is present in the flow stream.

According to Ingason et al. (2014), operating the 9 5/8" well with a flow rate of 50 kg/s of superheated steam could lead to erosion at the wellhead, recommending well operation at flow rates lower than 40 kg/s. The simulation shows that at a wellhead pressure of 30 bar, a temperature of approximately 350°C, the flow rate of 50 kg/s corresponds to a velocity of around 80 m/s. The selection of casing and wellhead materials, as well as site-specific considerations of the reservoir, will influence and restrict the suggested fluid velocities at the wellhead.

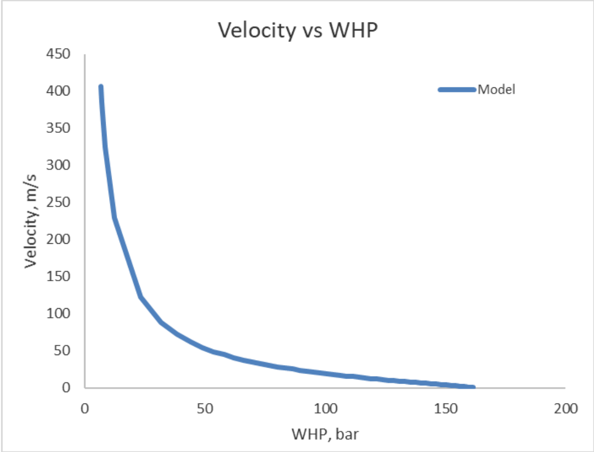

Figure 4: Simulated fluid velocity at the wellhead across a range of wellhead pressure.

4.2 Well IDDP-2

IDDP-2 is considered the deepest well drilled in Iceland which was completed late January of 2017. It was drilled in the Reykjanes area by deepening the existing geothermal well RN-15 to access the supercritical reservoir at depths exceeding 4 km. The well successfully obtained its objective by reaching a measured depth of 4659 m (approximately 4500 m vertical depth) with temperature and pressure readings of 426°C and 340 bar, respectively, obtained from measured logs. Moreover, good indications of permeability were found at this depth.

Well RN-15 has an original depth of 2500 m, and was drilled further down to set the production casing at 3000 m. A 7" production liner was then installed with perforation spanning from 3130 m down to 4500 m, while remaining barefoot down to the bottom. Detailed information about the drilling process and reservoir conditions can be found in the works by Stefansson et al. (2017).

Throughout the drilling and heat-up phase of the well, numerous temperature and pressure logs were recorded. Although stable reservoir temperature and pressure were not achieved during these measurements, they have proven highly valuable in characterising the conditions of the deep supercritical reservoir.

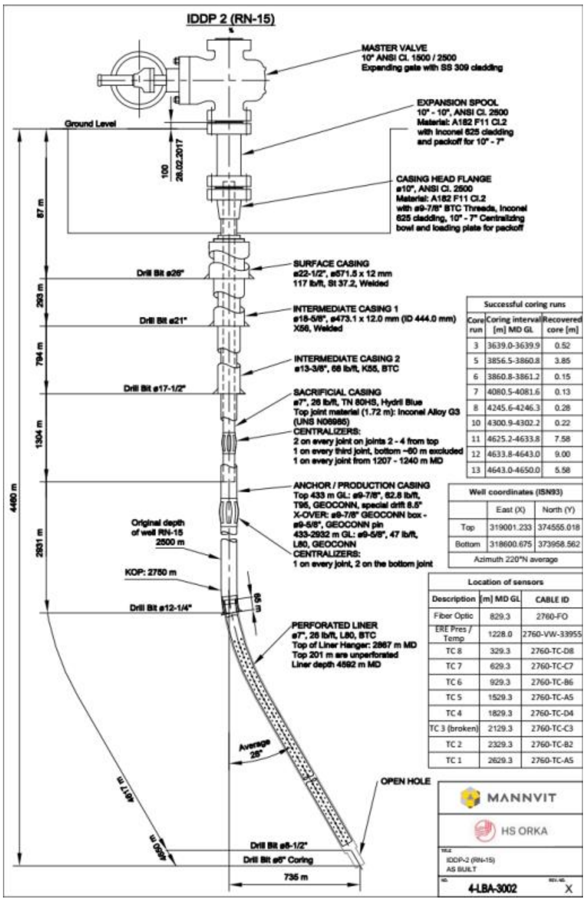

Figure 5: IDDP-2 well casing profile drawing (as built) (Stefansson et al., 2017).

