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Exergy profile analysis by wellbore simulation

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ABSTRACT

This paper presents exergy in the wellbore. Exergy analysis is considered between the wellhead to the reservoir with geothermal brine at saturated conditions. The field data input parameters were wellhead pressure, mass flow rates of steam and brine, wellbore diameter, and the reservoir depths (deeper/2nd depth and shallow). The pressure-temperature (PT) profile was simulated using the wellbore model developed in 1988. The exergy profiles estimated feed zone depths of -1000 - (-)2800 m.a.s.l for a directional well. The research investigated liquid-dominated Olkaria Domes wells, OW-901, OW-902 and OW-903A. The profiles predicted convective and conductive heat transfers points. For wellhead temperatures of between 160 and 184°C, the reservoir temperatures from the wellbore simulator are high at 250°C in OW-913A, and formation pressure is between 3,978 kPa. The formation pressures simulated are between 1,077 to 12,487.9 kPa for wellhead pressure of 459 to 1,720 kPa. The thermodynamic parameters (temperature and pressure) from the wellbore simulator were input parameters in the EES code. The calculated values in EES were entropy, enthalpy, and specific exergy. Exergy wellbore simulation of the geothermal reservoir predicted the geological stratification of the geothermal field. The study demonstrates the importance of connecting the reservoir and wellhead via a wellbore simulation and exergy profiles.

1. INTRODUCTION

This paper will link surface and sub-surface of wells in Olkaria Domes using wellbore simulation, and exergy analysis. The main representative parameters in geothermal energy are temperature and pressure. The wellbore simulator gives the two parameters for further interrogation. The objective is to consider the coupling of the reservoir in Olkaria Domes with a wellbore simulator. The Olkaria Domes reservoir has been modelled and updated as part of the entire Olkaria prospect. Linking the surface and subsurface by exergy concept is performed for Olkaria Domes. For sustainable development of geothermal resources in Kenya, it is vital to model a reservoir that would predict the actual field data. Wellbore simulator gives pressure and temperature results close to the actual field flowing data for some OW-901, OW-902 and OW-903A wells in Olkaria Domes.

The link between the reservoir and the surface is wellbore, delivering the resource for utilisation. In geothermal power plants, exergy analysis has been performed based on wellhead conditions. Faust and Mercer (1979) developed a numerical simulation of geothermal reservoirs using three-dimensional flow composed of partial differential equations posed in fluid pressure and enthalpy.

Liquid-dominated geothermal systems have fluid flowing in the wellbore from the reservoir as compressed water (Itoi et al.). The application of geothermal energy mainly depends on the thermodynamic specification, geographical situation, resources' thermal energy, or electricity (Bina et al.). The evaluation point is at wellhead conditions for energy, exergy, environmental or exergoeconomic analysis. Evaluation at the wellhead would not relate clearly to the source of the geothermal reservoir. Prediction of the life-cycle of the reservoir-power plant is by a conceptual model developed to connect reservoir and power plant using production and reinjection wells (Blöcher et al.).

Available reservoir simulators simplify the wellbore analysis for coupling the reservoir and the surface facilities (Hadgu et al.). In the study to couple of reservoir simulators for steady and Darcy flow, temperature, pressure, and flow rates were considered enthalpy in respect with time (Hadgu et al.). The results of the production test analysis of 29 wells in Olkaria Domes show wells are high temperatures with an average power equivalent of 7.1 MWe per well (Rop). The coupling of heat transfer and fluid flow equations gives pressure drop and temperature change profiles (Hirakawa and Mitsuishi). 3D visualisation of Olkaria Domes shows that one of the up-flow zones is below 914 (Kandie et al.). Wellbore simulator was used to calibrate the suitability of downhole measurements for matching analysis application, and it included impurity content estimation of CO_2 and NaCl (Gunn et al.). Flow data is necessary to analyse and design power plants. Computer modelling has been a standard practice applied in the planning, developing, and managing geothermal fields (O'Sullivan et al.). Wellbore simulation of Hatchobaru power plant, showed that the simulated pressures agreed with actual pressure decline in fluid gathering system (Tokita et al.).