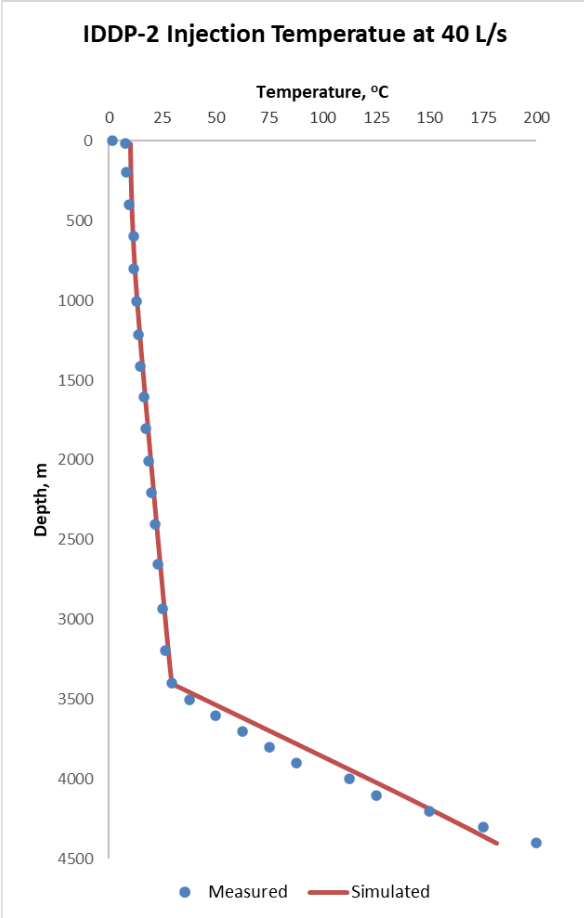

Figure 6: IDDP-2 Calibration: measured injection temperature at 40 L/s (blue circles) and simulated temperature (red line).

4.2.1 IDDP-2 Calibration using Injection Temperature

The wellbore model follows the well profile and reservoir parameters described in the works of Sæther (2020) and Friðleifsson and Elders (2017).

The well model consists of three feedzones located at depths of 2300 m, 3400 m, and 4400 m. Calculation is initiated using the parameters at the feedzones with the fluid thermodynamic properties computed up the wellbore. The well configuration has a 9 5/8" casing set from the surface to 3000 m, with a 7" sacrificial casing from the surface to 1300 m. Beyond that, a 7" perforated liner is used until reaching the bottom feedzone. To account for thermal energy loss, the estimated formation temperature from Hokstad and Tanavsuu-Milkeviciene's work in 2017 is considered.

Through the simulation, the model is calibrated to match the temperature measurements while injecting water at a rate of 40 L/s and a temperature of 10ºC. Figure 6 displays the result of the calibration match. The productivity index (in m^3) is estimated which represents the fluid flow in the permeable zones, and the injectivity index per feedzone is also calculated based on the simulation, as presented in Table 1.

Table 1: Calculated productivity index and injectivity index per feedzone from injection temperature calibration.

Feedzone Depth, m	Productivity Index, m^3	Injectivity Index, L/s/bar
2300	1.36×10^{-13}	0.013
3400	3.27×10^{-12}	0.356
4400	2.85×10^{-14}	0.017

4.2.2 IDDP-2 Production Output Estimation

The productivity indices obtained from the calibration process were utilised in conducting a well flow simulation for the IDDP-2 deep well. The main purpose of this simulation was to assess the flow performance and to estimate the potential well output once it reached its fully heated state and was ready for discharge. Although this estimation may not perfectly represent the output, it serves as a valuable indicator of the well's flow performance.

The same well model was used, featuring three different feedzones for production. The reservoir pressure was calculated assuming hydrostatic conditions, accounting for depth and water density, starting from the water level at 540 m (Sæther, 2020). These profiles were used to assign the appropriate reservoir parameters to each feedzone.