Wellbore radius is usually infinitely small compared to the extent of the geothermal reservoir. Calculating the pressure drop line source solution approximation can be applied and using the superstition concept to determine the effects of boundary conditions by studying pressure distribution in a number of wells (Hussain).

Wellbore profile is mainly a hydrostatic pressure integral from the well bottom to the wellhead. Models have been developed for temperature-pressure profile for a given mass flow rate (both steam and brine), well diameter(s) and depths(s), pipe roughness, and wellhead pressure (Itoi and Zarrouk). The wellbore model is a good indication of the flowing profile of geothermal well/fields, which is difficult to measure in most cases. The model would best be coupled to the reservoir using TOUGH2. It is improved to include the frictional pressure drop and velocity pressure gradient. Analysis of well discharge can be done using the Lip pressure method or separator method (Mubarok et al.; Biru). The Lip pressure method application for the Olkaria Domes field has been recorded and well documented for most wells at different pipe diameters.

Wellbore flows and modelling affect isotherm plots constructed using temperature log data in geothermal field simulation to obtain reliable results (O'Sullivan et al.; Marcolini et al.). Simulation of the flow in geothermal fields is the first step in coupling a reservoir with well-flowing data. In wellbore, temperature calculations, the assumption ignores heat losses between the wellhead and downhole conditions (Grant et al.).
Flashing in the wellbore is the driving force that uplifts the geothermal fluid due to expansion and reduction in hydrostatic pressure (Grant et al.). Wellbore simulation is applied in matching the available down-log data sets. Geothermal systems are complex and involve mass, energy, and transport through a porous medium. The models used in linking wellbore and reservoir have been developed from the oil industry (Gudmundsdottir et al.; Gudmundsdottir). Vertical wellbore assuming isenthalpic flow coupled with the radial horizontal flow with a uniform reservoir thickness shows initial water saturation does not significantly affect steam flow for low wellhead pressure (Khasani et al.). A multi-feed zone wellbore simulator with arbitrary feed zones was used to estimate flow rates and enthalpies of each feed zones during discharge and injection (Bjornsson and Bodvarsson).
Other researchers have simulated wellbore and reservoirs independently. This paper proposes to loop the preceding methods and optimise geothermal resources by coupling reservoir and wellbore by exergy concept.

Table 1: Some of the wells locations and characteristics of the liquid dominated geothermal wells in Olkaria Domes.

Well	KOP (m)	Drilled depth (m)	2nd depth (m)	TVD (m)	Production casing depth (m)
OW-901	-	2199.15	1440.68	2199.15	758.47
OW-902	-	2,201	1552.72	2,201	648.28
OW-903A	400	2,810	2,353	2,782.78	1,197

2. METHODOLOGY AND FLUID FLOW EQUATIONS

The estimated amount of energy stored in the reservoir is delivered for optimisation at the surface via a geothermal well. The quality (exergy) of delivered brine was calculated based on wellhead reference conditions. EES code calculates thermophysical parameters, P, T, h, and entropy.

A wellbore simulator simulates the pressure-temperature profiles of geothermal wells in Olkaria Domes field data. A wellbore model developed by Itoi (1988) used the following assumptions (Itoi et al.; Tateishi et al.):

i. Steady and isenthalpic flow.
ii. Average specific volume for two-phase flow.
iii. Mass flow rate as a boundary condition.
iv. There is no effect of dissolved chemicals and non-condensable gases (NCG) in geothermal brine.

Brine and steam flow rates measured at the wellhead in Olkaria fields were input parameters in the wellbore simulator. The input data measurements are wellhead pressure (bar), flow rates, well diameter, true vertical length (TVD) (shallow/first depth and deep/second depth), and the pipe surface roughness. Directional wells assume a kick-off point (KOP) angle of 20^{o}C to the vertical at depths of 400 m below the wellhead. The second (2nd) depth is between the shallow and the deep reservoir/the total drilled depth. The wellbore simulator gave temperature and pressure profiles and the formation pressure with the available flow rates, wellhead pressure, and wellbore specifications. The obtained parameters and the well log recorded data plotted the reservoir exergy profiles for the wells in Olkaria Domes in the EES code.

Figure 1 shows a simplified mathematical model of a typical geothermal well. The mass, momentum and energy equations 1, 2 and 3, respectively, are the main foundational equations applied in wellbore analysis (Itoi et al.).

$$w = \frac{\dot{m}v}{A} \tag{1}$$

$$\mathrm{dp} + \frac{\mathrm{dw}^2}{2\mathrm{v}} + \frac{\lambda \mathrm{w}^2}{2\mathrm{Dv}}\mathrm{dz} + \mathrm{gdz} = 0 \tag{2}$$

$$\mathrm{di} + \frac{\mathrm{dw}^2}{2} + \mathrm{gdz} = \mathrm{dq} \tag{3}$$

where A is the well cross-sectional area (m^2), $\dot{m}$ is the geothermal fluid flow rate (kg/s), D is the wellbore diameter (m), z is the well true vertical depth (m), p is the pressure in (Pa), w is the velocity (m/s), v is the specific volume ($\frac{m^3}{kg}$), λ is the frictional factor (-), i is the specific enthalpy (J/kg) and q is the heat energy (J/kg).

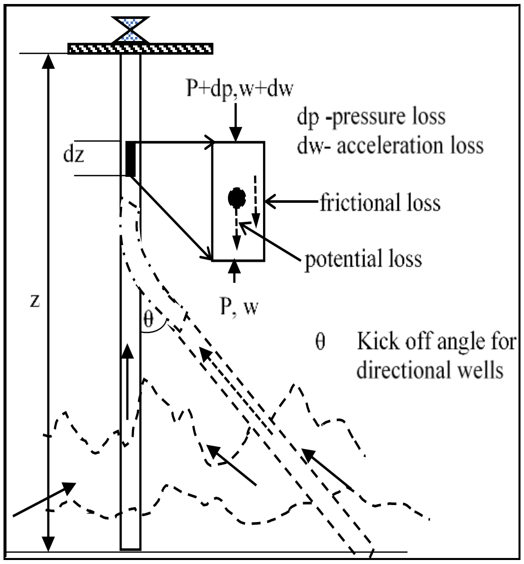

Figure 1: Basic wellbore model showing fluid flow from the reservoir up to wellhead (Itoi et al.)**.**

For momentum balance, the average velocities, $\overline{w}$ (m/s), for multiphase is given by equations 4 and 5 for steam and water, respectively (Faust and Mercer; C. R. Faust et al.; C. R. R. Faust et al.):

$$\overline{w}_s = \frac{K_T k_s}{\mu_s \left(\frac{\partial p_s}{\partial x_j} - \rho_s g\right)} \qquad (4)$$

and

$$\overline{w}_w = \frac{K_T k_w}{\mu_w \left(\frac{\partial p_w}{\partial x_j} - \rho_w g\right)} \qquad (5)$$

where K_T (m^2) is the permeability tensor.

For a mixture and average density, ρ is given in equation (6) and neglecting the effect of capillary pressure, energy mass and momentum equations yields equation (7).

$$\rho = \rho_s S_s + \rho_w S_w \qquad (6)$$

$$\frac{\partial}{\partial x_i}\left\{\frac{K_T k_w \rho_w}{\mu_w}\left(\frac{\partial p}{\partial x_j} - \rho_w g\right)\right\} + \frac{\partial}{\partial x_i}\left\{\frac{K_T k_s \rho_s}{\mu_s}\left(\frac{\partial p}{\partial x_j} - \rho_s g\right)\right\} + q_w + q_s = \frac{\partial(\emptyset\rho)}{\partial t} \qquad (7)$$

Thermal equilibrium is assumed to be instantaneous. The specific volume, v in equation (8) is a function of void fraction, α, equation (9) as per Smith's formula (Godbole et al.). Void fraction in geothermal fluid flow varies.

$$v = \frac{1}{\alpha\,\rho_s + (1-\alpha)\rho_s} \qquad (8)$$

The simulation of directional wells is an approximation of the cosine value of the angle between the wellbore axis and the vertical direction from the kick-off point (Marcolini et al.).