The simulation results are shown in Figure 7 and Figure 8, illustrating the output and enthalpy curves at various wellhead pressures, respectively. The maximum production flow rate of the well was around 30-60 kg/s when operated between 50-100 bar wellhead pressure and can be at maximum of 75 kg/s at 10 bar. Additionally, the enthalpy of the fluid ranged from 1800 to 1900 kJ/kg, indicating a two-phase state of the fluid. This is because the well is assumed to produce mainly from the 3400 m feedzone with temperature of 370°C and pressure of 227 bar. The enthalpy at saturation in this condition is around 1825 kJ/kg. However, pressure drawdown can be experienced within the vicinity of the well during operation, which may cause the pressure to lower, and the fluid saturation increases which may lead to production of saturated or superheated steam at the feedzone.

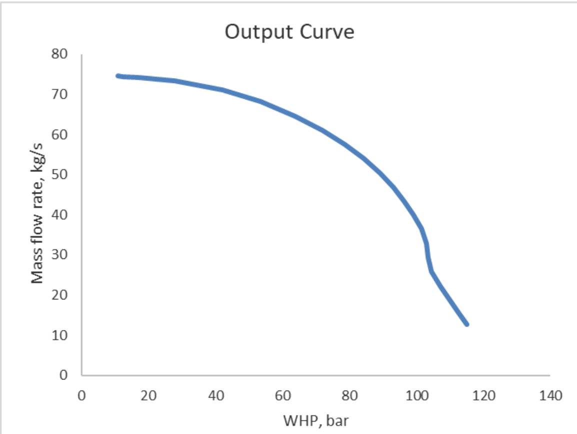

Figure 7: Simulated IDDP-2 mass flow rate across range of wellhead pressures.

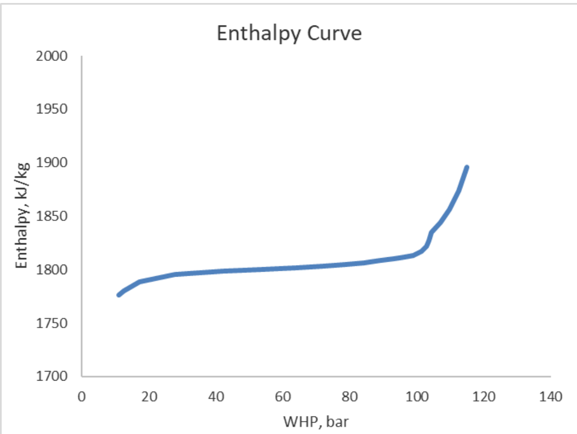

Figure 8: Simulated IDDP-2 wellhead enthalpy across range of wellhead pressures.

5. CONCLUSION

GFlow wellbore simulator was successfully used to implement wellbore modelling and simulation of well producing supercritical fluid for calibration and output estimation.

As shown in the case study, the supercritical capability of the GFlow simulator handled discharge test and injection calibration, as well as the output estimation with feedzones of temperature and pressure at supercritical condition.

REFERENCES

Albertsson A., Bjarnason J.O., Gunnarsson T., Ballzus C., Ingason K.: Iceland Deep Drilling Project: Part III - fluid handling and evaluation. *IDDP Feasibility Report III*. 32p. (2003).

Ansari, A. M., Sylvester, N. D., Sarica, C., Shoham, O., and Brill, J. P.: A Comprehensive Mechanistic Model for Upward Two-Phase Flow in Wellbores. *SPE Production & Facilities*, 143–165, May (1994).

Aziz, K., Govier, G., and Fogarasi, M.: Pressure Drop in Wells Producing Oil and Gas. *Journal Canadian Petroleum Technology* 4, 38–48. (1972).

Butcher, J.C.: A history of Runge-Kutta methods. *Applied Numerical Mathematics. Volume 20, Issue 3*. Pages 247-260. (1996)

Duns, H., and Ros, N. C. J.: Vertical Flow of Gas and Liquid Mixtures in Wells. *Proc. 6th World Petroleum Congress*. Section II, Paper 22–PD 6, Frankfurt Am Main, Germany, pp. 451-465, (1963).

Driesner, T and Heinrich, C.A.: The system H2O–NaCl. Part I: Correlation formulae for phase relations in temperature–pressure–composition space from 0 to 1000 °C, 0 to 5000 bar, and 0 to 1 XNaCl. *Geochimica et Cosmochimica Acta*. 71 Issue 20:4880-4901. (2007a).