$$\alpha = \left\{1 + \rho_s/\rho_l\,(1-x)/x\right)\left[0.4 + 0.6\left(\frac{\frac{\rho_l}{\rho_s} + 0.4\left(\frac{1}{x}-1\right)}{1+0.4\left(\frac{1}{x}-1\right)}\right)^{0.5}\right]\Bigg\}^{-1} \quad (9)$$

For steady-state analysis, simulation and measurements boiling point for depth curve and conductive heat flux as a function of thermal conductivity is considered as shown in equation (10) (Watson).

$$\dot{q}_{(z)} = \lambda(P_s, T_s)\left(\frac{dT}{dz}\right) \quad (10)$$

3. RESULTS AND DISCUSSION

The presented study projected the link between wellhead and reservoir by exergy profile. Feed zones, strata, and the type of heat transfer were predicted by using a wellbore simulator for well in Olkaria Domes. The research investigated liquid-dominated Olkaria Domes wells, OW-901, OW-902, OW-903A. Wellbore simulation profiles represent well-flowing data under steady-state conditions and can be used to couple reservoir and wellhead. Exergy profiles of geothermal wells predict some subsurface behavior of geothermal reservoirs. The estimated cap-rock depth of the subsurface is in the hypothesis of the study.

In the case of boiling curve exergy, the exergy profile is like temperature profile for the hydrostatic pressure below the surface, as shown in Figure 2.

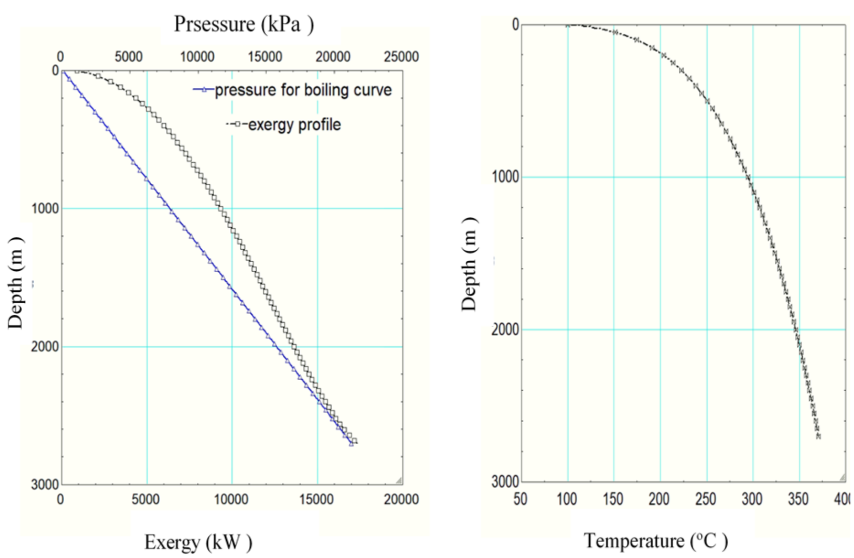

Figure 2: Exergy profile vs. depth, depth in m for the boiling curve saturated temperature and pressure simulated using EES code.

The maximum temperature reported in OW-901 is 342.3°C after 59 days of heating. Figure 3 shows the simulated temperature is lower than the formation/reservoir at 218°C. The flowing temperature and pressure data (on 09.02. 2000 and 26.07.1999) for OW-901 shows a good match with the simulated results. The feed zones are predicted to be between 1,550 -1,000 m.a.s.l. The bottom hole temperature increased from 233 to 250°C.

The wellbore simulator is closely related to the flowing field data recorded for OW 901, as shown in Figure 3. Pressure and temperature flowing patterns have similar gradients with the wellbore simulator. The good match between flowing and simulated data approves the reliability of the wellbore simulator to couple reservoir and wellbore. As in the case of T profiles, the flowing well data shows a good match to the wellbore simulated, with the good match being 1999 flowing data.

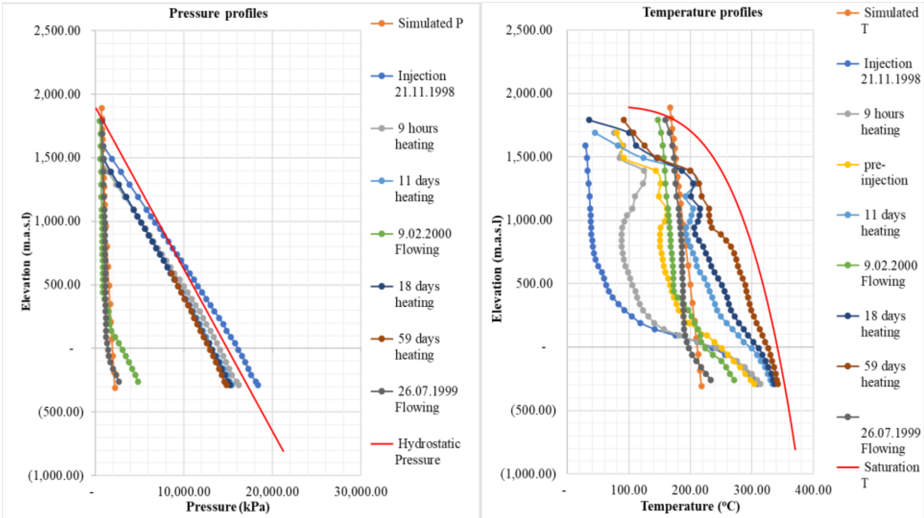

Figure 3: OW-901 pressure and temperature profiles vs. m.a.s.l.

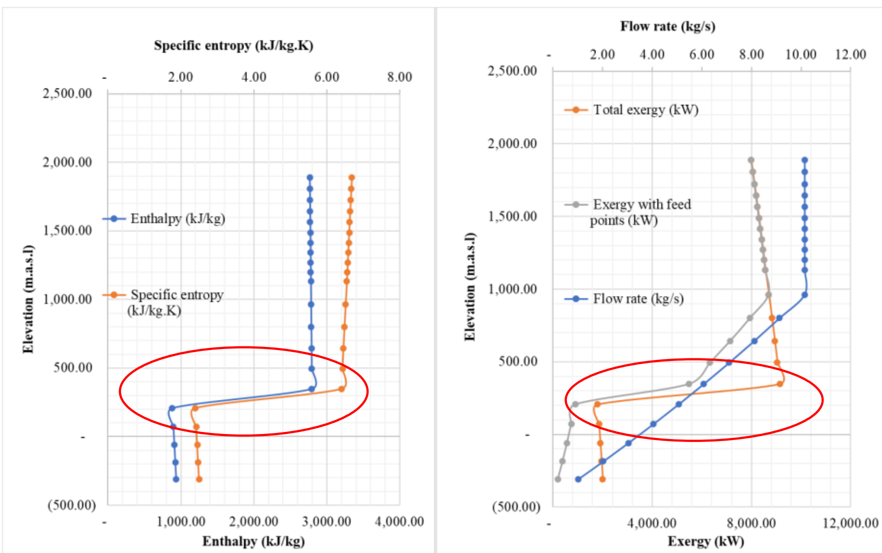

Figure 4: OW-901 exergy, enthalpy, and flow rate diagrams.

Figure 4 shows the exergy, enthalpy, and entropy profiles for OW-901. The exergy values at inferred reservoir location are at a minimum, and depths of around 250 m.a.s.l exergy increase then follow a steep gradient to the wellhead.. The feed zone points inferred below the casing shoe and exact locations are unclear. For the exergy profiles, the gradient is linear to depths beneath cap-rock. The cap-rack is predicted to levels where abrupt changes in exergy. The exergy changes correspond to the same depths for the enthalpy and entropy changes shown in Figure 4 for OW-901.