Driesner, T.: The system H2O–NaCl. Part II: Correlations for molar volume, enthalpy, and isobaric heat capacity from 0 to 1000°C, 1 to 5000bar, and 0 to 1 XNaCl. *Geochimica et Cosmochimica Acta*. 71 Issue 20: 4902-4919. (2007b).

Friðleifsson G.Ó., Elders W.A., Albertsson A.: The concept of the Iceland deep drilling project. *Geothermics*. 49:2–8. doi:10.1016/j.geothermics.2013.03.004. (2014).

Friðleifsson G.Ó., Pálsson B., Albertsson A.L., Stefánsson B., Gunnlaugsson E., Ketilsson J., Gíslason Þ.: IDDP-1 Drilled Into magma – World's first magma-EGS system created. *Proc. World Geothermal Congress 2015*, Melbourne, Australia. (2015).

Fridleifsson G.O. and Elders W.A.: The Iceland Deep Drilling Project geothermal well at Reykjanes successfully reaches its supercritical target. *GRC Bulletin.* March/April:30–33. (2017).

Fridleifsson G.O. and Elders W.A.: Successful Drilling for Supercritical Geothermal Resources at Reykjanes in SW Iceland. *GRC Transactions.* 42:1095-1107. (2017).

Hasan, A. R. and Kabir, C. S.: Fluid Flow and Heat Transfer in Wellbores. *Society of Petroleum Engineers.* (2002).

Hasan, A. R. and Kabir, C. S.: Modeling two-phase fluid and heat flows in geothermal wells. *Journal of Petroleum Science and Engineering*. *71*(1-2): 77–86. http://doi.org/10.1016/j.petrol.2010.01.008. (2010).

Hokstad K. and Tanavuu-Milkeviciene K.: Temperature Prediction by Multigeophysical Inversion: Application to the IDDP-2 Well at Reykjanes, Iceland. *GRC Transactions:* 41: 1114-52. (2017).

IAPWS-IF97: The International Association for the Properties of Water and Steam: Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam. Lucerne, Switzerland. (2007).

Ingason K., Kristjánsson V., Einarsson K.: Design and development of the discharge system of IDDP-1. *Geothermics*.49:58–65. doi:10.1016/j.geothermics.2013.05.002. (2014).

Kato M., Okabe T., Ujyo S., Takanashi K., Kunzman R.: Development of wellbore simulator and verification test of high temperature PTS+FLUID sampler logging system for a highly deviated geothermal well. *Proc. World Geothermal Congress 2015*; Melbourne, Australia. (2015).

Mao S., Duan Z., Hu J., Zhang D.: A model for single-phase PVTx properties of CO2–CH4–C2H6–N2–H2O–NaCl fluid mixtures from 273 to 1273K and from 1 to 5000bar. *Chemical Geology*. 275 Issues 3–4: 148-160. (2010).

Orkiszewski, J.: Predicting Two-Phase Pressure Drops in Vertical Pipe. *Journal of Petroleum Technology*. 829–838, June (1967).

Pálsson B., Hólmgeirsson S., Guðmundsson Á., Bóasson H.Á., Ingason K., Sverrisson H., Thórhallsson S.: Drilling of the well IDDP-1. *Geothermics*. 49:23–30. doi.org/10.1016/j.geothermics.2013.08.010. (2014).

Rivera, J., Carey B.S.: Comparative Geothermal Well Performance – Supercritical and Subcritical. *GNS Science report, 2023/01*, GNS Science, Lower Hutt, NZ (2023). Retrievable from https://assets.website-files.com/5ee80754caf15981698cc972/640e2cc22c36120414b7731a_SR2023-01%20Supercritical%20Wellbore%20FINAL.pdf

Sæther S.: Estimating Flow Performance of IDDP2/DEEPEGS Well by Introducing Local Injectivity Indexes for Different Reservoir Depths. *Proc. World Geothermal Congress 2020+1*. Reykjavik, Iceland (2020).

Stefánsson A., Gíslason Þ., Sigurðsson Ó., Friðleifsson G.Ó.: The Drilling of RN-15/IDDP-2 Research Well at Reykjanes in SW Iceland. *GRC Transactions* 41:512-522. (2017).

Rutugarama, U.: the role of well testing in geothermal resource assessment. *United Nations University, Geothermal Training Program,* Iceland. (2012).