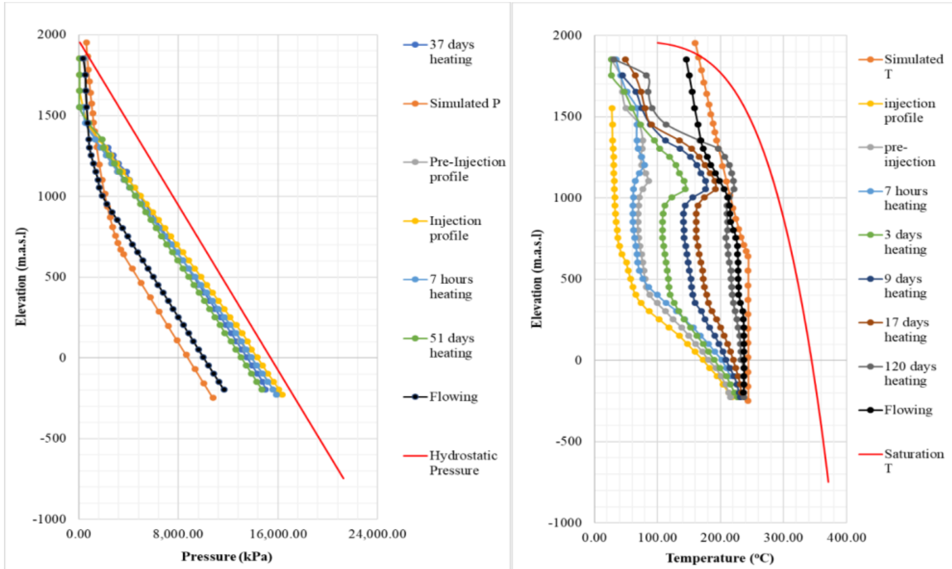

Figure 5: Pressure and temperature profiles during well tests, flowing and simulated using wellbore simulator for OW-902.

Figure 5 shows the OW-902 profiles with depth. The exciting part is that the flowing and simulated data have similar trends: the maximum formation pressure and temperature are almost identical. The simulated bottom hole pressure and temperature are 1,078 kPa and 244°C, respectively.

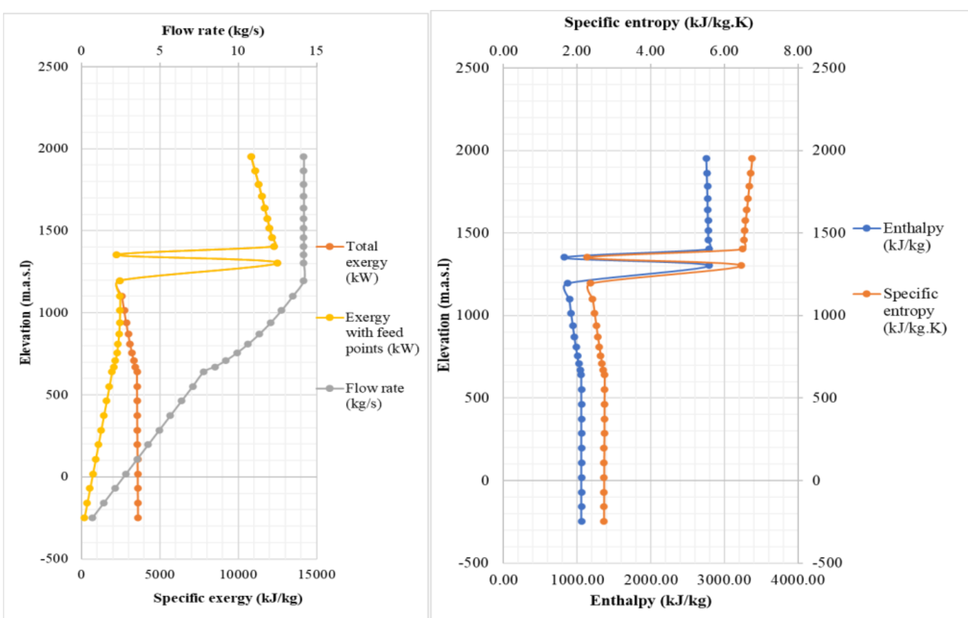

Figure 6: OW-902 exergy, enthalpy, and flow rate diagrams.

Figure 6 shows OW-902 exergy and enthalpy profile and the flow rate relation to m.a.s.l. At depths of approximately 1400 m.a.s.l, the well shows exergy losses and gains.

For wells OW-901 and OW-902, the actual exergy assumes that the flow rate is uniform from well bottom to wellhead, which is not the case in all the wells. The exergy and flow rates diagrams (as a possible scenario) consider a multi-feed zone between the well bottom and production casing depth. In the plots for flow rates, the flow rate and exergy increase with depth, and actual, and total exergy is the same at the production casing depth. Exergy insights are to couple the wellbore and reservoir because the data simulated are approximately close to actual flowing data, as seen in the cases of OW-902 and OW-901.

Table 2:Results of simulated temperature and pressure of wells in Olkaria Domes.

Well	Wellhead			Steam	Water	Simulated	
	P (kPa)	T (^oC)	Enthalpy (kJ/kg)	flow rate (t/hr)		Bottom T (^oC)	Formation P (kPa)
OW-901	735	166.93	1630.52	16.40	20.10	218.1	2,237.2
OW-902	618	160	1050.9	9.20	41.8	244	1,077.8
OW-903A	1,120	184		52	39	250	3,978

Figure 7 shows the well test completion tests for well OW-903A. The exergy profile of the well shows two distinct parts, the lower section of convective heat transfer and upper convective heat transfer above the cap rock. At a depth of 1,000 m.a.s.l, the temperature reduces, and there is exergy gain. For the reservoir beneath well OW-903A, the section with sharp exergy change inferred to be the cap rock layer.

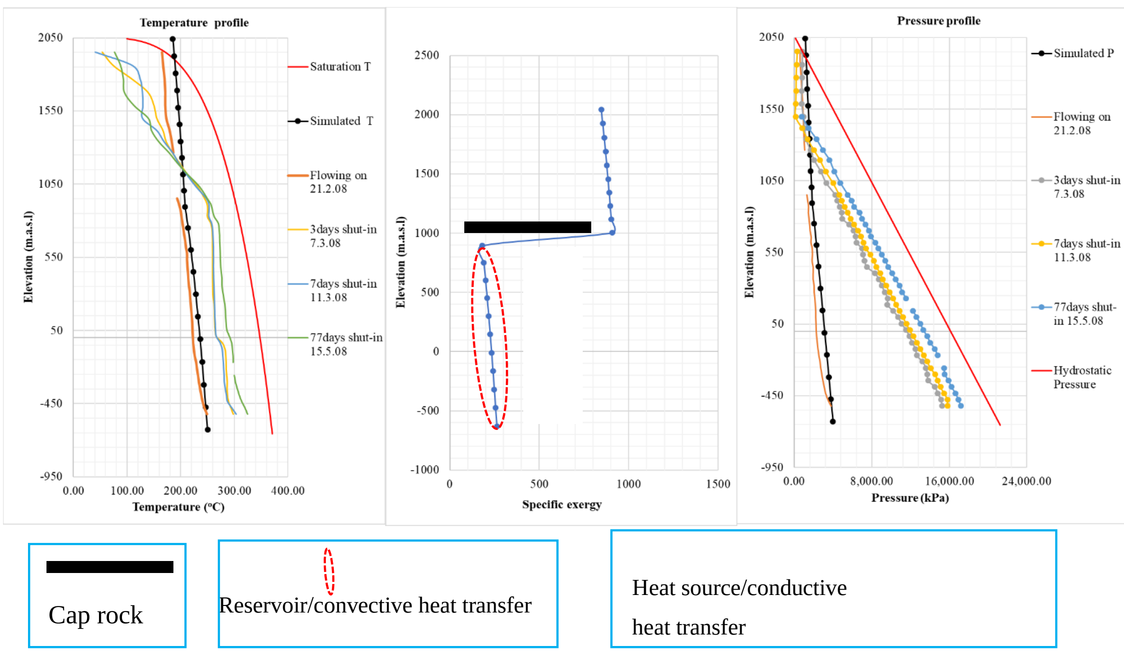

Figure 7: Well, OW-903A downhole pressure-temperature log profiles during well testing and simulated temperature, exergy, and pressure profiles.

4. CONCLUSION

Exergy is a powerful tool for optimal utilisation of geothermal resources at the surface and power plants. A wellbore simulator was used to obtain temperature and pressure profiles of water-dominated geothermal wells in Olkaria Domes geothermal field. The exergy concept is applied to plot corresponding exergy profiles. Convective heat transfer is in the reservoir section below cap rock and above 0 m.a.s.l. The exergy profile shows the convective and conductive heat transfer regions and upflow zone. From the exergy profile, the location of the reservoir, cap rock, and heat source are hypothesised. Thus, the need to couple wellbore and reservoir.

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